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A Refinement and Extension of the No-Envy Concept

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A REFINEMENT AND EXTENSION OF THE NO-ENVY CONCEPT

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1. Introduction

The concept that has recently played the most important role in the economic analysis of equity issues is probably that of no-envy (Foley, 1967): an allocation z is **envy-free** if no agent would prefer someone else's consumption to his own. Of course, the introduction of this concept did not solve all distributional issues. This is in part because the set of envy-free and efficient allocations may be quite large or it may be empty. In the first case, there arises the issue of deciding which of the envy-free and efficient allocations are preferable from the viewpoint of distribution. In the second case, the concept offers no recommendation at all. Unfortunately, each of these two problems is quite frequent. For instance, in a two person exchange economy, the set of envy-free and efficient allocations usually strictly contains the set of efficient allocations that Pareto dominate equal division of resources (Figure 1). Conversely, in a production economy in which the agents are differently productive, there may be no envy-free and efficient allocations (Pazner and Schmeidler, 1974).

Strengthening the no-envy concept would help solve the multiplicity problem but would make matters worse so far as existence is concerned; weakening the concept would have the opposite effect. In this note, we propose a new concept of equity which simultaneously solves the two problems. This concept, which is still very much in the spirit of Foley's original concept of no envy, can be seen as maximally strengthening it to solve the multiplicity problem and minimally weakening it to recover existence.

2. Notation, definitions, result

There are k private goods, m public goods, n agents, and n types of "time", one for each agent. Time of type i can either be consumed by agent i as leisure or contributed to the production process as labor. (We could have more agent-specific inputs with no difficulty.) We denote the set of agents by N.

Agent i, for each $i \in N$, is characterized by (i) a closed and convex consumption set $Z_i \subset \mathbf{R}_+ \times \mathbf{R}_+^k \times \mathbf{R}_+^m$ containing the origin, and (ii) a preference relation, defined on Z_i, and assumed to admit a continuous numerical representation $u_i : Z_i \to \mathbf{R}_+$. Let $U \equiv (u_1, \ldots, u_n)$.

Let $\Omega = (L, X) \in \mathbf{R}^n_{++} \times \mathbf{R}^k_{++}$ be the vector of initial endowments. L_i, for i in N, is the time endowment of agent i; X_q, for $q = 1, \ldots, k$, is the aggregate endowment of the qth private good. Note that X is not indexed by agents; all agents are collectively entitled to all goods, initially available or produced, except time, which cannot be redistributed.

There is a production set $Y \subset \mathbf{R}^n_- \times \mathbf{R}^k \times \mathbf{R}^m_+$, which is closed and such that $Y + \Omega \cap \mathbf{R}^n_+ \times \mathbf{R}^k_+ \times \mathbf{R}^m_+$ is bounded from above. Note that some or all of the private goods can be inputs as well as outputs, labor is only an input, and public goods are only outputs[1].

The allocation space is $\mathcal{A} = \mathbf{R}^n_+ \times \mathbf{R}^{nk}_+ \times \mathbf{R}^m_+$. An allocation $(l, x, y) \in \mathcal{A}$ is **feasible for** (U, Ω, Y) if for all i, $(l_i, x_i, y) \in Z_i$, and $(l - L, \sum x_i - X, y) \in Y$. Let $A(\Omega, Y) \subset \mathcal{A}$ be the set of feasible allocations of (U, Ω, Y), and $P(U, \Omega, Y) \subset A(\Omega, Y)$ its set of Pareto efficient allocations.

An **equity criterion** E associates with each economy (U, Ω, Y) a subset $E(U, \Omega, Y)$ of $A(\Omega, Y)$ of allocations at which agents are thought to be equitably sharing in the society's resources. The intersection of the equity criterion E with the Pareto criterion P is denoted by EP. The criterion that has been the object of the greatest interest is the following.

Definition. An allocation $z = (l, x, y) \in A(\Omega, Y)$ is **envy-free for** (U, Ω, Y) if there is no pair $i, j \in N$ such that $u_i(l_i, x_i, y) < u_i(l_j, x_j, y)$. Let $F(U, \Omega, Y)$ designate the set of these allocations.

As noted earlier, $FP(U, \Omega, Y)$ may be very large, but it also may be empty.

We now turn to our concept, for which we draw upon ideas recently developed by Chaudhuri (1986). This author proposes evaluating the extent to which an allocation may fail to be envy-free by comparing each agent's consumption to the other agents' consumptions subjected to appropriate radial contractions. More precisely, suppose that agent i envies agent j, i.e. $u_i(z_j) > u_i(z_i)$. Chaudhuri

[1]Our theorem does not depend upon this restriction.

suggests taking the value of λ for which $u_i(\lambda z_j) = u_i(z_i)$ as a measure of how much agent i envies agent j. He then defines an aggregate measure of envy by summing up these individual measures over all pairs i, j such that $u_i(z_j) > u_i(z_i)$.

We propose here first to consider radial contractions **and expansions** of consumptions; this allows us to evaluate the extent to which an allocation may fail to meet the no-envy requirement **as well as the extent to which an allocation may exceed it.** Then, by taking the **maximal** λ for which $u_i(z_i) \geq u_i(\lambda z_j)$ for all i, j as a measure of envy in the economy we identify which allocations minimally violate the no-envy criterion when the criterion cannot be met by any efficient allocation, or maximally satisfy it when it is met by multiple efficient allocations. Our approach enables us to perform selections from the set of envy-free and efficient allocations when it is not empty; Chaudhuri's approach is not sufficient for this.[2] Also, minimizing Chaudhuri's aggregate measure of envy can lead to allocations at which the distribution of envy is very skewed. We feel that our criterion, which is designed to equate envy, or distance from envy, across agents, is more in keeping with the spirit that has guided the search for equity criteria.

Definition. Given $\lambda \in \mathbf{R}_+$, the allocation $z \in A(\Omega, Y)$ is **λ-envy-free for** (U, Ω, Y) if there is no pair $i, j, i \neq j$, such that $u_i(l_i, x_i, y) < u_i(\lambda l_j, \lambda x_j, \lambda y)$. Let $F^\lambda(U, \Omega, Y)$ be the set of these allocations.

Note that $F^1(U, \Omega, Y) = F(U, \Omega, Y)$, and $F^0(U, \Omega, Y) = A(\Omega, Y)$. Also, if $\lambda > \lambda'$, $F^\lambda(U, \Omega, Y) \subset F^{\lambda'}(U, \Omega, Y)$.

Given (U, Ω, Y), let $\lambda(U, \Omega, Y)$ be the maximal λ such that $F^\lambda P(U, \Omega, Y) \neq \emptyset$. The following example shows that $\lambda(U, \Omega, Y)$ may not exist and, similarly, $F^\lambda(U, \Omega, Y)$ may be non-empty for all $\lambda \in \mathbf{R}_+$.

Example 1. There are no labor inputs, and $k = 2$, $m = 0$, $n = 2$. Let $u_1(z_1) = z_{11}$, $u_2(z_2) = z_{22}$. Also, $Y \equiv \{ z_o \in \mathbf{R}^2_+ \mid z_o \leq (1,1) \}$[3]. In this (exchange) economy, $P(U, \Omega, Y) = \{ ((1,0),(0,1)) \} \equiv \{ z^* \}$, and $z^* \in F^\lambda(U, \Omega, Y)$ for all

[2] Chaudhuri also advocates using radial contractions of bundles only if preferences are homothetic. We have not imposed this restriction.

[3] Vector inequalities: $\gg, >, \geq$.

$\lambda \in \mathbf{R}_+$.

Although we could meaningfully extend the domain of definition of the function λ by allowing it to take on the value $+\infty$ in economies such as the one in the example, we will find it more convenient to make assumptions on the economy guaranteeing that given any $(l, x, y) \in A(\Omega, Y)$ there is λ such that for no pair i, j $u_i(l_i, x_i, y) < u_i(\lambda l_j, \lambda x_j, \lambda y)$.

For any positive integer s, for any two sets $X, Y \subset \mathbf{R}^s$, the **ray mapping** $r : X \to Y$ associates with each point $x \in X$ the set of points $y \in Y$ such that there exists $\mu \in \mathbf{R} \backslash \{0\}$ for which $y = \mu x$.

Assumption A. For all i, u_i is strictly increasing and for all $\bar{u}_i \in$ range u_i, the set $\{ (l_i, x_i, y) \in Z_i \mid u_i(l_i, x_i, y) = \bar{u}_i \}$ is homeomorphic to Δ^{k+m} with the ray mapping.

Under A our main definition, given next, is non-vacuous, as we will show.

Definition. Given (U, Ω, Y) such that $\lambda(U, \Omega, Y)$, the maximal λ such that $F^\lambda P(U, \Omega, Y) \neq \emptyset$ exists, let $F^* P(U, \Omega, Y) \equiv F^{\lambda(U,\Omega,Y)} P(U, \Omega, Y)$.

[Figure 1 about here]

The definition is illustrated in Figure 1, where it is put to use to perform a selection from $FP(U, \Omega, Y)$. In the Figure, $FP(U, \Omega, Y)$ is the curvilinear segment $[z^1, z^2]$. z^1 is such that $u_1(z_1^1) = u_1(z_2^1)$; z^2 satisfies $u_2(z_1^2) = u(z_2^2)$. There is a unique allocation $z^* \in F^* P(U, \Omega, Y)$. It is such that for some $\lambda > 1$, $u_1(z_1^*) = u_1(\lambda z_2^*)$ and $u_2(z_2^*) = u_2(\lambda z_1^*)$.

For all $z \in A(\Omega, Y)$, for all i, j, let

$$\beta_{ij}(z) \equiv \{ \lambda \in \mathbf{R}_+ \mid \lambda z_j \in Z_i,\ u_i(z_i) \geq u_i(\lambda z_j) \}, \text{ and}$$

$$\lambda_{ij}(z) \equiv \max\{\lambda \in \mathbf{R}_+ \mid \lambda \in \beta_{ij}(z) \}.$$

Lemma. Under A, each $\lambda_{ij} : A(\Omega, Y) \to \mathbf{R}_+$ is a continuous function.

Proof: For all $z \in A(\Omega, Y)$, $\beta_{ij}(z) \neq \emptyset$, because $0 \in \beta_{ij}(z)$. $\beta_{ij}(z)$ is also closed, by the closedness of Z_i and the continuity of u_i, and bounded above, by assumption

A. Therefore, for all $z \in A(\Omega, Y)$, $\lambda_{ij}(z) \neq \emptyset$. Clearly, $\lambda_{ij}(z)$ is a singleton, thus λ_{ij} is a well-defined function.

To show continuity, let $f : \mathbf{R}_+ \times A(\Omega, Y) \rightarrow \mathbf{R}_+$ be defined by $f(\lambda, z) \equiv \lambda$. Obviously, f is a continuous function. We have:

$$\lambda_{ij}(z) = \max\{ \, f(\lambda, z) \mid \lambda \in \beta_{ij}(z) \, \}.$$

Let $\lambda^*_{ij}(z)$ be equal to the (unique) solution to the equation in λ $u_i(l_i, x_i, y) = u_i(\lambda l_j, \lambda x_j, \lambda y)$ if such a solution exists, and be set equal to infinity if for all $\lambda \in \mathbf{R}_+$ either $u_i(l_i, x_i, y) > u_i(\lambda l_j, \lambda x_j, \lambda y)$, or if $(\lambda l_j, \lambda x_j, \lambda y) \notin Z_i$ for all $\lambda > \bar{\lambda}$ at which $u_i(l_i, x_i, y) > u_i(\bar{\lambda} l_j, \bar{\lambda} x_j, \bar{\lambda} y)$. The function $\lambda^*_{ij} : A(\Omega, Y) \rightarrow \mathbf{R}_+ \cup \{+\infty\}$ so defined is continuous.

We claim that β_{ij} is a compact-valued and continuous correspondence. In the discussion below, a barred variable represents upper bounds to the consumption set in the direction of the corresponding good — if there is no upper bound in some direction, it is $+\infty$ by convention. We have already shown compact-valuedness of β_{ij}; continuity follows because β_{ij} can be written as

$$\beta_{ij}(z) = \{ \, \lambda \in \mathbf{R}_+ \mid \lambda \leq \min[\bar{l}_i/l_j, \bar{x}_{i1}/x_{j1}, \ldots, \bar{x}_{ik}/x_{jk}, \lambda^*_{ij}(z)] \, \};$$

(see Hildenbrand, 1974, p. 22, Ex. 3, and p. 26, Ex. 3).

Thus, by a corollary to the maximum theorem (Hildenbrand, 1974, p. 30) λ_{ij} is an upper hemi-continuous correspondence, hence it is continuous, since it is a function (Hildenbrand, 1974, p. 21, Ex. 1).

Q.E.D.

Theorem. Under A, $F^*P(U, \Omega, Y) \neq \emptyset$.

Proof: Let $z \in A(\Omega, Y)$ be given. Let λ_{ij} be defined as above, and let

$$\lambda_i(z) \equiv \min\{ \, \lambda_{ij}(z) \mid j \neq i \, \}, \quad \text{and} \quad \lambda(z) \equiv \max\{ \, \lambda_i(z) \mid i \in N \, \}.$$

By the lemma, the function $\lambda : A(\Omega, Y) \rightarrow \mathbf{R}_+$ is well defined and continuous. We have $F^*P(U, \Omega, Y) = \operatorname{argmax} \{ \, \lambda(z) \mid z \in P(U, \Omega, Y) \, \}$.

$A(\Omega, Y)$ is a compact set. $P(U, \Omega, Y) \subset A(\Omega, Y)$, and $P(U, \Omega, Y)$ is a closed set, by the continuity of the u_i and the closedness and boundedness of Y. Therefore, $P(U, \Omega, Y)$ is a compact set, and thus $F^*P(U, \omega, Y) \neq \emptyset$.

Q.E.D.

We discussed earlier the main advantages of our concept: it is an ordinal concept, very much in the spirit of the no-envy concept, it is minimal as an extension of this concept, and maximal as a refinement. We now pursue in greater detail the comparison of the two concepts and we mention a few open questions.

If $n = 2$, and $z \in F^*P(U, \Omega, Y)$, then for each $i \in N$ $u_i(z_i) = u_i(\lambda(U, \Omega, Y)z_j)$. This is an appealing result which says that envy (or lack of envy) has truly been equalized across agents. However, we do not know whether the following extension of this result to $n > 2$ is true: if $z \in F^*P(U, \Omega, Y)$, then, for all $i \in N$ there exists $j \in N$ such that $u_i(z_i) = u_i(\lambda(U, \Omega, Y)z_j)$. Similarly, we do not have an answer to the related question of essential single-valuedness of F^*P, i.e. whether, if $z, z' \in F^*P(U, \Omega, Y)$, then for all $i \in N$, $u_i(z_i) = u_i(z'_i)$.

The two concepts share the following limitations. (i) If $z \in F^*P(U, \Omega, Y)$, then z need not Pareto-dominate equal division. (ii) Pareto-indifference is violated: it is possible to have $z \in F^*P(U, \Omega, Y)$, $z' \in P(U, \Omega, Y)$ such that $u_i(z_i) = u_i(z'_i)$ for all $i \in N$, and yet $z' \notin F^*(U, \Omega, Y)$. (iii) Finally, the following somewhat puzzling phenomenon may occur (Thomson 1987): in the Edgeworth box, of all the allocations that are Pareto-indifferent to $z \in F^*P(U, \Omega, Y)$, z is the farthest away from equal division (Figure 2).

[Figure 2 about here]

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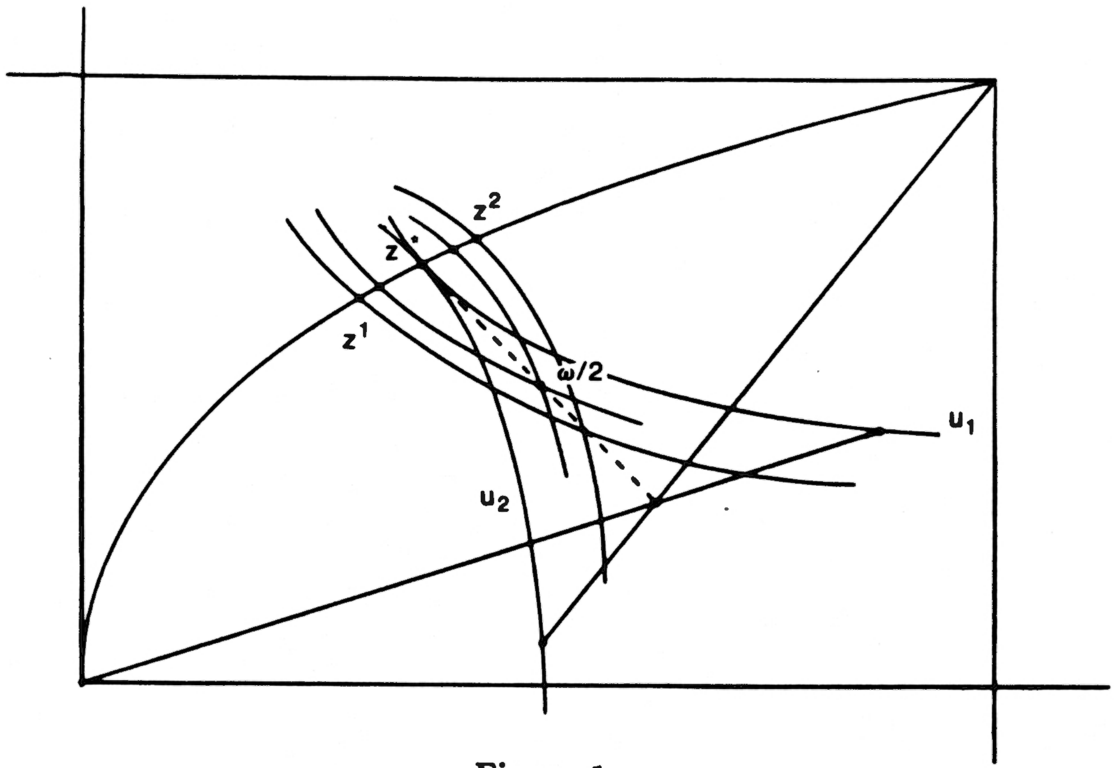

Figure 1

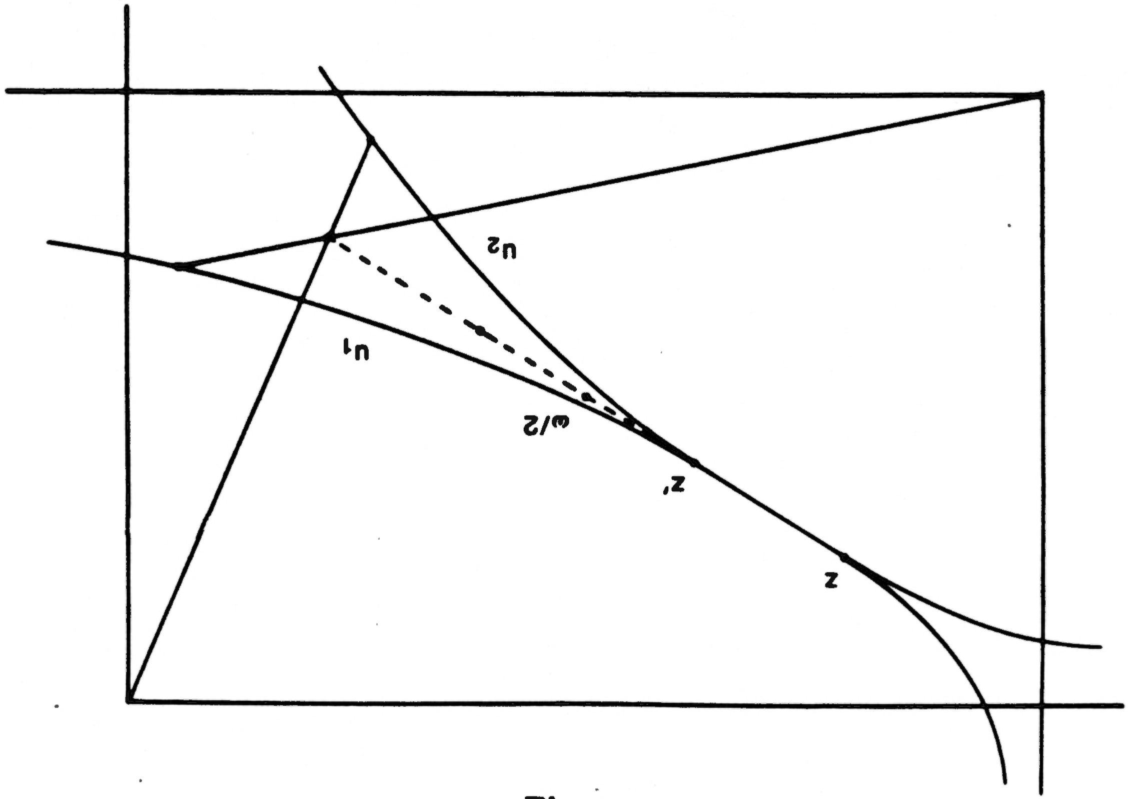

Figure 2

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