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**Consistent Solutions in Exchange
Economies: a Characterization of the Price
Mechanism***

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Abstract

We characterize the Walrasian allocations correspondence by means of four axioms: consistency, replica invariance, individual rationality and Pareto optimality. It is shown that for any given class of exchange economies any solution that satisfies the axioms is a selection from the Walrasian allocations with slack. Preferences are assumed to be smooth, but may be satiated and non-convex. A class of economies is defined as all economies whose agents' preferences belong to an arbitrary family (finite or infinite) of types. The result can be modified to characterize equal budget Walrasian allocations with slack by replacing individual rationality with individual rationality from equal division. The results are valid also for classes of economies in which core-Walras equivalence does not hold.

1. INTRODUCTION

The most important solution concept in economics is price equilibrium. However there is a rather limited amount of literature which characterizes the price mechanism as a consequence of more basic assumptions. Most of the literature concentrates on identifying economies in which price equilibrium coincides with other solutions such as the core (e.g. Aumann, 1964). This state of affairs is much different than that of cooperative game theory and bargaining where most solution concepts are axiomatically characterized.

It is now known that almost all the major solution concepts in cooperative game theory and bargaining satisfy a certain consistency property (the Davis-Maschler, 1965, reduced game property) and can be exactly characterized by this property and some more additional requirements. These solutions include the core of TU and NTU games (Peleg 1986, 1985), the Nash bargaining solution (Lensberg 1988), the prenucleolus (Sobolev 1975), and the prekernel (Peleg 1986).¹

The study of consistency in models other than cooperative games or bargaining problems has developed by defining particular consistency properties to each model, and therefore it is difficult to compare results obtained in different models. Another feature is that most literature is confined to situations where the agents have a collective endowment, and thus the major descriptive solutions in economics cannot be studied in the existing framework.

This paper identifies a consistency property that can be defined on a large range of economic situations where agents have private endowments. The paper provides a characterization of the Walrasian equilibrium with slack by four axioms: consistency, replica

¹An exception is the Shapley value; however it was characterized by a different reduced game property by Hart and Mas-Colell (1989).

invariance, individual rationality and Pareto optimality.² The characterization result holds for many classes of economic situations, and in particular can be applied to the class of economies with convex and locally non satiated preferences, and to the single-peaked preferences problem. In addition, by replacing individual rationality with individual rationality from equal division we obtain a characterization of the equal budget Walrasian equilibrium with slack. This latter result generalizes Thomson (1988, Theorem 3) and Thomson (1994, Theorem 4) who characterized equal budget Walrasian allocations in locally non satiated exchange economies, and the uniform rule of the fair division problem when preferences are single peaked, respectively.

Consistency properties in exchange economies with private endowments were first considered by Thomson (1992). Assume a certain allocation is a solution of a given economy. The question is how to define a reduced economy whose members are a subset of the whole set of agents and their possibilities are derived from the assumption that they should keep their agreement with the agents outside the reduced economy. Thomson (1992) proposed several definitions. The one we adopt is the following. In the reduced economy the agents have the same preferences as in the original economy, and the endowments are modified by dividing the trade with the rest of the world equally among the agents. Consider the case where the allocation is a Walrasian allocation (in the classical sense). In this case the value of the trade the agents do with the rest of the world is zero when evaluated by the Walrasian prices. Thus, dividing the trade equally will keep each agent's income fixed and therefore the equal division of the trade is sensible. The main result of this paper may be interpreted as that only when trades and bundles can be evaluated by prices such a division of the trade is sensible.

²The notion of Walrasian equilibrium with slack was studied by Mas-Colell (1988) and generalizes the concept of Walrasian equilibrium to economies with possibly satiated preferences.

The results of this paper are related to those of Thomson and Zhou (1993). They studied solutions to economies with a collective endowment and a continuum of agents. One of their important discoveries is that in the case of continuum economies, the domain of the solution can be very small: only a given economy and all its reduced economies. This paper establishes a result that has some similar features for economies with a finite number of agents. Indeed, here we require the domain to include economies with any finite number of agents, but the variety of preferences in the domain can be arbitrarily chosen. This observation is sufficient to conclude that different economic situations such as classical exchange economies and the fair division problem where preferences are single peaked do admit a unified treatment also in the case of economies with a finite number of agents. It should be noted that other results, (e.g. Thomson ,1994, Theorems 1 and 2), are valid only in the case where the domain includes a large variety of preferences, although they hold for domains with a finite number of potential agents (or more precisely names of agents).^{3 4}

Our analysis shows that convexity assumptions on preferences are not necessary for the main result, even when one considers finite agent economies. In particular we prove a variant of the second welfare theorem without convexity and local non satiation (Lemma 2). This lemma is inspired by Campbell (1988) who showed that an allocation whose replica is Pareto optimal in all replicas of the economy can be decentralized by prices. Both Campbell's theorem and Lemma 2 hold without any convexity or smoothness assumption. Lemma 2 generalizes Campbell's theorem to the case where preferences may be satiated.

Another definition of a reduced economy, proposed by Thomson (1992), was studied

³Thomson (1994) stated and proved his Theorems 1 and 2 for a variable number of agents, however Dagan (1995) had shown that the domain can be restricted.

⁴In a domain with a finite number of potential agents the economies are limited by size, however the choice of preferences is not limited, so one may consider different economies where the same "name" has different preferences.

by van den Nouweland, Peleg, and Tijs (1994), and by Dagan (1994). Their results are discussed in Section 4.2.

The paper is organized as follows. The model is presented in Section 2; consistency is discussed in Section 3; the Theorem is given and discussed in Section 4; Section 5 provides a "fair allocation" variant of the Theorem; and the proofs are given in Section 6.

2. THE MODEL

2.0 Notation

We denote the k -dimensional Euclidian space by \mathbb{R}^k ; the non negative orthant by \mathbb{R}_+^k ; and the interior of \mathbb{R}_+^k by \mathbb{R}_{++}^k . The interior of a set A is denoted by $\text{int}(A)$, and the convex hull of A by $\text{Co}(A)$. The cardinality of a set S is denoted by $\#S$.

2.1 A Model

A *type* on \mathbb{R}^k is a pair (X, R) where $X \subset \mathbb{R}^k$ is the consumption set, R is a reflexive preference relation on X . For a type (X, R) define the strict preference relation P as follows: For all $x, y \in X$ xPy if and only if xRy and not yRx . Note that by construction P is irreflexive. For all $x \in X$ let $R(x) := \{y \in X: yRx\}$ and $P(x) := \{y \in X: yPx\}$.

An *economy* is a pair $[\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$, where \mathbb{R}^k is the commodity space; N is a finite nonempty set of agents; for all agents $i \in N$ (X_i, R_i) is a type on \mathbb{R}^k , and $\omega_i \in \mathbb{R}^k$ is an endowment.

An *allocation* is a list $(x_i)_{i \in N}$ where for all $i \in N$ $x_i \in X_i$ and $\sum_{i \in N} \omega_i = \sum_{i \in N} x_i$.

2.2 Walrasian Equilibria with Slack

Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy. A *Walrasian equilibrium with slack* is a triple $[(x_i)_{i \in N}, p, s]$ where $(x_i)_{i \in N}$ is an allocation; $p \in \mathbb{R}^k \setminus \{0\}$; $s \in \mathbb{R}_+$; for all $i \in N$ $x_i \in \{x \in \mathbb{R}^k: px \leq p\omega_i + s\}$ and $P_i(x_i) \cap \{x \in \mathbb{R}^k: px \leq p\omega_i + s\} = \emptyset$. The allocation $(x_i)_{i \in N}$ associated with a Walrasian equilibrium with slack is called a *Walrasian allocation*. We

denote by $W(e)$ the set of all Walrasian allocations of e . As we do not assume monotonicity or free disposal, we allow prices to be negative. This generalization of Walrasian equilibrium to economies with satiated preferences is due to Mas-Colell (1988).

2.3 Individual Rationality and Pareto Optimality

Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy. An allocation $(x_i)_{i \in N}$ is *individually rational* if for all $i \in N$ $\omega_i \notin P_i(x_i)$.

An allocation $(x_i)_{i \in N}$ is *Pareto optimal* if there does not exist an allocation y such that for all $i \in N$ $y_i = x_i$ or $y_i \in P_i(x_i)$, and for some $i \in N$ $y_i \in P_i(x_i)$.

This definition of Pareto optimality is the finite agent analogue of the definition in Thomson and Zhou (1993). It is intermediate to the more standard stronger and weaker versions. The stronger version would be to ask $y_i \in R_i(x_i)$ instead of $y_i = x_i$ or $y_i \in P_i(x_i)$, and the weaker one would ask $y_i \in P_i(x_i)$ for all i .

Walrasian allocations are individually rational and Pareto optimal. Formally:

PROPOSITION 1: Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy. And let $[(x_i)_{i \in N}, p, s]$ be a Walrasian equilibrium with slack. Then $(x_i)_{i \in N}$ is individually rational and Pareto optimal.

Proof: By definition, for all $i \in N$ $x_i \in \{x \in \mathbb{R}^k : px \leq p\omega_i + s\}$ and $P_i(x_i) \cap \{x \in \mathbb{R}^k : px \leq p\omega_i + s\} = \emptyset$. As $s \geq 0$ $\omega_i \in \{x \in \mathbb{R}^k : px \leq p\omega_i + s\}$ for all i , and thus $\omega_i \notin P_i(x_i)$ for all i . Now, any allocation $(y_i)_{i \in N}$ that makes some of the agents better off, and leaves the rest of the agents *with the same bundle* satisfies $p \sum_{i \in N} \omega_i = p \sum_{i \in N} y_i > p \sum_{i \in N} x_i = p \sum_{i \in N} \omega_i$ a contradiction. Therefore $(x_i)_{i \in N}$ is Pareto optimal. ☺

Note that Walrasian allocations do not necessarily satisfy the stronger form of Pareto optimality in the case of satiated preferences.

2.4 Solutions

Let Ω be a non-empty set of economies. A *solution* on Ω is a correspondence that assigns each economy in Ω a set (possibly empty) of allocations.

3. CONSISTENCY

We begin with the definition of a reduced economy:

Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy, and $x = (x_i)_{i \in N}$ be an allocation, and $S \subset N$.

The *reduced economy* of e with respect to S and x is the economy:

$$e^{S,x} = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]^{S,x} = [\mathbb{R}^k, (X_i, R_i, \omega_i')_{i \in S}], \text{ where for all } i \in S \omega_i' = \omega_i + (1/\#S) \sum_{j \in N \setminus S} (\omega_j - x_j).$$

The reduced economy of e with respect to S and x is the economy whose members are the members of S , and the sum of the trades the members of S do with the rest of the agents is divided equally among the members of S .

Now we are ready to define consistency.

A solution f on Ω is *consistent* if for all economies $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ in Ω , and for all $S \subset N$, for all $x \in f(e)$, if $e^{S,x} \in \Omega$, then $x|_S \in f(e^{S,x})$.

If a consistent solution assigns an allocation to a given economy, then it assigns the reduced allocation to the reduced economy, provided the reduced economy is in the domain of the solution.

It turns out that the Walrasian allocations correspondence is consistent for all domains of economies. Formally we have:

PROPOSITION 2: Let Ω be a non empty set of economies. The solution that assigns all economies in Ω their Walrasian allocations is consistent.

Proof: Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy in Ω , and let $x = (x_i)_{i \in N}$ be a Walrasian

allocation. Thus there exists a price vector p and a slack s , such that $[x, p, s]$ is a Walrasian equilibrium with slack. Now let $S \subset N$. Define $s' = s - (1/\#S)p \sum_{j \in N \setminus S} (\omega_j - x_j)$. As x is an allocation $\sum_{j \in N} (x_j - \omega_j) = 0$, so $p \sum_{j \in N \setminus S} (\omega_j - x_j) = p \sum_{j \in S} (x_j - \omega_j) \leq (\#S)s$, thus $s' \geq 0$. Further note that for all $i \in S$ $p \omega_i + s = p[\omega_i + (1/\#S) \sum_{j \in N \setminus S} (\omega_j - x_j)] + s'$. Thus $[x|S, p, s']$ is a Walrasian equilibrium with slack of the economy $e^{S, x}$. ☺

Given an economy $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$, the m -fold replica of e is the economy $e(m) = [\mathbb{R}^k, (X_{ij}, R_{ij}, \omega_{ij})_{ij \in N \times M}]$ where $M = \{1, 2, \dots, m\}$ and for all $ij \in N \times M$ $(X_{ij}, R_{ij}, \omega_{ij}) = (X_i, R_i, \omega_i)$. The m -fold replica of an allocation $(x_i)_{i \in N}$ of e is an allocation $(x_{ij})_{ij \in N \times M}$ of $e(m)$ in which for all $ij \in N \times M$ $x_{ij} = x_i$.

A solution f on Ω is *replica invariant* if for all economies $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ in Ω , and for all $M = \{1, 2, \dots, m\}$, for all $(x_i)_{i \in N} \in f(e)$, if $e(m) \in \Omega$, then $(x_{ij})_{ij \in N \times M} \in f(e(m))$.

PROPOSITION 3: Let Ω be a non empty set of economies. The solution that assigns all economies in Ω their Walrasian allocations is replica invariant.

Proof: Trivial. ☺

4. THE MAIN RESULT

4.1 Theorem

In this section we restrict attention to economies in which the types of the agents satisfy the following assumptions. Let (X, R) be a type on \mathbb{R}^k .

A1 Upperhemi continuity: For all $x \in X$ $P(x)$ is open relative to X .

A2 Local non satiation at non satiated points: For all $x \in X$ if $P(x) \neq \emptyset$, then $P(x) \cap O(x) \neq \emptyset$, for all open balls $O(x)$ around x .

A3 *Smoothness*: $X = \mathbb{R}_+^k$ and for all $x \in X$ if $P(x) \neq \emptyset$, there exists at most one hyperplane through x with normal p such that for all $y \in P(x)$ $px \leq py$.

The main result of this paper is as follows:

THEOREM: Let T be a set of types on \mathbb{R}^k that satisfy A1-A3. Let $\Omega(T)$ be the class of all economies in which the agents types belong to T . If a solution f on $\Omega(T)$ is consistent, replica invariant and assigns individually rational and Pareto optimal allocations, then for all $e \in \Omega(T)$ $f(e) \subset W(e)$.

4.2 Discussion

The Theorem does not characterize the Walrasian allocations exactly, but only with inclusion. In order to derive exact characterizations, one usually considers domains Ω in which the solution is nonempty, and that contain a large enough variety of preferences to exclude nonempty subsolutions. We do not do this, as we are interested in phenomena that hold across many domains.

The Theorem can be modified to economies with a continuum of agents. In this case the result holds without replica invariance for a domain containing an economy and all its reduced economies. This domain is analogous to the one used in the Theorem of Thomson and Zhou (1993). They note that the domain in the continuum case is smaller (in an intuitive sense) than in the finite agent case, and therefore consistency is a weaker requirement. We disagree with this statement. Consider the following hypothetical domain: An economy with a countable number of agents and all its reduced economies that also contain a countable number of agents. This domain is not smaller in any respect than the domain we have in the Theorem, as the one in the Theorem can be viewed as the set of all finite agent reduced

economies of a countable economy. The hypothetical domain is intuitively analogous to the one needed in continuum economies.

An important feature of the Theorem is that there is no need for a variety of types in the domain of economies in which the solution is defined for. As noted in the Introduction other results such as Thomson (1994, Theorems 1 and 2) do require a large variety of types, although these other results do not require a large number of potential agents. Most previous literature on consistency makes note only of the differences in domains concerning the number of potential agents. We think that this is a consequence of the fact that the notion of the variety of types is meaningless in cooperative games, the area in which consistency was first analyzed.

Our result is related to Zhou (1992), who characterized equal budget Walrasian allocations in large economies as equivalent to strictly fair allocations. We show that the axioms imply that the allocations recommended by the solution satisfy a condition stronger than strict fairness (with respect to net-trades) and then apply a generalization of the Second Welfare Theorem to derive a generalization of Zhou's replica result. Zhou notes that other characterizations based on the weaker notion of fair allocations such as Champsaur and Laroque (1981) require a large variety of preferences in the given continuum economy, and therefore do not hold in finite type economies or replica sequences. We think that this phenomena is similar to the fact that the characterization of the uniform rule based on requiring the allocations to be envy-free (Thomson 1994, Theorem 1) is valid on a domain including a variety of preferences.

The Theorem does not hold in the case where preferences are not smooth.⁵ However, the axioms used in the Theorem are satisfied by the Walrasian allocations correspondence without requiring anything from preferences or from the domain

⁵A counter example can be constructed by using the example in Zhou (1992).

(Propositions 1,2 and 3).

Another consistency property, which also appears in Thomson (1992), was studied by van den Nouweland, Peleg, and Tijs (1994), and by Dagan (1994). Economies are defined there with a trade vector t that determines the market clearing conditions of the economy. Van den Nouweland, Peleg, and Tijs (1994) characterize the Walrasian allocations correspondence with consistency, converse consistency, Pareto optimality, and axioms that imply that the solution coincides with the Walrasian allocations correspondence of one agent economy. It should be noted that given any Pareto optimal solution that is consistent and conversely consistent with respect to a certain definition of a reduced economy can be characterized by these three properties and the requirement that the solution coincides with the one characterized for small economies. Thus, their result is not much different than stating that the Walrasian allocation correspondence is consistent and conversely consistent with respect to the specific definition of the reduced economy. Dagan (1994a) uses consistency and converse consistency in order to prove replica invariance. Then by requiring core selection and applying Debreu and Scarf (1963, Theorem 3) he gets a characterization of the Walrasian allocation correspondence. However, imposing replica invariance directly, consistency is actually not needed for this result.

4.3 An Example

In this subsection we present an application of the Theorem to economies with one good and single-peaked preferences. Consistency in this setting was studied by Thomson (1994) for the case where the agents have a collective endowment. Klaus, Peters, and Storcken (1995) considered the case of private endowments. The rule they proposed--the uniform reallocation rule--is the Walrasian allocations correspondence.

We consider now economies where the commodity space is \mathbb{R} , and for all i $X_i = \mathbb{R}_{++}$ and R_i is continuous, transitive and complete, and satisfies the following: There exists a

number $p(R_i)$ such that for all $x, y \in \mathbb{R}_{++}$ if $y < x \leq p(R_i)$ or $p(R_i) \leq x < y$, then $x P_i y$. We call $p(R_i)$ the peak of agent i , and denote $p(R_i)$ by p_i . Note that $X_i = \mathbb{R}_{++}$ implies that the preference relation R_i is smooth.

Let Ω be a set of economies with agents as described above, and with a strictly positive total endowment. The uniform reallocation rule is defined as follows:

The *uniform reallocation rule* on Ω , assigns each economy in Ω the unique allocation x that satisfies: for all $i \in N$, $x_i = \min(p_i, \lambda + \omega_i)$ if $\sum_{i \in N} \omega_i \leq \sum_{i \in N} p_i$, and $x_i = \max(p_i, \lambda + \omega_i)$ if $\sum_{i \in N} \omega_i \geq \sum_{i \in N} p_i$, where λ solves the equation $\sum_{i \in N} x_i = \sum_{i \in N} \omega_i$.

Note that when there is a shortage of the good, i.e. $\sum_{i \in N} \omega_i \leq \sum_{i \in N} p_i$, the allocation x , $p=1$ and $s=\lambda$ is the unique Walrasian equilibrium with slack. When there is a surplus of the good, i.e. $\sum_{i \in N} \omega_i \geq \sum_{i \in N} p_i$, then x , $p=-1$ and $s=-\lambda$ is the unique Walrasian equilibrium with slack.

The following characterization of the uniform reallocation rule is a consequence of the Theorem and the facts that this rule coincides with the Walrasian allocations and that it is always single valued.

PROPOSITION 4: Let T be a set of types as defined in the above example, and $\Omega(T)$ be the set of all economies whose agents types belong to T , and have a strictly positive total endowment. The uniform reallocation rule is the unique solution on $\Omega(T)$ which is nonempty, consistent, replica invariant, and assigns Pareto optimal and envy-free allocations.

5. EQUAL BUDGET WALRASIAN ALLOCATIONS

In this section we present a variant of the Theorem presented in Section 4 above. The solution characterized is the equal budget Walrasian allocations correspondence. We note

that the importance of this additional result lies in the fact that one may use the same model and consistency axiom in analyzing both solutions that respect private endowments and those who do not. In models of collective endowments private ownership situations cannot be studied.

Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy. The allocation x is an *equal budget Walrasian allocation* if it is a Walrasian allocation in the economy $e' = [\mathbb{R}^k, (X_i, R_i, \omega'_i)_{i \in N}]$, where for all $i \in N$ $\omega'_i = (1/\#N)\sum_{i \in N} \omega_i$. We say that an allocation is *individually rational from equal division* if for all $i \in N$ $\omega'_i \notin P_i(x_i)$.

The result of this section is:

PROPOSITION 5: Let T be a set of types on \mathbb{R}^k that satisfy A1-A3. Let $\Omega(T)$ be the class of all economies in which the agents types belong to T . If a solution f on $\Omega(T)$ is consistent, replica invariant and assigns individually rational from equal division and Pareto optimal allocations, then for all $e \in \Omega(T)$ $f(e) \subset W(e')$, where $e' = [\mathbb{R}^k, (X_i, R_i, \omega'_i)_{i \in N}]$, and for all $i \in N$ $\omega'_i = (1/\#N)\sum_{i \in N} \omega_i$.

The proof is similar to that of the Theorem, and therefore is left to the reader. ☺

Thomson (1988, Theorem 3) and Thomson (1994, Theorem 4) can be derived from Proposition 5. Moreover, note that the axioms in Proposition 5 do not require that the solution will not depend on individual endowments. Thus Proposition 5 is a stronger statement than the analogous statement on a domain in which individual endowments are not a part of the description of an economy.

6. PROOF OF THE THEOREM

Let $[\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy, and $(x_i)_{i \in N}$ an allocation. Let:

$$A(\omega, x) = \{t \in \mathbb{R}^k : t = (x_i - \omega_i) \text{ for some } i \in N\}.$$

An allocation $(x_i)_{i \in N}$ is extremely strictly envy free if for all $i \in N$ $[P_i(x_i) - \{\omega_i\}] \cap \text{Co}(A(\omega, x)) = \emptyset$, where $P_i(x_i) - \{\omega_i\} = \{t : t = y - \omega_i, \text{ for some } y \in P_i(x_i)\}$.

Lemma 1: Let T be a set of types on \mathbb{R}^k that satisfy A1, and the consumption sets X are open. Let $\Omega(T)$ be the class of all economies in which the agents types belong to T . If a solution f on $\Omega(T)$ is consistent, replica invariant and assigns individually rational allocations, then for all $e \in \Omega(T)$ for all $x \in f(e)$ x is extremely strictly envy free.

Proof: Let $e = [\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}] \in \Omega(T)$. And let $(x_i)_{i \in N} \in f(e)$. Let $t \in \text{Co}(A(\omega, x))$.

There exist weights $(\alpha_i)_{i \in N}$ such that for all $i \in N$ $\alpha_i \geq 0$ and $\sum_{i \in N} \alpha_i = 1$, and $t = \sum_{i \in N} \alpha_i (x_i - \omega_i)$.

Fix an agent j .

Step 1: First consider the case where for all $i \in N$ α_i are rational and $\alpha_j > 0$. Thus there exist integers $(\beta_i)_{i \in N}$ and γ such that for all $i \in N$ $\alpha_i = \beta_i / \gamma$. Now consider the γ fold replica of the economy. By replica invariance, the replica of x belongs to $f(e(\gamma))$. Now consider the reduced economy of $e(\gamma)$ in which j is a member and there are β_i members of each type i . Denote this economy by e' . By consistency the restriction of the replica of x to e' belongs to $f(e')$. Note that j 's endowment in e' is $\omega_j + t$, thus by individual rationality $t \notin P_j(x_j) - \{\omega_j\}$.

Step 2: Now consider any trade $t \in \text{Co}(A(\omega, x))$. There exists a sequence of trades in $\text{Co}(A(\omega, x))$ that satisfy the conditions of step 1 and converge to t . As $P_j(x_j)$ is open relative to \mathbb{R}^k , $t \notin P_j(x_j) - \{\omega_j\}$ as well. ☺

Lemma 2: Let $[\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy, whose agents satisfy A1 and A2. Let $(x_i)_{i \in N}$

be an allocation that satisfies for all $i \in N$ $x_i \in \text{int}(X_i)$ and whose replica is Pareto optimal in all replicas of the economy. Then there exists a price $p \neq 0$ such that for all $i \in N$ for all $y \in P_i(x_i)$ $py > px_i$.

Proof: Let $[\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy, whose agents satisfy A1 and A2. Let $(x_i)_{i \in N}$ be an allocation that satisfies for all $i \in N$ $x_i \in \text{int}X_i$ and whose replica is Pareto optimal in all replicas of the economy. Let $S = \{i \in N: P_i(x_i) \neq \emptyset\}$.

Case 1: $S = \emptyset$. Then the lemma is trivially satisfied.

Case 2: $S \neq \emptyset$. Let $G = \text{Co}\{\sum_{i \in S} P_i(x_i) - \{\omega_i\}\}$. Note that $\text{int}(G)$ is nonempty. Now we will show that $0 \notin \text{int}(G)$. Assume that $0 \in \text{int}(G)$. Then there exists a finite set K , trades $(t_i)_{i \in K}$ all belonging to $\{\sum_{i \in S} P_i(x_i) - \{\omega_i\}\}$, and weights $(\alpha_i)_{i \in K}$ such that for all $i \in K$ $\alpha_i \geq 0$ and $\sum_{i \in K} \alpha_i = 1$, and $0 = \sum_{i \in K} \alpha_i t_i$. We can assume without loss of generality that for all $i \in K$ α_i are rational. Thus there exist integers $(\beta_i)_{i \in K}$ and γ such that for all $i \in K$ $\alpha_i = \beta_i / \gamma$. Now consider the γ fold replica of the economy. First note that for all $i \in K$ there exist trades $(t_{ij})_{j \in S}$ such that $(t_{ij} + \omega_j) P_j x_j$ for all $j \in S$, and $t_i = \sum_{j \in S} t_{ij}$. Note that the following allocation is feasible and is Pareto superior to the γ fold replica of x -- a contradiction: For all agents of type $j \in N \setminus S$ assign x_j ; For all $i \in K$ for all $j \in S$ for β_i agents of type $j \in S$ assign $t_{ij} + \omega_j$. Thus we have $0 \notin \text{int}(G)$.

Now, by Minkowski's Separating Hyperplane Theorem there exist a hyperplane with normal $p \neq 0$ such that for all $y \in \text{int}(G)$ $py \geq 0$. By upperhemi continuity of preferences G is a subset of the closure of $\text{int}(G)$, thus for all $y \in G$ $py \geq 0$. If for some $i \in S$ and some $y \in P_i(x_i)$ $py < px_i$, then by local non satiation at non satiated points we may find bundles $y'_j \in P_j(x_j)$ for all other agents, such that $y + \sum_{j \in N \setminus i} y'_j < 0$, contradicting the last result, therefore for all $i \in S$ for all $y \in P_i(x_i)$ $py \geq px_i$. Now, for all $i \in N$ $x_i \in \text{int}(X)$ and $P_i(x_i)$ is open, thus it follows from a standard argument that for all $i \in S$ for all $y \in P_i(x_i)$ $py > px_i$.



Lemma 3: Let $[\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy, whose agents satisfy A1, A2, and A3. Let $(x_i)_{i \in N}$ be an allocation that is extremely strictly envy free and whose replica is Pareto optimal in all replicas of the economy. Then there exists a price p and a slack s such that $[x, p, s]$ is a Walrasian equilibrium with slack.

Proof: Let $[\mathbb{R}^k, (X_i, R_i, \omega_i)_{i \in N}]$ be an economy, whose agents satisfy A1, A2, and A3. Let $(x_i)_{i \in N}$ be an allocation that is extremely strictly envy free and whose replica is Pareto optimal in all replicas of the economy. By lemma 2 there exists a price p such that for all $i \in N$ for all $y \in P_i(x_i)$ $py > px_i$. Let p be such a price. For all $i \in N$ Let $s_i = p(x_i - \omega_i)$.

Step 1: If for some i and j in N $s_i < s_j$ then $P_i(x_i) = \emptyset$. As x is extremely strictly envy free at any point t on the line segment connecting $(x_i - \omega_i)$ and $(x_j - \omega_j)$ it is satisfied that $\omega_i + t \notin P_i(x_i)$. By A3 the intersection of any line segment that goes through x_i and a point z satisfying $pz > px_i$ with $P_i(x_i)$ is nonempty whenever $P_i(x_i) \neq \emptyset$; this should hold also for $z = (x_j - \omega_j) + \omega_i$, thus $P_i(x_i) = \emptyset$.

Step 2: Let $s = \max\{s_i : i \in N\}$. Note that $[x, p, s]$ is a Walrasian equilibrium with slack.



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