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Implementation of Walrasian Allocations in Economies with Infinite Dimensional Commodity Spaces

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Abstract

This paper considers the problem of implementing constrained Walrasian allocations for exchange economies with infinitely many commodities and nitely many agents. The mechanism we provide is a feasible and continuous mechanism whose Nash allocations and strong Nash allocations coincide with constrained Walrasian allocations. This mechanism allows not only preferences and initial endowments but also coalition patterns to be privately observed, and it works not only for three or more agents, but also for two-agent economies, and thus it is a uni ed mechanism which is irrespective of the number of agents.

1 Introduction

This paper considers the problem of double implementation of constrained Walrasian allocations in Nash and strong Nash equilibria using a feasible and continuous mechanism for pure exchange economies with infinitely many commodities and nitely many agents.

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It is by now widely acknowledged that the finite-dimensional setting is too restrictively modeled in many economic situations such as intertemporal decisions, uncertainty, and differentiated commodities. Infinite-dimensional models have become prominent in economics and finance because they capture nature aspects of the world that cannot be examined in finite-dimensional models. It has become clear that economic models capable of addressing real policy questions must be both stochastic and dynamic. A dynamic model requires infinite-dimensional spaces. If time is modeled as continuous, then time series of economic data reside in infinite-dimensional functional spaces. Even if time is modeled as being discrete, we are forced to use infinite-dimensional models when we are to make realistic models of money or growth. Other features of the world that arguably require infinite-dimensional modeling are uncertainty and commodity differentiation.

Incentive mechanism theory in general and implementation theory in particular, however, have ignored the economic environment with infinite-dimensional settings. There are numerous papers on implementation of (constrained) Walrasian allocations in various solution concepts in implementation literature, including Hong (1995),Hurwicz (1972, 1979), Hurwicz, Maskin, and Postlewaite (1995), Nakamura (1990), Peleg (1996), Postlewaite and Wettstein (1989), Schmeidler (1980), Suh (1994), and Tian (1990, 1999, 2000). All the mechanisms mentioned above only work with the infinite-dimensional economic environments, and there are no mechanisms given in the literature which implements Pareto and individually rational allocations for economies with infinite-dimensional commodity spaces.

This paper gives a mechanism that Nash implements constrained Walrasian allocations for exchange economies with an infinite-dimensional commodity space. The commodity space we adopt are all the sequence spaces $l_p(1 \leq p \leq 1)$ and the Lebesgue spaces $L_p(1 \leq p \leq 1)$. Thus, we allow for commodity spaces which are general enough to include most of the spaces used economic analysis. It will be noted that our implementation result holds on a very large domain of economic environments. Only the strict monotonicity condition is assumed. No continuity and convexity assumptions on preferences are needed, and further, preferences may
be nontotal or nontransitive. The mechanism is simple and natural. It is a type of market game and thus is similar to the Walras rule: the strategies of the mechanism are prices and quantities, and agents' consumptions are chosen from their budget sets. The natural mechanism design provides at least a partial response to a common concern about much of the implementation literature, namely that the implementing mechanisms are highly unrealistic and impossible for a real player to use. In addition, the mechanism works not only for three or more agents, but also for a two-agent world.

We should emphasize that the continuous and feasible mechanism design in the infinite-dimensional setting differs in important ways from the continuous and feasible mechanism design in the finite-dimensional setting. There are mainly four difficulties that arise in infinite-dimensional settings, but do not arise in finite-dimensional setting: (1) the feasible sets may not be compact; (2) there may not exist a compact and convex subset of the positive cone of the dual space; and (3) the wealth map may not be jointly continuous as a function of quantities and prices so that the feasible correspondence may not continuous, and (4) the projection of a point to a convex compact set may not be unique so that the feasible outcome function may not be single-valued. The first three difficulties are needed to be solved in order to show the feasible correspondence is continuous so that the outcome function obtained from the projection mapping to the feasible set is continuous. The fourth difficulty should be solved for the outcome function to be a single-valued function.

To understand why these difficulties arise in the infinite-dimensional setting, we discuss briefly below these issues which distinguish a feasible and continuous mechanism design in the infinite-dimensional setting from the feasible and continuous mechanism design in the finite-dimensional setting, and the ways in which we deal with them.

The first of these difficulties is that the feasible set may not generally be compact in a given topology of the commodity space, in many cases, the best we can hope for is that they will be compact in some weaker topology. In order to be sure that optimization solutions exist, we will need to assume that such a weak topology does
inde exist and the feasible correspondence are suitably continuous in this weak topology. These assumptions will be satisfied for the class of infinite-dimensional spaces we consider.

The second difficulty concerns the existence of a compact and convex subset of the positive cone of the dual space. In the finite-dimensional setting, the unit simplex is convex and compact. In the infinite-dimensional setting, however, such a compact and convex set may not exist. To be sure the existence of such a set so that we can prove that the feasible correspondence is continuous, we adopt an assumption introduced by Mas-Colell (1986) that, together with other assumptions we make in the papers, can guarantee the existence of a convex and compact subset of a positive cone.

The third difficulty is that the wealth map $p\cot x$ may not be jointly continuous. We need this joint continuity of the wealth map to prove that the feasible correspondence is continuous. In the finite-dimensional setting, this map is jointly continuous. In the infinite-dimensional setting, in order that the feasible correspondence is compact-valued and there exist a convex and compact subset of positive cone $L^+_x$, we are led to consider a weak topology on the commodity space. Unfortunately, as shown by Mas-Colell and Zame (1992), such a pair of choices may lead to failure of joint continuity. Thus, we need to make sure that the wealth map is jointly continuous for the commodity space under consideration.\(^1\)

The fourth of these difficulties is about the single-valuedness of the feasible outcome function. In the finite-dimensional setting, the single-valued and feasible outcome function can be obtained by a projection mapping from each proposed allocation that may not be feasible to the feasible correspondence. In other words, the outcome determined by the mechanism is the point in the feasible set that is closest to the proposed allocation, i.e., which minimizes the distance between the proposed outcome and any point in the feasible set for a given message. It is known that such a projection in the finite-dimensional setting is unique if and only if the

\(^1\)The second and third difficulties do not arise, if the feasible sets have nonempty interior. In such a case, one can easily prove the feasible correspondence is continuous.
feasible set is closed and convex. Furthermore, the projection is continuous (cf Mas-Colell (1985)). In the infinite-dimensional setting, however, the projection is generally not unique. In order to be sure that single-valued projection exists, we will need to assume the functional spaces are either the sequence spaces or Lebesgue spaces. Fortunately, we can prove the projection is unique for either the sequence spaces or Lebesgue spaces.\(^2\) In fact, as we will show, these four difficulties can be solved with suitable choices of a compatible topologies for these two classes of infinite-dimensional spaces.

The remainder of the paper is organized as follows. Section 2 presents notions, definitions, and solution concepts which will be used in the paper. Section 3 presents a specific mechanism that is feasible and continuous. Section 4 proves the equivalence among Nash allocations, strong Nash allocations, and constrained Walrasian allocations and the mechanism doubly implements the constrained Walrasian correspondence. Finally, some concluding remarks are given in Section 5.

2 Notation and Definitions

2.1 Economic Environments

To make this paper relatively self-contained, we begin with a brief review of the basic properties of ordered normed spaces.

A normed space is a real vector space \(L\) equipped with a norm, i.e., a function 
\[
\|x\| : L \to [0, 1]
\]
such that \(\|x\| = 0\) if and only if \(x = 0\); \(\|x + y\| \leq \|x\| + \|y\|\) for all \(x, y \in L\); \(\|\lambda x\| = |\lambda| \|x\|\) for all \(x \in L\) and \(\lambda \in \mathbb{R}\).

By the dual space of \(L\) we mean the space \(L^*\) of continuous linear functionals \(p : L \to \mathbb{R}\). As usual, if \(p \in L^*\), then value \(\langle x, p \rangle\) will also be denoted by \(p(x)\), i.e., \(\langle x, p \rangle = p(x)\). The dual space of \(L\) is also a normed space, when equipped with the norm \(\|p\| = \sup \{p(x) : x \in L, \|x\| \leq 1\}\).

In addition to the normed topologies, we shall be interested in several other topologies on normed spaces. The weak topology on \(L\), denoted by \(\tau(L; L^*)\), is the

\(^2\)It seems this has only been proved for Hilbert space (cf. Gariepy and Ziemer (1995)).
weakest topology with respect to which all the elements of $L''$ are continuous. The weak-star topology on $L''$, denoted by $\beta(L'';L)$, is the weakest topology on $L''$ with respect to which all the elements of $L$ are continuous.

A normed lattice (or called normed Riesz space) is a normed space $L$, together with a partial order $\cdot$ on $L$ (i.e., a reflexive, antisymmetric, transitive relation on $L$) that satisfies: $x \cdot y$ implies $x + z \cdot y + z$ for all $x; y; z \in L$; $x \cdot y$ implies $\lambda x \cdot \lambda y$ for all $x; y \in L$ and $\lambda > 0$; every pair of elements $x; y \in L$ has a supremum (least upper bound) $x \_ y$ and an infimum (greatest lower bound) $x ^\wedge y$; $\|x\| \leq \|y\|$ implies $\|x \cdot y\| \leq \|x\| \cdot \|y\|$, where $\|x\|$ is the absolute value of $x$ that is defined by $\|x\| = x ^+ + x ^-$ with $x ^+ = x \_ 0$ (positive part of $x$) and $x ^- = x ^\wedge 0$ (negative part of $x$). The notation $x \_ y$ is, of course, equivalent to $y \cdot x$. Also, $x > y$ means $x \_ y$ and $x \not\leq y$. $x$ is positive if $x \_ 0$ and $x \not\leq 0$. Denote by $L^+ = \{a \in L : a \not\leq 0\}$ the set of all positive elements of $L$; $L^+$ is referred to the positive cone. $L^+$ may sometimes be called the nonnegative cone.

In a Riesz pair $L; L^+$, a positive vector $x \in L^+$ is strictly positive, written $x > > 0$, if $px > 0$ for each $0 < p \in L^0$. Denote by $L^+ = \{a \in L : a < 0\}$ the set of all strictly positive elements $L$; $L^+$ is referred to be the strictly positive cone. A strictly positive vector is also called a quasi-interior point. An equivalent characterization is that an element $x \in L^+$ is strictly positive if and only if the sequence $f_kx ^\wedge yg$ converges in norm to $y$ as $k$ tends to infinity for each $y \in L^+$. Note that if the positive cone $L^+$ of $L$ has non-empty (norm) interior, then the set of strictly positive elements coincides with the interior of $L^+$. However, many Banach lattices contain strictly positive elements even though the positive cone $L^+$ has an empty interior. For more information about normed spaces and normed lattices, we refer to Aliprantis and Border (1994).

We formalize the notion of an economy in the usual way. Exchange economies under consideration have a commodity space $L$ that is the one either in the family of $L_p(S; \#; 1)$-spaces or in the family of $L_p$-spaces, where $1 \leq p \leq 1$, $S$ is the set of states, $\#$ the set of a $\delta$-algebra of subsets of $S$, and $1$ a finite and positive measure defined on $\#$ and $L_p(S; \#; 1)$ is the class of all $1$-measurable functions $f$ for which...
$\mathbb{R}^p$ if $p^d \leq 1$ for $1 \leq p < 1$ and $L_1$ is the space all 1-measurable functions with finite essential supremum in which the $L_1$-norm is defined $k f k_1 = \text{ess sup } f = \text{sup } \{ t : \int \text{t} f(x) = t g > 0 \}$. When time is modeled as a sequence of discrete dates, one may use a space $L_p$. For instance, space $L_1$ plays a major role in the neoclassical theory of growth and discrete-time dynamic macroeconomic models. If there is an exhaustible resource in a setting, the $L_1$ may be an appropriate setting for the time series. When function spaces arise in models of uncertainty or time is continuous, one may use a space $L_p(S; \mathbb{S};^1)$. For $x, y \in L_p$, define $x \equiv y$ if $x(s) = y(s)$ for $^1$-almost all $s \in S$. We can endow $L_p$ with the following partial order relation $\cdot$. We say $x \cdot y$ if $x(s) \geq y(s)$ for $^1$-almost all $s \in S$. We say $x < y$ if $x \cdot y$ and there exists a $^1$ nonnull subset $E \subset S$ such that $x(s) < y(s)$ for $^1$-almost all $s \in E$. We say $x < y$ if $x(s) < y(s)$ for $^1$-almost all $s \in S$. Thus, the Lebesgue vector spaces $L_p(1 \leq p \leq 1)$ with the above defined partial orders are clearly Banach lattices.

We assume that there are $n$ agents in economies. Denote by $N = \{1; 2; \ldots; n\}$ the set of agents. Each agent's characteristic is denoted by $e_i = (P_i; \bar{\omega}_i)$, where $P_i$ is the strict (irreflexive) preference defined on $L_+$ which may be nontotal or nontransitive, and $\bar{\omega}_i \in L_+$ is the initial endowment of the agent. We assume preference relation $P_i$ is strictly monotonic in the sense that $(x_i + v_0)P_i x_i$ for any $v_0 \in L_+$ if $0 g$. To require well-behaved preferences that they admit supporting prices, we assume that the canonical conjugate $R_i$ of $P_i$ is uniformly proper on the order interval $[0; \bar{\omega}]$, where $\bar{\omega} = \sum_{i=1}^{n} \bar{\omega}_i$.4

3If we define the binary relation $R_i$ by $x \equiv y$ if and only if $b \equiv b R_i a$ where $b$ stands for "it is not the case that", then $R_i$ is the weak (reflexive) preference and is called the 'canonical conjugate' of $P_i$ (see Kim and Richter (1986). If concepts used in this paper such as Nash equilibrium and the constrained Walrasian allocations are interpreted in terms of the $R_i$, then the results obtained in this paper for $P_i$ are, in particular, valid for the $R_i$.

4The concept of properness was introduced by Mas-Colell (1986). The preference relation $R_i$ is said to be proper at $x$ with respect to the total endowment $\bar{\omega}$, if there is an open cone $\bar{\omega}$ at $0$, containing $\bar{\omega}$, such that $x_i \not\equiv x_x$ does not intersect the preferred set $x_0 \in L_0 \equiv x_0 R_i x_0$, i.e., if $x_0 R_i x$, then $x_i \not\equiv x_0 \in L_0 \equiv x_0 R_i x_0$. The interpretation is that the total endowment is desirable, in the sense that loss of an amount $\bar{\omega}$ (\$ > 0\) cannot be compensated for by an additional amount $\bar{\omega}$ of any
An economy is the full vector \( e = (e_1; \ldots; e_n) \) and the set of all such economies is denoted by \( E \).

It will not generally be true in the infinite dimensional setting that the feasible consumption set is compact in the norm topology of the commodity space. To avoid this difficulty, we should explicitly assume the existence of a Hausdorff vector space topology \( \tau \) such that the feasible consumption set is compact. Thus we have the following notion.

A Hausdorff topology \( \tau \), on the Banach lattice \( L \), will be called compatible if

(a) \( \tau \) is weaker than the norm topology of \( L \),

(b) \( \tau \) is a vector space (i.e., the vector space operations on \( L \) are continuous in the topology \( \tau \)),

(c) all order intervals \([0; z]\) in \( L \) are \( \tau \)-compact.

The topology will vary according to the underlying Banach lattice \( L \); it may be the norm topology itself, or the weak topology, or the weak-star. For instance, if the commodity space is the Lebesgue space \( L_p \), \( 1 < p < 1 \), the compatible topology will be the weak topology. This follows from the fact that the Lebesgue space \( L_p \), \( 1 < p < 1 \), are normed vector lattices with continuous norm, order intervals are weakly compact (see Aliprantis and Burkinshaw (1985, Theorem 12.9)). If the commodity space is \( L_1 \) (\( L_1 \)), the compatible topology will be the weak* topology. Recall that Alaoglu's theorem implies that order intervals are weak* compact (see Aliprantis and Burkinshaw (1985, Theorem 9.20)). Finally, if the commodity space is the space of sequences \( l_p \), \( 1 < p < 1 \), the compatible topology will be the norm topology.\(^5\) This follows from the standard result that order intervals in \( l_p \), \( 1 < p < 1 \), are norm compact.

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\(^5\)If the commodity space is \( l_1 \), the weak and norm topologies have the same compact set, so there is certainly nothing to be gained by taking for \( \tau \) the weak topology. This is one of the few settings in which the feasible consumption will be norm compact.
2.2 The Constrained Walrasian Allocations

By an allocation, we mean an n-tuple $x := (x_1; \ldots; x_n) \in L^n$.

An allocation $x \in L^n$ is feasible if $x_i \in L_+$ for all $x_i \in L_+$, and

$$\sum_{i=1}^{n} x_i \leq \sum_{i=1}^{n} \omega_i;$$

An allocation $x^* = (x_1^*; x_2^*; \ldots; x_n^*) \in L^n$ is a Walrasian allocation for an economy $e$ if there is a price vector $p^* \in L_+ \setminus \{0\}$ such that

1. $p^* c x_i^* \leq p^* \omega_i$ for all $i \in N$,

2. for all $i \in N$, there does not exist $x_i \in L_+$ such that
   2.a) $x_i \geq P_i x_i^*$;
   2.b) $p^* c x_i \leq p^* \omega_i$;
   2.c) $x_i \leq \sum_{j=1}^{n} \omega_j$,

3. $\sum_{j=1}^{n} x_j \leq \sum_{j=1}^{n} \omega_j$.

The $n + 1$-tuple $(x_1^*; \ldots; x_n^*; p^*)$ is then called a Walrasian equilibrium. Denote by $W(e)$ the set of all Walrasian allocations.

An allocation $x^* = (x_1^*; x_2^*; \ldots; x_n^*) \in L^n$ is a constrained Walrasian allocation for an economy $e$ if there is a price vector $p^* \in L_+ \setminus \{0\}$ such that

1. $p^* c x_i^* \leq p^* \omega_i$ for all $i \in N$,

2. for all $i \in N$, there does not exist $x_i \in L_+$ such that
   2.a) $x_i \geq P_i x_i^*$;
   2.b) $p^* c x_i \leq p^* \omega_i$;
   2.c) $x_i \leq \sum_{j=1}^{n} \omega_j$,

3. $\sum_{j=1}^{n} x_j \leq \sum_{j=1}^{n} \omega_j$.

The $n + 1$-tuple $(x_1^*; \ldots; x_n^*; p^*)$ is then called a constrained Walrasian equilibrium. Denote by $W_c(e)$ the set of all such allocations.
Remark 1 From the above definition, we can see that every ordinary Walrasian allocation (competitive equilibrium allocation) is a constrained Walrasian allocation and that a constrained Walrasian allocation differs from a Walrasian allocation only in the way that each agent maximizes his preferences not only subject to his budget constraint but also subject to total endowments available to the economy.

An allocation \( x \) is Pareto-efficient with respect to strict preference profile \( P = (P_1; \ldots; P_n) \) if it is feasible and there does not exist another feasible allocation \( x^0 \) such that \( x_i^0 P_i x_i \) for all \( i \in N \).

An allocation \( x \) is individually rational with respect to \( P \) if \( \hat{w}_i P_i x_i \) for all \( i \in N \).

It can be easily shown that every constrained Walrasian allocation is Pareto-efficient and individually rational.

An coalition \( C \) is a non-empty subset of \( N \).

A group of agents (a coalition) \( C \subseteq N \) is said to block an allocation \( x \) if there exists some allocation \( (x^0; y^0) \) such that

(i) \( \forall i \in C \), \( P_{iC} x_i^0 \geq P_{iC} x_i \)

(ii) \( x_i^0 P_i x_i \) for all \( i \in C \).

A feasible allocation \( x \) is said to be in the core of \( e \) if there does not exist any coalition \( C \) that can improve upon \( x \).

Note that an allocation cannot be improved upon by \( N \) if and only if it is Pareto-efficient, and an allocation cannot be improved upon by any single person if and only if it is individually rational. Also every constrained Walrasian allocation is in the core of \( e \).

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6This definition coincides with the conventional definition when \( P_i \) is the asymmetric part of a reflexive, transitive, and total preference \( R_i \).

7For weak preferences, Thomson (1985) showed that a constrained Walrasian allocation may not be (regular) Pareto-efficient (i.e., there is no way of making everyone at least as well off and one person better off) even if preferences satisfy local non-satiation. However, when preferences satisfy strict monotonicity, it is (regular) Pareto-efficient by Theorem 2.4.2 of Tian (1988).
2.3 Mechanism

Let \( F \) be a social choice rule, i.e., a correspondence from \( E \) to the commodity space \( L \). In the rest of the paper, we will use the constrained Walrasian correspondence as a social choice rule.

Let \( M_i \) denote the \( i \)-th message (strategy) domain. Its elements are written as \( m_i \) and called messages. Let \( M = \bigcup_{i=1}^{n} M_i \) denote the message (strategy) space. Let \( X : M \rightarrow L \) denote the outcome function, or more explicitly, \( X_i(m) \) is the \( i \)-th agent's outcome at \( m \). A mechanism consists of \( hM;X \) defined on \( E \). A message \( m^* = (m^n_1, \ldots, m^n_n) \) is a Nash equilibrium (NE) of the mechanism \( hM;hi \) for an economy \( e \) if for any \( i \in N \) and for all \( m_i \in M_i \),

\[
X_i(m^* = m_i; i) \geq \prod_{j \neq i} X_j(m^*),
\]

where \((m^* = m_i; i) = (m^n_1, \ldots, m^n_{i-1}, m_i, m^n_{i+1}, \ldots, m^n_n)\). The outcome \( X(m^*) \) is then called a Nash (equilibrium) allocation. Denote by \( N_{M;hi}(e) \) the set of all such Nash equilibria and by \( W_{c}(e) \) the set of all such Nash (equilibrium) allocations.

A mechanism \( hM;hi \) fully Nash-implements the constrained Walrasian correspondence \( W_{c} \) on \( E \) if, for all \( e \in E \), \( N_{M;hi}(e) = W_{c}(e) \).

Remark 2 Note that the above definition which was due to Hurwicz [5, p. 219] allows the social choice correspondence \( W_{c} \) and the set of Nash equilibria to be empty for the main purpose of this paper is to study the equivalence of the constrained Walrasian correspondence and the set of Nash equilibrium allocations under the minimal possible assumptions. A stronger definition of full Nash-implementation used in the literature is that not only \( N_{M;hi}(e) = F(e) \) but also \( N_{M;hi}(e) \neq \emptyset \) for all \( e \in E \). Thus, if we restrict the domain of \( W_{c} \) to the one on which \( W_{c} \) is nonempty-valued, our results, to be presented below, will be equivalent for both definitions.

A message \( m^* = (m^n_1, \ldots, m^n_n) \) is said to be a strong Nash equilibrium of the mechanism \( hM;hi \) for an economy \( e \in E \) if there does not exist any coalition \( C \)
and $m_C \in \mathcal{P}_{\mathcal{Q}} M_i$ such that for all $i \in C$,
\[ X_i(m_C; m^n_C) P_i X_i(m^n): \]

$X(m^n)$ is then called a strong Nash (equilibrium) allocation of the mechanism for the economy $e$. Denote by $S_V M; X(e)$ the set of all such strong Nash equilibria and by $S_N M; X(e)$ the set of all such strong Nash (equilibrium) allocations.

The mechanism $h M; h$ is said to doubly implement the constrained Walrasian correspondence $W_c$ on $E$, if, for all $e \in E$, $S_N M; N(e) = N M; X(e) = W_c(e)$.

A mechanism $h M; h$ is individually feasible if $X(m) \in L^+_n$ for all $m \in M$.

A mechanism $h M; h$ is weakly balanced if for all $m \in M$
\[ \sum_{j=1}^{X_i(m)} \tilde{w}_j: \]

A mechanism $h M; h$ is feasible if it is individually feasible and weakly balanced.

Sometimes we say that an outcome function is individually feasible, balanced, or continuous if the mechanism is individually feasible, balanced, or continuous.

### 3 A Feasible and Continuous Mechanism

In this section, we present a simple feasible and continuous mechanism which doubly implements the constrained Walrasian correspondence on $E$. The mechanisms we use in the paper are reminiscent from the those given in Tian (1992, 2000) in the finite-dimensional context.

Let $c \subseteq L^+_n$ be a weak$^*$-compact and convex set such that $p \cdot w = 1$ for every $p \in c$. By Theorem 9.1 in Mas-Colell and Zame (1991), such a set exists.

For each $i \in N$, let the message domain of agent $i$ be of the form
\[ M_i = (0; \tilde{w}_i] \subseteq L^+_n; \]

where $(0; \tilde{w}_i] = \{w_i \in L^+_n : 0 \leq w_i \cdot \tilde{w}_i g\}$. A generic element of $M_i$ is $m_i = (w_i; p; x_{i1}; \ldots; x_{in})$ whose components have the following interpretations. The component $w_i$ denotes a profession of agent $i$'s endowment, the inequality $0 \leq w_i$.
means that the agent cannot overstate his own endowment bundle; on the other hand, the endowment can be understated, but the claimed endowment \( w_i \) must be strictly positive. The component \( p_i \) is the price vector proposed by agent \( i \) and is used as a price vector of agent \( i + 1 \), where \( i + 1 \) is read to be \( n \) when \( i = 1 \). The component \( x_{ij} \) is interpreted as the trade that agent \( i \) is willing to make to agent \( j \) (a negative \( x_{ij} \) means agent \( i \) wants to get \( |x_{ij}| \) amount of goods from agent \( j \)).

Define agent \( i \)'s price vector \( p_i : M \rightarrow \mathbb{R} \) by

\[
p_i(m) = p_{i+1};
\]

where \( n + 1 \) is to be read as \( 1 \). Note that although \( p_i(\phi) \) is a function of proposed price vector announced by agent \( i + 1 \), for simplicity, we can write \( p(\phi) \) as a function of \( m \) without loss of generality.

Define a feasible correspondence \( B : M \rightarrow L_+^n \) by

\[
B(m) = \{ x \in L_+^n : \sum_{i=1}^{n} x_{ij} w_i & \sum_{i=1}^{n} x_{ij} w_i \leq \sum_{i=1}^{n} w_i \sum_{i=1}^{n} p_i(m) k p_i(m) \leq 1 \}, \quad \forall i \in N \}
\]

which is nonempty, convex, and \( \omega \)-compact for all \( m \in M \) by the set is norm bounded by the total endowments and \( \omega \)-closed. We will show the following lemma in the Appendix.

Lemma 1 \( B(\phi) \) is \( \omega \)-continuous on \( M \).

Let \( x_i = \sum_{i=1}^{n} x_{ij} \) which is the sum of contributions that agents are willing to make to agent \( j \) and \( \bar{x} = (x_1; x_2; \cdots; x_n) \).

The outcome function \( X : M \rightarrow L_+^n \) is given by

\[
X(m) = \{ x \in L_+^n : \min_{x \in B(m)} k x \leq k \bar{x} \}
\]

which is the closest to \( \bar{x} \).

We then have the following lemma.

Lemma 2 \( X(\phi) \) is a single-valued continuous function.
Proof. Since the distance function $d(x; y) = \|x - y\|$ is continuous in $y$, we know that $d$ will reach its maximum on $B(m)$. Thus, $X$ is a nonempty correspondence. We want to show $X$ is in fact a single-valued function on $B$. If $x \notin B(m)$, then $d(x; B(m)) = 0$, and thus $X(m) = x$. So we only consider the case where $x \in B(m)$.

Suppose by way of contradiction that there are two points $x_1$ and $x_2$ in $B(m)$ such that $kx_1 x = kx_2 x = d(x; B(m))$ for some $m \in M$. Since $B(m)$ is convex, the convex combination $x_\lambda = \lambda x_1 + (1 - \lambda) x_2 \in B(m)$ with $0 < \lambda < 1$, and thus, by Minkowski's inequality, we have

$$kx_\lambda x = k(x_1 x) + (1 - \lambda)(x_2 x) = k(x_1 x)k + k(x_2 x)k = d(x; B(m))$$

Thus, we must have

$$k(x_1 x) + (1 - \lambda)(x_2 x)k = k(x_1 x)k + (1 - \lambda)(x_2 x)k$$

Notice that the Minkowski's inequality become equality if and only if there is some $t = 0$ such that

$$\lambda(x_1 x) = (1 - \lambda)t(x_2 x):$$

Taking the norm on both sides and noting that $k(x_1 x)k = k(x_2 x)k$, we must have

$$\lambda = (1 - \lambda)t:$$

Consequently, we have

$$x_1 x = x_2 x$$

and therefore $x_1 = x_2$, a contradiction. Thus, $X$ is single-valued.

Finally, since $B(m)$ is a continuous correspondence, then, by Berge's Maximum Theorem (Berge (1963)), we know $X$ is a upper hemi-continuous correspondence. However, since $X$ is also single-valued, and thus it is a continuous function on $B$.

Also, since $X(m) \in L^n$ and

$$X_\lambda X = \sum_{i=1}^{n} w_i$$

for all $m \in M$, the mechanism is feasible and continuous.
Remark 3 Note that the above mechanism does not depend on the number of agents. Thus it is a unified mechanism which works for two-agent economies as well as for economies with three or more agents. For two-agent economies, only the feasible and continuous mechanism which Nash implements the constrained Walrasian correspondence was given by Nakamura (1990). Here we give an even simpler feasible and continuous mechanism which doubly implements the constrained Walrasian correspondence not only for economies with a finite-dimensional consumption space but also for economies with an infinite-dimensional consumption space.

4 Results

The remainder of this paper is devoted to the proof of equivalence among Nash allocations, strong Nash allocations, and constrained Walrasian allocations. Proposition 1 below proves that every Nash allocation is a constrained Walrasian allocation. Proposition 2 below proves that every constrained Walrasian allocation is a Nash allocation. Proposition 3 below proves that every Nash equilibrium is a strong Nash equilibrium. To show these results, we first prove the following lemmas.

Lemma 3 If \( m^w \in V_M;X(e) \), then \( p_1^w = p_2^w = \cdots = p_n^w \), and thus \( p_1(m^w) = p_2(m^w) = \cdots = p_n(m^w) = p^w \) for some \( p^w \in \mathcal{C} \).

Proof: Suppose, by way of contradiction, that \( p_i^w \not\in p_{i+1}^w \) (i.e., \( p_i^w \not\in p_{i}(m^w) \)) for some \( i \in \{1, 2, \ldots, n\} \). Then \( p_i(m^w) \rho X_i(m^w) < p_{i+1}(m^w) \rho X_i(m^w) \), and thus there is \( x_i \in 2^{L^+} \) such that \( p_i(m^w) \rho x_i \) and \( x_i \rho X_i(m^w) \) by strict monotonicity of preferences. Now if agent \( i \) chooses \( p_i = p(m^w) \), \( x_{ii} = x_i \) for \( i \neq i \), and keeps \( w_i^w \) unchanged, then \((0; \cdots; 0; x_i; \cdots; 0)\) \( \not\in B(m_i^w; m_i^w) \), and thus \( X_i(m_i^w; m_i^w) = x_i \). Therefore, \( X_i(m_i^w; m_i^w) \rho p_i X_i(m^w) \), which contradicts \( X(m^w) \not\in N_{M;X}(e) \). Thus we must have \( p_i^w = p_2^w = \cdots = p_n^w \), and therefore \( p_1(m^w) = p_2(m^w) = \cdots = p_n(m^w) = p^w \) for some \( p^w \in \mathcal{C} \). Q.E.D.

Lemma 4 If \( m^w \not\in N_{M;X}(e) \), then \( w_i^w = \emptyset_i \) for all \( i \in \{1, 2, \ldots, n\} \).
Proof: Suppose, by way of contradiction, that \( w_i^n \neq \omega_i \) for some \( i \in \mathbb{N}^+ \). Then \( p_i(m^n) cX_i(m^n) < p_i(m^n) c\omega_i \), and thus there is \( x_i \in \mathbb{L}^+ \) such that \( p_i(m^n) cX_i(m^n) < p_i(m^n) c\omega_i \) and \( x_i \in P_i X_i(m^n) \) by strict monotonicity of preferences. Now if agent \( i \) chooses \( w_i = \omega_i \), \( x_{ii} = x_i \), \( x_j = i \) for \( j \neq i \) and keeps \( p_j^{m^n} \) unchanged, then \( (0; \ldots; 0; x_i; 0; \ldots; 0) \) is a Nash equilibrium, and thus \( X_i(m^n) = x_i \). Hence, \( X_i(m^n) = x_i \). This contradicts \( X(m^n) \neq N_{M,X}(e) \) for all \( e \in E \). Q.E.D.

Lemma 5 If \( X(m^n) \neq N_{M,X}(e) \), then \( p_i(m^n) cX_i(m^n) = p_i(m^n) c\omega_i \).

Proof: Suppose, by way of contradiction, that \( p_i(m^n) cX_i(m^n) < p_i(m^n) c\omega_i \) for some \( i \in \mathbb{N}^+ \). Then there is \( x_i \in \mathbb{L}^+ \) such that \( p_i(m^n) cX_i(m^n) < p_i(m^n) c\omega_i \) and \( x_i \in P_i X_i(m^n) \) by strict monotonicity of preferences. Now if agent \( i \) chooses \( x_{ii} = x_i \), \( x_j = i \) for \( j \neq i \) and keeps \( p_j^{m^n} \) and \( w_j^{m^n} \) unchanged, then \( (0; \ldots; 0; x_i; 0; \ldots; 0) \) is a Nash equilibrium, and thus \( X_i(m^n) = x_i \). Hence, \( X_i(m^n) = x_i \). This contradicts \( X(m^n) \neq N_{M,X}(e) \). Q.E.D.

Proposition 1 If the mechanism \( M; X_i \) defined above has a Nash equilibrium \( m^n \) for \( e \in E \), then \( X(m^n) \) is a constrained Walrasian allocation with \( p^n \) as a competitive equilibrium price vector, i.e., \( N_{M,X}(e) = \frac{1}{2} W_c(e) \) for all \( e \in E \).

Proof. Let \( m^n \) be a Nash equilibrium. Then \( X(m^n) \) is a Nash equilibrium allocation. We wish to show that \( X(m^n) \) is a constrained Walrasian allocation. By Lemmas 2 { 4, \( p_i(m^n) = \cdots = p_i(m^n) = p^n \) for some \( p^n \in \mathbb{P}^+ \) \( , w_i^n = \omega_i \), and \( p(m^n) \in X_i(m^n) = p(m^n) c\omega_i \) for all \( i \in \mathbb{N}^+ \). Also, by the construction of the mechanism, we know that \( X(m^n) \neq \mathbb{L}^+ \) and \( \mathbb{P}^+ X_j(m^n) = \mathbb{P}^+ X_j(m^n) \). So we only need to show that each individual is maximizing his or her preferences. Suppose, by way of contradiction, that for some agent \( i \), there exists some \( x_i \in \mathbb{L}^+ \) such that \( X_i(m^n) = X_i(m^n) \) and \( x_i \in P_i X_i(m^n) \). Let \( x_{ii} = x_i \), \( x_j = i \) for \( j \neq i \), and keep \( p_j^{m^n} \) and \( w_j^{m^n} \) unchanged, then \( (0; \ldots; 0; x_i; 0; \ldots; 0) \) is a Nash equilibrium, and thus \( X_i(m^n) = x_i \). Therefore, we have \( X_i(m^n) = X_i(m^n) \). This contradicts \( X(m^n) \neq N_{M,X}(e) \). So \( X(m^n) \) is a constrained Walrasian allocation. Q.E.D.
Proposition 2 If \( x^n = (x^n_1; x^n_2; \ldots; x^n_n) \) is a constrained Walrasian allocation with a competitive equilibrium price vector \( p^n \geq 2 c \) for \( e \in E \), then there exists a Nash equilibrium \( m^n \) of the mechanism \( \Pi_M; X \) defined above such that \( X_i(m^n) = x^n_i \), \( p_i(m^n) = p^n \) for all \( i \in N \), i.e., \( W_c(e) \frac{1}{2} N_{M;X}(e) \) for all \( e \in E \).

Proof. Since preferences satisfy the strict monotonicity condition and \( x^n \) is a constrained Walrasian allocation, we must have \( p^n \geq 2 c \), \( \sum_{j=1}^{n} x^n_j \leq \sum_{j=1}^{n} \bar{w}_j \) and \( p^n c x^n_i = p^n c \bar{w}_i \) for \( i \in N \). Now for each \( i \in N \), let \( m^n_i = (p^n; x^n_{i+1}; \ldots; x^n_n) \), where \( x^n_{i+1} = x^n_i \) and \( x^n_{ij} = 0 \) for \( j \neq i \).

Then \( x^n \) is an outcome with \( p^n \) as a price vector, i.e., \( X_i(m^n) = x^n_i \) for all \( i \in N \), and \( p_i(m^n) = p^n \). We show that \( m^n \) yields this allocation as a Nash allocation. In fact, agent \( i \) cannot change \( p_i(m^n) \) by changing his proposed price (i.e., \( p_i(m_i; m^n_{-i}) = p^n \) for all \( i \in M \)). Announcing a different message \( m_i \) by agent \( i \) may yield an allocation \( X(m_i; m^n_{-i}) \) such that \( X_i(m_i; m^n_{-i}) > 0 \) and

\[
p(m^n) c X_i(m_i; m^n_{-i}) > p(m^n) c \bar{w}_i. \tag{9}
\]

Now suppose, by way of contradiction, that \( m^n \) is not a Nash equilibrium. Then there are \( i \in N \) and \( m_i \) such that \( X_i(m_i; m^n_{-i}) > X_i(m^n) \). Since \( X_i(m_i; m^n_{-i}) > p(m^n) c \bar{w}_i \), we must have, by the definition of the constrained Walrasian allocation, \( p(m^n) c X_i(m_i; m^n_{-i}) > p(m^n) c \bar{w}_i \). But this contradicts the budget constraint (9).

Thus we have shown that agent \( i \) cannot improve his/her utility by changing his/her own message while the others' messages remain fixed for all \( i \in N \). Hence \( x^n \) is a Nash allocation. Q.E.D.

Proposition 3 Every Nash equilibrium \( m^n \) of the mechanism defined above is a strong Nash equilibrium, that is, \( N_{M;X}(e) \mu S N_{M;X}(e) \).

Proof: Let \( m^n \) be a Nash equilibrium. By Proposition 1, we know that \( X(m^n) \) is a constrained Walrasian allocation with \( p(m^n) \) as a price vector. Then \( X(m^n) \) is Pareto optimal and thus the coalition \( N \) cannot be improved upon by any \( m \in \mathcal{M} \).

Now for any coalition \( C \) with \( \emptyset \neq C \subseteq N \), choose \( i \in 2 C \) such that \( i + 1 \notin C \). Then no strategy played by \( C \) can change the budget set of \( i \) since \( p_i(m) \) is determined.
by \( p_{i+1} \). Furthermore, because \( X(m^n) \leq W_c(e) \), it is the preference maximizing consumption with respect to the budget set of \( i \), and thus \( C \) cannot improve upon \( X(m^n) \). Q.E.D.

Since every strong Nash equilibrium is clearly a Nash equilibrium, then by combining Propositions 1-3, we have the following theorem.

Theorem 1 For the class of exchange economies \( E \), there exists a feasible and continuous mechanism which doubly implements the constrained Walrasian correspondence. That is, \( N_{M;X}(e) = SN_{M;X}(e) = W_c(e) \) for all \( e \in E \).

5 Concluding Remarks

This paper gives a simple mechanism which doubly implements the constrained Walrasian correspondence in Nash and strong Nash equilibrium for economies with infinitely many commodities. Infinite-dimensional commodity spaces arise naturally when we consider economic activity over an infinite time horizon, or with uncertainty about the possible infinite number of states of the world, or in a setting where an infinite variety of commodity characteristics are possible. The mechanism we give is feasible, continuous, and allows coalition patterns, preferences and endowments to be unknown to the designer. Furthermore, preferences under consideration may not be total, transitive, continuous, and convex preferences. In addition, unlike most mechanisms proposed in the literature, it gives a unified mechanism which is irrespective of the number of agents.

Though this paper only considers double implementation of the constrained Walrasian correspondence for economies with infinite-dimensional spaces, one can similarly consider implementation of other social choice rules such as Lindahl allocations for economies with infinitely many commodities.
Appendix

Proof of Lemma 1: First note that \( c \) is weak* compact. Also, if \( x_k \downarrow x \) in the norm topology of \( L, p_k \downarrow p \) in the weak* topology of \( L^* \) and \( f p_k g \) is order bounded, \( p_k c x_k \downarrow p c x \) [Yannelis and Zame (1986, Lemma A, p. 107)]. Then \( B(\phi) \) has closed graph by the continuity of \( p(\phi) \) and \( p(\phi) c x \). Since the range space of the correspondence \( B(\phi) \) is weakly bounded by the total endowments \( \prod_{i=1}^{n} w_i \), it is weakly compact. Thus, \( B(\phi) \) is upper hemi-continuous on \( M \). So we only need to show that \( B(m) \) is also lower hemi-continuous at every \( m \in M \). Let \( m \in M \), \( x = (x_1; \ldots; x_n) \in B(m) \), and let \( f m_k g \) be a sequence such that \( m_k \uparrow m \), where \( m_k = (m_1^k; \ldots; m_n^k) \) and \( m_i^k = (w_1^k; \ldots; z_i^k; \ldots; z_n^k) \). We want to prove that there is a sequence \( f x_k g \) such that \( x_k \downarrow x \), and, for all \( k \), \( x_k \in B(m_k) \), i.e., \( x_k = (x_{1k}; \ldots; x_{nk}) \in B_+ \), \( p_i(m_k) c x_{ik} \downarrow \frac{1}{1 + k p_i^m} p_i(m_k) c w_i^k \) for all \( i \geq 2 \), and \( p_i(m_k) c x_{ik} \downarrow \frac{1}{1 + k p_i^m} p_i(m_k) c w_i^k \) for all \( i \geq 2 \). For each \( i \geq 2 \), two cases will be considered.

Case 1. \( p_i(m) c x_{ik} < \frac{p_i(m)c w_i^k}{1 + k p_i^m p_i(m_k)} \). Hence, for all \( k \) larger than a certain integer \( k^0 \), we have \( p_i(m_k) c x_{ik} < \frac{p_i(m_k)c w_i^k}{1 + k p_i^m p_i(m_k)} \) by noting that \( p_i(\phi) \) is continuous. Let \( x_{ik} = x_i \) for all \( k > k^0 \) and \( x_{ik} = 0 \) for \( k < k^0 \). Then, we have \( p_i(m_k) c x_{ik} \downarrow \frac{p_i(m_k)c w_i^k}{1 + k p_i^m p_i(m_k)} \).

Case 2. \( p_i(m) c x_{ik} = \frac{p_i(m)c w_i^k}{1 + k p_i^m p_i(m_k)} \). Note that, since \( p_i(m) > 0 \) and \( w_i > 0 \) for all \( i \), we must have \( x_{ik} > 0 \). Let \( \beta_i = \frac{1}{p_i(m_k)c w_i^k} \) and \( \alpha_i = \frac{1}{p_i(m_k)c w_i^k} \). Define \( x_{ik} \) as follows:

\[
    x_{ik} = \begin{cases} 
        \frac{1}{p_i(m_k)c w_i^k} x_i & \text{if } p_i(m_k)c w_i^k \leq 1 \\
        x_i & \text{otherwise}
    \end{cases}
\]

Then \( x_{ik} \downarrow x_i \), and \( p_i(m_k) c x_{ik} \downarrow \frac{p_i(m_k)c w_i^k}{1 + k p_i^m p_i(m_k)} \). Also, since \( \frac{1}{p_i(m_k)c w_i^k} \uparrow \frac{1}{p_i(m_k)c w_i^k} = 1 \), we have \( x_{ik} \downarrow x_i \). Thus, in both cases, there is a sequence \( f x_k g \) such that \( x_k \downarrow x \), and, for all \( k \), \( x_k \in B(m_k) \), and \( p_i(m_k) c x_{ik} \downarrow \frac{p_i(m_k)c w_i^k}{1 + k p_i^m p_i(m_k)} \) for all \( i \geq 2 \).

We now show that there is a sequence \( f x_k g \) such that \( x_k \downarrow x \), and, for all \( k \), \( x_k \in B(m_k) \), and \( \prod_{i=2}^{n} x_{ik} \downarrow \prod_{i=2}^{n} w_i^k \).

We first show this for the sequence spaces \( l_p \). There are two cases will be con-
sidered for each component of vector $\mathbf{x} = (x^1; x^2; \ldots; x^t; \ldots)$ with $1 \leq t < 1$.

Case 1. \( P_{i \in \mathbb{N}} x^i < P_{i \in \mathbb{N}} w^i \). Hence, for all $k$ larger than a certain integer $k^0$, we have $P_{i \in \mathbb{N}} x^i < P_{i \in \mathbb{N}} w^i$. For each $i \in \mathbb{N}$, let $x_{ik}^i = x^i$ for all $k > k^0$ and $x_{ik}^i = 0$ for $k \leq k^0$. Then, we have $P_{i \in \mathbb{N}} x_{ik}^i < P_{i \in \mathbb{N}} w_i$.

Case 2. $P_{i \in \mathbb{N}} x^i = P_{i \in \mathbb{N}} w^i$. Note that, since $w_i > 0$ for all $i$, we must have $P_{i \in \mathbb{N}} x^i > 0$. For each $i \in \mathbb{N}$, define $x_{ik}^i$ as follows:

$$x_{ik}^i = \begin{cases} P_{i \in \mathbb{N}} x^i & \text{if } P_{i \in \mathbb{N}} x_{ik}^i \leq 1 \\ 0 & \text{otherwise} \end{cases}$$

Then $x_{ik}^i \neq x^i$, and $P_{i \in \mathbb{N}} x_{ik}^i \neq P_{i \in \mathbb{N}} w_i$. Also, since $P_{i \in \mathbb{N}} x_{ik}^i = 1$, we have $x_{ik}^i = x^i$. Thus, in both cases, there is a sequence $f \mathbf{x}_k g$ such that $\mathbf{x}_k \rightarrow \mathbf{x}$, and, for all $k$, $\mathbf{x}_k \in \mathbb{L}_+^\infty$ and $P_{i \in \mathbb{N}} x_{ik}^i = P_{i \in \mathbb{N}} w_i$. Here $\mathbf{x}_k = (x^1_k; x^2_k; \ldots)$.

Similarly, we can show this for the Lebesgue spaces $L_p$ by considering two cases:

1. $P_{i \in \mathbb{N}} x_i(s) < P_{i \in \mathbb{N}} w_i(s)$, and
2. $P_{i \in \mathbb{N}} x_i(s) = P_{i \in \mathbb{N}} w_i(s)$ for each $s \in \mathbb{S}$.

Finally, let $x^0_k = \min(x_k; x_k)$ with $x^0_{ik} = \min(x_{ik}; x_{ik})$ for $i = 1; \ldots; n$. Then $x^0_k \rightarrow x$ since $x_k \rightarrow x$ and $x_k \rightarrow x$. Also, for every $k$ larger than a certain integer $k$, we have $x^0_k \neq x_k$, $0 \leq P_{i \in \mathbb{N}} x^0_i \leq P_{i \in \mathbb{N}} w_i$ because $x^0_k \neq x_k$, and $P_{i \in \mathbb{N}} x_{ik} \leq P_{i \in \mathbb{N}} w_i$. Let $x_k = x^0_k$ for all $k > k$ and $x_k = 0$ for $k \leq k$. Then, $x_k \rightarrow x$, and $x_k \in \mathbb{B}(m_k)$ for all $k$. Therefore, the sequence $f \mathbf{x}_k g$ has all the desired properties. So $\mathbb{B}_x(m)$ is lower hemi-continuous at every $m \in \mathbb{M}$. Q.E.D.
References


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