A Unifying Approach to Axiomatic Non-expected Utility Theories: Correction and Comment

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Chew and Epstein attempted to provide a unifying axiomatic framework for a number of generalizations of expected utility theory. Wakker pointed out that Theorem A, on which the central unifying proposition is based, is false. In this note, we apply Segal's result to prove that Theorem 2 is nevertheless valid with minor modifications. Journal of Economic Literature Classification Number: D1. © 1993 Academic Press, Inc.

1. INTRODUCTION

In Chew and Epstein [2], two of us attempted to provide a unifying axiomatic framework for a number of generalizations of expected utility theory. Our approach was to weaken the independence axiom by requiring its associated separability to hold only on suitable subsets of the domain of state-contingent outcomes. Then we invoked Theorem A of Appendix 3 which extended the additive utility representation results of Debreu [3] and Gorman [5] from the case of full Cartesian products to more general domains. Theorem A claims, given a continuous and strictly increasing preference ordering, that the Debreu-Gorman additive representation can be extended to connected subsets of $\mathbb{R}^N$ when indifference sets are
connected. Unfortunately, as was first pointed out by Wakker [7], Theorem A is false.

Segal [6] proves that Theorem A holds under the additional restrictions that the domain is open, and its intersections with translations of coordinate hyperplanes are connected. Here, we use Segal's result to prove that the central unifying proposition [2, Theorem 2] is nevertheless valid with minor modifications. Wakker [8, 9] provided earlier additive representation theorems for rank-ordered subsets of a Cartesian product. These papers also provided examples to demonstrate that the question of existence of additive representations is a delicate one when the domain is not a full Cartesian product. In addition, these papers contain references to the literature where errors similar to Theorem A occur.

2. The Unifying Representation

Let the set of prizes \( X \) be an open interval and denote by \( D^c(X) \) the set of c.d.f.'s with compact support in \( X \), i.e., \( D^c(X) = \bigcup \{ D(K) : K \subset X \text{ is a compact interval} \} \). Modify Theorem 2 by requiring that the axioms for \( \geq \) are satisfied and that the desired representations apply on \( D^c(X) \), rather than on \( D(X) \). Difficulties with utility being driven to infinity at the boundary (see [9, Example 3.8]) are avoided in this way.

We provide the additional arguments needed to show that in (the modified) Theorem 2, the axioms imply the desired representation. Notation is as in [2] except that we often abbreviate \( \sum_{i=1}^{N} (1/N) \delta_x \) and \( \sum_{i=1}^{N} (1/N) \delta_y \) by \((x_1, \ldots, x_N)\) and \((y_1, \ldots, y_N)\). We provide details corresponding to Case (iv) of the proof of Theorem 2. The other cases are more elementary and analogous.

Let \( \mathcal{F}(\bar{x}) = \mathcal{F}(\bar{x}) \cap X_N^N \). The superscript "0" applied to a subset of \( X_N^N \) refers to its restriction to exclude elements which have non-distinct components. For example, \( \mathcal{F}^0_1(\bar{x}) = \{ x \in \mathcal{F}_1(\bar{x}) : \text{the components of } x \text{ are distinct} \} \). Let \( V \) be a continuous and increasing utility function that represents \( \geq \) on \( D^c(X) \).

Lemma. For \( \bar{x} \in X_N^N \), \( \mathcal{F}^0_1(\bar{x}) \) is arc connected.

Proof. Let \( x \neq y \in \mathcal{F}^0_1(\bar{x}) \). We construct an arc from \( x \) to \( y \) within \( \mathcal{F}^0_1(\bar{x}) \) through vectors \( x = x^0, x^1, x^2, \ldots \), where each subsequent vector has one or two components more in common with \( y \) than its predecessor. Let \( j \) be the smallest index for which \( x_j > y_j \), \( i \) the largest index for which \( x_i < y_i \). By \( x_{-i}, v_i, v_j \), we denote \( x \) with \( x_i, x_j \) replaced by \( v_i, v_j \). Note (for \( j > 1 \)
that \( y_i > y_{i-1} \geq x_{i-1} \), and (for \( i < N \)) that \( y_i < y_{i+1} \leq x_{i+1} \). Suppose \( x_{i,j}, y_{i,j}, y_i \subseteq y \) (the case \( y_i \supseteq x_{i,j}, y_i, y_j \) is analogous). Then for each \( z_i \) between \( x_i, y_i \), there is a unique \( z_j \) between \( y_j, x_j \) such that \( x_{i,j}, z_i, z_j \sim y \). Note that our choices of maximal \( f \) and minimal \( i \) imply inequalities such as \( z_i \geq y_j, y_j \geq x_j \) and \( z_i \leq y_i, y_i \leq x_i, x_i \), guaranteeing \( x_{i,j}, z_i, z_j \in \mathcal{F}^0_i(\tilde{x}) \) (also if \( j = i + 1 \)). For \( z_j = y \), the associated \( z_i \) is denoted as \( y' \). \( y' \subseteq y \). We define \( x^1 := x_{i,j}, y', y_j \). Now \( x_{i,j}, z_i, z_j \) provides an arc from \( x \) to \( x^1 \) within \( \mathcal{F}^0_i(\tilde{x}) \), where \( x^1 \) has at least one component more in common with \( y \) than \( x \) (the \( i \)th component). We construct \( x^2 \) from \( x^1 \) as we constructed \( x^1 \) from \( x \), again obtaining one more component in common with \( y \). After at most \( N \) steps the constructed alternative becomes identical to \( y \). Between each subsequent pair of vectors \( x^k, x^{k+1} \) there is an arc within \( \mathcal{F}^0_i(\tilde{x}) \). These arcs together constitute an arc from \( x \) to \( y \). Indeed \( \mathcal{F}^0_i(\tilde{x}) \) is arc connected.

**Case (iv) IRLU.** The ordering \( \succeq_i \) is continuous, strictly increasing, and completely separable on

\[
\mathcal{F}_i(\tilde{x}) \ni \{ x \in X^N : \exists z \in X \text{ such that } (x, z) \in \mathcal{F}(\tilde{x}) \text{ and } z \text{ is the } i \text{th rank component of } (x, z) \}.
\]

Let \( \mathcal{F}^0_i(\tilde{x}) = \mathcal{F}_i(\tilde{x}) \cap \mathcal{F}^0_i(\tilde{x}) \). To apply Segal’s theorem, we must show:

(a) \( \mathcal{F}^0_i(\tilde{x}) \) is open and connected in \( \mathbb{R}^N \), and

(b) \( \forall c \in X, \mathcal{F}^0_i(\tilde{x}) \cap \{ x \in X^N : x_k = c \} \) is connected, for each \( k \neq i \).

**Proof of (a).** The arc connectedness of \( \mathcal{F}^0_i(\tilde{x}) \) implies that its projection \( \mathcal{F}^0_i(\tilde{x}) \) is connected, using [4, p. 115]. To prove openness, let \( x \in \mathcal{F}^0_i(\tilde{x}) \), i.e., \( x' = (x, z) \sim \tilde{x} \) and \( z \) is the \( i \)th rank component of \( (x, z) \). Then \( \exists \delta > 0 \exists (x, z + \delta) \supset x > (x, z - \delta) \Rightarrow \exists \varepsilon > 0 \exists y - x \| < \varepsilon \| y - x \| < \varepsilon \| < \varepsilon \| \in \mathcal{F}^0_i(\tilde{x}) \sim \tilde{x}' \sim x' \). Thus, \( \{ y \in X^N : \| y - x \| < \varepsilon \} \in \mathcal{F}^0_i(\tilde{x}) \sim \).

**Proof of (b).** Path connectedness of

\( S = \mathcal{F}^0_i(\tilde{x}) \cap \{ x \in X^N : x_k = c \} \)

may be proven as in the lemma. Thus its projection \( \mathcal{F}^0_i(\tilde{x}) \cap \{ x \in X^N : x_k = c \} \) is connected, completing the proof of (b).

Given the additive representation provided by Segal’s theorem, we proceed as in [2, pp. 233–234] to derive \( \psi : \text{dom}(\psi) \subseteq X \times [0, 1]^N \times \mathbb{R} \), such that \( \psi(x, p, y) \) is continuous in \( x \) for each \( (p, y) \); \( \psi(\cdot, 0, \cdot) = 0; \)

\[
\psi(x, p, y) - \psi(x, p', y) - \psi(x', p, y) + \psi(x', p', y) > 0 \quad (1)
\]
if \( p > p' \) and \( x > x' \), such that \( \psi \) represents \( \succeq \) on \( D'(X) \) in the sense that on \( X^N_1 \), for any \( N \),

\[
\sum_{i=1}^{N} \left( \frac{1}{N} \right) \delta_{a_i} \succeq \sum_{i=1}^{N} \left( \frac{1}{N} \right) \delta_{a_i} \iff m \left( \sum_{i=1}^{N} \left( \frac{1}{N} \right) \delta_{a_i} \right) \geq m \left( \sum_{i=1}^{N} \left( \frac{1}{N} \right) \delta_{a_i} \right),
\]

where for \( F = \sum_{i=1}^{N} (1/N) \delta_{a_i} \), \( m(F) \) is defined by

\[
\sum_{i=1}^{N} \left[ \psi(x_i, i/N, m(F)) - \psi(x_i, (i-1)/N, m(F)) \right] = 0.\]

Given \( y \in X \), define

\[
x^*(p, y) = \sup \{ z' \in X : p \delta_z + (1 - p) \delta_y \sim \delta_z \ \text{for some } z < z' \},
\]

and for \( x < y \),

\[
p^*(x, y) = \sup \{ q \in [0, 1] : q \delta_x + (1 - q) \delta_y \sim \delta_x \ \text{for some } y < z' \}.
\]

Then \( \text{dom}(\psi) = \bigcup_{y \in X} \text{dom}(\psi(\cdot, y)) \), where

\[
\text{dom}(\psi(\cdot, y)) = \{ (x, p) \in X \times [0, 1] : x < x^*(p, y); p < p^*(x, y) \}.
\]

We show that \( \forall y \in X, \psi(\cdot, \cdot, y) \) is continuous on \( \text{dom}(\psi(\cdot, \cdot, y)) \). Pick \( F \in D'(X), F = \sum_{i=1}^{M} q_i \delta_{x_i} \) such that \( y = m(F) \). For \( 1 < k < N, p := \sum_{i=1}^{k} q_i \) is the probability under \( F \) of receiving an outcome that is not greater than \( x_k \). Let \( j \neq k \). Let \( x^n_j \rightarrow x_j, p^n \rightarrow p, x^n_k \rightarrow x_k \) such that \( x_{j-1} < x^n_j < x_{j+1}, x_{k-1} < x^n_k < x_{k+1} \), and \( F_n \sim F \) for all \( n \), where \( F_n \) is derived from \( F \) by replacing \( (x_j, x_k, p) \) by \( (x^n_j, x^n_k, p^n) \). In other words, \( F_n = \sum_{i=1}^{M} r^n_i \delta_{x^n_i} \), where \( x_i = x^n_i \) except for \( i = j, k \), and \( \sum_{i=1}^{k} r^n_i = p^n \); \( r^n_i = q_i \) except for \( i = k, k + 1 \). Note that a choice of \( p^n, x^n_k \) by indifference to \( F \) uniquely determines \( x^n_j \). That such sequences \( x^n_j, p^n, x^n_k \) exist is straightforwardly derived from weak continuity. From indifference to \( F \), it follows that

\[
\left[ \psi \left( x^n, \sum_{i}^{j} q_i, y \right) - \psi \left( x, \sum_{i}^{j} q_i, y \right) \right] + \left[ \psi(x^n, p^n, y) - \psi(x, p, y) \right] = 0.
\]

By the continuity of \( \psi \) in the first argument, the first bracket approaches 0. Therefore, \( \psi(x^n_j, p^n, y) - \psi(x_k, p, y) \) also approaches 0. Thus, \( \forall y \in X, \psi(\cdot, \cdot, y) \) is continuous on \( \text{dom}(\psi(\cdot, \cdot, y)) \).

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1 For \( p = k/N \) and \( p' = j/N \), \( \psi(x, p, y) - \psi(x, p', y) - \psi(x', p, y) + \psi(x', p', y) \) is, according to the construction, given by \( \sum_{i=1}^{k} [u^n(x, y) - u^n(x', y)] > 0 \).

2 Strictly speaking, the representation obtains only for lotteries in \( D'(X) \) which have distinct outcomes. The extension to non-distinct outcomes is accomplished via weak continuity.
For each \( y \in X \), we extend \( \psi(\cdot, \cdot, y) \) continuously to
\[
\{(x, p, y) \in X \times [0, 1] \times X : x \leq x^*(p, y); p \leq p^*(x, y)\}.
\]
We further extend \( \psi(\cdot, \cdot, y) \) to all of \( X \times [0, 1] \) by defining
\[
\psi(x, p, y) = \begin{cases} 
\psi(x^*(p, y), p, y), & x \in (x^*(p, y), \infty), \\
\psi(x, p^*(x, y), y), & p \in (p^*(x, y), 1].
\end{cases}
\]
By construction, \( \forall y \in X, \psi(\cdot, \cdot, y) \) is jointly continuous on \( X \times [0, 1] \) and satisfies (1). Therefore, \( \psi(\cdot, \cdot, y) \) defines a positive Lebesgue-Stieltjes measure \( \lambda(\cdot ; y) \) on \( X \times [0, 1] \) \([1, \text{p. 149, Theorem } 12.5]\). Let \( \ast F \) denote the epigraph of \( F \). Then the representation of the ordering on \( D^c(X) \) can be expressed as: \( \forall F \in D^c(X) \),
\[
\lambda(\ast F, m(F)) = \lambda(\ast \delta_{m,F}, m(F)).
\]
Since \( D^c(X) \) is dense in \( D(X) \), in order to extend the representation to \( D^c(X) \), it suffices to show that
\[
\lambda(\ast F_n \setminus \ast F, m(F)) + \lambda(\ast F \setminus \ast F_n, m(F)) \to 0 \tag{2}
\]
whenever \( \{F_n\} \subset \mathcal{F}(F) \to F \) and \( \exists \) compact interval \( K \subset X \) such that \( \text{supp}(F_n) \subset K \), \( \forall n \). Let \( 1_A \) denote the indicator function for a set \( A \). Then (2) is implied by the countable additivity of \( \lambda \) if on \( K \times [0, 1] \),
\[
1_{\ast F_n} \to 1_{\ast F} \text{ a.e. } [\lambda].
\]
The above convergence can fail only for points \( (x, p) \in S \cup \text{gr} \ F \), where
\[
\text{gr} \ F = \{(x, p); p = F(x)\},
\]
and
\[
S = \{(x, F(x)); x \text{ is a discontinuity point of } F\}.
\]
Since \( F \) has at most countably many discontinuity points and since \( \psi \) is continuous in \( x \), \( \lambda(S, m(F)) = 0 \). Thus, it remains to prove that \( \forall F \in D^c(X) \),
\[
\lambda(\text{gr} \ F, m(F)) = 0 \tag{3}
\]
It follows from the continuity of \( \psi(\cdot, \cdot, m(F)) \) that \( \lambda(\text{gr} \ F, m(F)) = 0 \), \( \forall F \in D^c(X) \cap \mathcal{F}(F) \). Suppose \( \exists F \in D^c(X) \setminus D^c(X) \) such that \( \lambda(\text{gr} \ F, m(F)) > 0 \). Pick \( (t, q) \in \text{gr} \ F \) with \( q \in (0, 1) \) such that the \( \lambda(\cdot, m(F)) \) measure of either the portion \( A \) of \( \text{gr} \ F \) above \( (t, q) \) or of the portion \( B \) below \( (t, q) \) is strictly positive. Without loss of generality, say \( \lambda(A, m(F)) > 0 \). Let \( F' \in D^c(X) \cap \mathcal{F}(F) \) be such that \( F' \) coincides with \( F \) at and above \( (t, q) \) and
supp(F') to the left of t is nonempty and finite. It follows that the 
\( \lambda(\cdot, m(F)) \) measure of the portion of \( \text{gr } F' \) below \((t, q)\) is 0.

We may assume \( F' = F \). By weak continuity and monotonicity of \( \supseteq \), sequences \((G_n)\) and \((H_n)\) in \( D'(X) \cap \mathcal{F}(F) \) can be obtained that converge in distribution to \( F \) such that \( d(G_n, H_n) \to 0 \) (\( d \) is the Prohorov metric), and for all \( n \), \( G_n \) and \( H_n \) each cross \( F \) once at \((t, q)\) with \( G_n(H_n) \) strictly below (above) for \( x < t \) and with \( G_n(H_n) \) strictly above (below) for \( x > t \). Let \( C_n \) \( (D_n) \) be the difference between \( *G_n \) and \( *H_n \) above (below) the point \((t, q)\). Since \( G_n \sim H_n \sim F \).

\[
\lambda(C_n, m(F)) = \lambda(D_n, m(F)).
\] (4)

The difference between \( B \) and \( \bigcap_{n=1}^{\infty} D_n \) is contained within vertical line segments associated with the finite number of discontinuity points of \( F \), hence has \( \lambda \) measure 0. Therefore, \( \lambda \) being countably additive, 0 = \( \lambda(B, m(F)) = \lambda(\bigcap_{n=1}^{\infty} D_n, m(F)) \), and \( \lambda(D_n, m(F)) \to 0 \). But for every \( n \), \( \lambda(C_n, m(F)) \geq \lambda(\text{gr } F, m(F)) > 0 \), which yields a contradiction to (4). Thus, (3) has been proved. □

To conclude, we point out that Lemma B of [2, Appendix 2], which provides sufficient conditions on \( \psi \) for the corresponding certainty equivalent functional \( m \) to be continuous, should include an additional assumption to guarantee (3). For this, continuity of \( \psi_{12}(\cdot, \cdot, y) \) for all \( y \in X \) suffices.

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