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EXPECTATION AND VARIATION IN MULTI-PERIOD DECISIONS

BY ITZHAK GILBOA[1]

Multi-period decisions are decisions which determine an individual's payoffs in several periods in the future. This paper examines the theoretical foundations of the prevalent weighted average assumption. More specifically, we use a multi-period interpretation of the famous Ellsberg paradox in decision under uncertainty to show that in many cases of interest additively-separable functionals (in general) and weighted average ones (in particular) do not seem appropriate for the representation of the decision maker's preferences.

We then suggest replacing the sure-thing principle, which may be used to axiomatize a weighted average functional, by a weaker version of it. Using the weakened axiom in Schmeidler's nonadditive measure model (reinterpreted for the multi-period context) yields an axiomatization of a larger class of decision rules which are representable by a weighted average of the utility in each period *and* the utility variation between each two consecutive periods.

The weighted average assumption is a special case of the generalized model, a case in which the decision maker is variation neutral. Similarly, we define and characterize variation aversion and variation liking, and show an example of the economic implications of these properties.

KEYWORDS: Multi-period decisions, intertemporal separability, Ellsberg paradox, sure-thing principle, non-additive measures.

1. INTRODUCTION

THERE IS A LARGE CLASS of economic problems in which a decision maker is asked to choose one alternative out of a choice set, each of the elements of which determines his payoff (or expected payoff) in several periods in the future. We will refer to these problems as multi-period problems.

Examples in which this structure is explicit are, for instance, models of investment, labor planning, and all problems which may be formulated as repeated games. There are, however, many more examples in which the same structure is implicitly assumed. In fact, it seems that one can hardly think of a real life decision problem (whether under certainty or uncertainty) that may be satisfactorily represented as a single-period problem. (In Savage (1954), for instance, the individual's single choice is among acts which provide, for each state of nature, a complete description of the aspects of the world relevant to him at *every* point of time in the future.)

It is assumed in most of the economic literature that there exists an instantaneous utility function, u, and a long-run function, U, such that each alternative $f=(f_1, f_2, \dots)$ is assessed by $U(u(f_1), u(f_2), \dots)$. In many cases, no restrictions are set upon U (apart from monotonicity, quasi-concavity and so forth). In most of the cases in which U's functional form is specified, it is assumed to be a weighted average $\sum_i p_i u(f_i)$, where common weights are $p_i=(1-\beta)\beta^{i-1}$ for

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$0 < \beta < 1$, $i \geq 1$, and $p_i = 1/T$ for $1 \leq i \leq T$, where T is the number of periods under consideration.

Such a functional is discussed and axiomatized in Koopmans (1960), and Koopmans, Diamond, and Williamson (1964). More general (nonseparable) functionals are axiomatized, discussed, and used in more recent papers. See, for example, Kreps and Porteus (1978), Lucas and Stokey (1984), Epstein and Zin (1987a and 1987b), and others.

The purpose of this paper is to examine the theoretical foundations of the separable functional form from a different viewpoint, and to provide an axiomatization of a slightly more general form, which is quite simple and seems to be more suitable for some of the possible applications.

1.1. *Motivation*

It is well known that Savage's formulation of the decision-under-uncertainty problem may be interpreted in other ways as well: in Savage (1954) an *act* is a function from the *states of the world* into the set of *consequences*. But if one chooses to replace the states of the world by individuals in a population, the resulting problem is a social choice problem; if the states are replaced by criteria and the consequences by grades, we obtain a model of a multi-criteria decision problem; and if the "states of the world" are interpreted as points of time, we end up with a multi-period decision problem.

It follows then that Savage (1954), and Anscombe and Aumann (1963), provide axiomatic foundations for the equivalents of the expected utility paradigm in the other contexts, that is to say, for the hypothesis that the relevant functional U is a weighted average of $\{u(s)\}_{s \in S}$ where S is the domain on which acts are defined.

However, even in their "native" interpretation—namely, in the realm of decisions under uncertainty—the classical models have been seriously attacked. (See, for instance, Allais (1952) and Ellsberg (1961).) It is, therefore, our task to examine their axioms carefully before applying them to any other field of decision theory.

Let us first consider a simple example: a decision maker is faced with a choice problem, and his decision determines his payoffs in the next four periods. At each period his payoff may be either high (H) or low (L). He has four alternatives, which are (H, H, L, L), (H, L, H, L), (L, H, L, H), and (L, L, H, H). Suppose that in some sense (which is quite vague to us at this point) the utility in each period receives equal weight. However, there is a certain "cost of adjustment" incurred by any change in the payoff level. For example, the payoffs may be the instantaneous utility from commodity bundles or the standard of living levels, and the costs are the socio-psychological costs of changing the social status. One may also think of a firm where the payoffs are the revenue (and profit) levels, the variation of which involves some organizational cost due to the changes in the production level. Naturally, some inventory constraints must be assumed in such a model. However, there are many cases in which such constraints do exist—for instance, the allowable storage time may be very short compared to the periods under consideration.

Of course, one may argue that the "adjustment costs" should be incorporated into the payoffs, complying with the classical economic approach. However, by doing so we may overlook the properties of the special functional form which will be revealed by the reduced-form model considered here.

In these cases it seems plausible that the decision maker's preference relation $\succsim$ would satisfy

$$(H, H, L, L) \sim (L, L, H, H) \succ (H, L, H, L) \sim (L, H, L, H)$$

(where $\succ$ means strict preference and $\sim$ means equivalence).

It is easy to see that such preferences do not comply with the weighted average hypothesis. That is, there do not exist a utility function $u = (u(H), u(L))$ and a measure $p = (p_1, p_2, p_3, p_4)$ such that the preferences discussed above may be explained by maximization of the integral of u with respect to p. Moreover, note that these preferences cannot be accounted for by either a separable functional with state-dependent utility function, or by a concave utility function (which may reflect some aspects of variation-aversion if more than two utility levels are considered).

In fact, this example is mathematically equivalent to the famous Ellsberg paradox (Ellsberg (1961)), which challenged Savage's sure-thing principle. We will now discuss this principle.

1.2. *The Sure-Thing Principle*

Roughly, the principle (Axiom P2 in Savage (1954)) says that, if two possible acts yield the same consequences whenever an event A occurs, the preferences between them should be determined only by the values they assume outside A. Or, formally, if f, g, f', and g' are four acts (functions from the set of states of the world S to the set of consequences X), and

$$f(s) = g(s), \qquad f'(s) = g'(s) \quad \text{for all } s \in A,$$

$$f(s) = f'(s), \qquad g(s) = g'(s) \quad \text{for all } s \in A^c.$$

Then, $f \succsim g$ iff $f' \succsim g'$.

In the original interpretation of the model, the principle seems almost unobjectionable: by definition, exactly one of all possible states of the world actually obtains, hence there cannot eventually be any situation in which the decision maker is affected by the consequences attached by his act to other states of the world.

Of course, the principle has proved to be objectionable after all. (This is an empirical fact.) However, we claim that in other interpretations its foundations are considerably weaker to start with. Consider, for example, the social choice interpretation of the same decision problem discussed in subsection 1.1. Assume H and L represent high and low salaries, respectively, and let the domain be (fair-haired in city A; dark-haired in city A; fair-haired in city B; dark-haired in city B). It is perfectly reasonable to assume that a central planner should have no bias toward either city, nor towards either hair color, but would strictly prefer that the poorly-paid employees will not concentrate in any single city.

In the context of long-run decisions we have already seen that the sure-thing principle may not be as compelling an axiom as it purports to be in its original context. There is, however, a slight modification of it which seems to be a reasonably sound foundation for our theory.

1.3. *Variation-Preserving Sure-Thing Principle*

In the context of long-run decisions, as opposed to the other ones, there is a natural linear ordering on the domain of the acts: time points (or periods) are ordered by their very definition, while states of the world and individuals in a society are not. This additional structure imposed on our model allows us to reject the sure-thing principle as formulated, without renouncing the gist of its essence.

Let us consider the example of subsection 1.1 once more. The prospect (H, H, L, L) is preferred to (L, H, L, H), but if we replace the payoffs in periods 2 and 3 by (L, H), we obtain the prospects (H, L, H, L) and (L, L, H, H), respectively, with the latter preferred to the former. One may observe that the replacement of (H, L) by (L, H) in periods 2 and 3 is biased in a certain sense: it increases the variation of (H, H, L, L) but decreases that of (L, H, L, H). If the variation of the acts should play any role in our theory, there is no reason to wonder at the preference reversal. But if we restrict ourselves to such changes which *do not* affect the variation asymmetrically, we may expect the principle to hold.

A simple way in which we can assure that changing f to f' will have the same effect on the variation of f as changing g to g' will have on that of g is to restrict the scope of discussion to changes over time intervals on the edges of which f and g coincide. The weaker axiom which results will be called *variation-preserving sure-thing principle*. It is easy to see that it allows the preference reversal of subsection 1.1, since the time interval under discussion (periods 2 and 3) does not satisfy our additional condition: on its edges (periods 1 and 4) the two relevant acts ((H, H, L, L) and (L, H, L, H)) do *not* coincide.

1.4. *A Description of the Model and the Results*

We will use the framework of Anscombe and Aumann (1963) rather than that of Savage (1954), since it allows for a finite domain and a denumerable one with a continuous measure. Our whole discussion will, in fact, be restricted to these two cases. (The generalization to continuous time, for instance, meets the difficulties of axiomatizing measurability and continuity of various functions which are endogenous in the model. The author is not aware of any set of reasonably intuitive axioms which may guarantee the desired technical properties.)

Since we reject the sure-thing principle, we cannot adhere to the Anscombe-Aumann model; we therefore turn to its generalization suggested by Schmeidler (1982, 1986) using the concept of nonadditive measures. On this basic model we impose the variation-preserving sure-thing principle and, roughly, we obtain the following result:

There are a utility function, u, and two functions, p and δ, on the set of periods $\{s_1, s_2, \dots, s_n\}$, such that the preferences relation is represented by the functional

$$U(f) = \sum_{i=1}^{n} \left[p(s_i) u(f(s_i)) + \delta(s_i) |u(f(s_i)) - u(f(s_{i-1}))| \right]$$

(with an appropriate definition of $u(f(s_0))$). That is to say, there exists an "intrinsic weight" $p(s_i)$ to each period s_i, and the first element in the summation is the expected utility with respect to the measure $p(\cdot)$. The second element for each period s_i is an extra cost/bonus incurred by the mere variation of the function $u(f(\cdot))$.

A precise formulation and a proof of the representation theorem are to be found in Section 2. The extension to an infinite horizon is contained in Section 3. A by-product of this section is a characterization of continuous measures in Schmeidler's model, and a proof that the Choquet integral (see Choquet (1955)) is continuous in the appropriate sense.

Given the functional form (for a finite or infinite horizon), one may ask what an individual's attitude is towards variation. Indeed, it turns out that we may define and characterize the notions of variation aversion, variation neutrality, and variation liking. This is done in Section 4.

Finally, Section 5 provides an example of the implications of our model. It shows that even if two "identical" individuals play a repeated zero-sum game, the super game need not be zero-sum—that is, such two individuals may have a positive surplus of cooperation.

2. THE MODEL AND THE FINITE-HORIZON REPRESENTATION THEOREM

2.1. *Schmeidler's Model and Result*

Let X be a nonempty set of *consequences* and let Y denote the set of finite-support distributions over X ("lotteries"):

$$Y = \left\{ y\colon X \to [0,1] \,|\, y(x) \neq 0 \text{ for only finitely many } x\text{'s in } X \text{ and } \sum_{x \in X} y(x) = 1 \right\}.$$

Let S be a nonempty set of *points of time* and let Σ be an algebra of subsets of S. We will define F, the set of *acts*, to be a subset of the functions from S to Y, including all the constant functions. We assume that a binary (preference) relation $\succsim$ is given on F such that F is exactly the set of all Σ-measurable bounded functions with respect to $\succsim$: given $\succsim \subseteq F \times F$ we define $\succsim \subseteq Y \times Y$ by identifying a lottery y in Y with the constant act which assumes the value of y over all S. As usual, $\succ$ and $\sim$ are defined to be the asymmetric and symmetric parts of $\succsim$, respectively. An act $f \in F$ is Σ-measurable if $\{s | f(s) \succ y\}, \{s | f(s) \succsim y) \in \Sigma$ for all $y \in Y$. We may then assume that

$$F = \Big\{ f\colon S \to Y | f \text{ is } \Sigma\text{-measurable and there are } \underline{y}_f, \bar{y}_f \in Y \text{ such that } \bar{y}_f \succsim f(s) \succsim \underline{y}_f \text{ for all } s \in S \Big\}.$$

Linear operations are performed on F pointwise. Two acts, $f, g \in F$, are *comonotonic* iff there are no $s, t \in S$ for which $f(s) \succ f(t)$ and $g(t) \succ g(s)$.

Schmeidler's axioms are:

A.1 Weak Order: $\succsim$ *is complete and transitive.*

A.2 Comonotonic Independence: *If f, g, $h \in F$ are pairwise comonotonic and* $\alpha \in (0,1)$, *then $f \succsim g$ iff $\alpha f + (1-\alpha) h \succsim \alpha g + (1-\alpha) h$.*

A.3 Continuity: *If f, g, $h \in F$ satisfy $f \succ g \succ h$ then there are* $\alpha, \beta \in (0,1)$ *such that*

$$\alpha f + (1-\alpha) h \succ g \succ \beta f + (1-\beta) h.$$

A.4 Monotonicity: *If $f, g \in F$ satisfy $f(s) \succsim g(s)$ for all $s \in S$, then $f \succsim g$.*

A.5 Nondegeneracy: *There are $f, g \in F$ such that $f \succ g$.*

Note that A.1–A.3 imply that $\succsim$ satisfies the von Neumann-Morgenstern (1947) axioms on Y.

Axiom A.2 deserves comment. In Anscombe and Aumann (1963), it was assumed in a stronger form, without the comonotonicity condition. Their theorem proves that such a preference relation is representable by expected utility maximization. Hence, it satisfies the sure-thing principle, which is too restrictive for our theory.

The following example illustrates why Anscombe-Aumann's original Axiom A.2 is incompatible with some of the preference patterns we would like to explain, and why the weaker version suggested above seems more appropriate. Suppose we have a four-period model, and for any two instantaneous expected utility levels, $L < H$, the preferences over acts satisfy, as in the example given in the introduction.

$$(L, L, H, H) \sim (H, H, L, L) \succ (L, H, L, H) \sim (H, L, H, L).$$

Suppose further that, for acts f, g, and h,

$$Eu(f) = (20, 20, 0, 0),$$
$$Eu(g) = (20, 0, 20, 0), \quad \text{and}$$
$$Eu(h) = (-20, 0, 0, 20).$$

For $\alpha = 1/2$, we obtain

$$Eu(\alpha f + (1-\alpha)h) = (0,10,0,10)$$

and

$$Eu(\alpha g + (1-\alpha)h) = (0,0,10,10).$$

The preference relation we have chosen satisfies $f \succ g$ but $\alpha g + (1-\alpha)h \succ \alpha f + (1-\alpha)h$, so it violates the original (and stronger) version of A.2.

It can be easily seen that f, g, and h in this example are not pairwise comonotonic. Moreover, the mixing of f with h increases the number of maximal length intervals on which f is monotonic (from 1 to 3) while it decreases the corresponding number for g (from 3 to 1). However, if we require that f, g, and h be pairwise comonotonic, the mixing with h cannot have this asymmetric affect on the monotonicity of f and g and the weakened independence axiom which results is a reasonable one.

We now define a (nonadditive) *measure* v on (S, Σ) to be a function $v\colon \Sigma \to [0,1]$ which satisfies:

(i) $\quad v(\varnothing) = 0; \quad v(S) = 1;$

(ii) $\quad A \subset B \subset S \Rightarrow v(A) \le v(B).$

For a Σ-measurable and bounded real function $\psi\colon S \to R$, the (*Choquet*) *integral* of ψ (on S) with respect to v is

$$\int_S \psi\, dv = \int_{-\infty}^{0} \left[v(\{s \mid \psi(s) > t\}) - 1 \right] dt + \int_0^{\infty} v(\{s \mid \psi(s) > t\})\, dt$$

(where the integrals on the right side are Riemann's). When no confusion is likely to arise, the subscript, S, will be omitted and we will denote the integral simply by $\int \psi\, dv$.

Note that for an additive v the Choquet integral coincides with the usual (Lebesgue) one.

We now quote:

SCHMEIDLER'S THEOREM: $\succsim$ *satisfies* A.1–A.4 *iff there are an affine utility* $u\colon Y \to \mathbb{R}$ *and a measure* v *on* (S, Σ) *such that*

$$f \succsim g \Leftrightarrow \int u(f)\, dv \ge \int u(g)\, dv, \qquad \forall f, g \in F.$$

Furthermore, if A.1–A.5 hold, then u is unique up to a positive linear transformation (p.l.t.) and v is unique.

2.2. *The Model*

We now introduce additional assumptions. First of all, we assume that there exists a linear order $\gg$ defined on S. This is, of course, the "later than" relation defined on points of time. Next we assume (until Section 3) that S is finite and that $\Sigma = 2^S$. Without loss of generality, we assume that $S = \{s_i\}_{i=1}^n$ where $s_{i+1} \gg s_i$ for $1 \leq i \leq n-1$. We extend $\gg$ to subsets of S as follows: for $A \subset S$ and $s \in S$, $s \gg (\ll) A$ if $s \gg (\ll) t$ for all $t \in A$. Similarly, for $A, B \subset S$, $B \gg (\ll) A$ if $B \gg (\ll) t$ for all $t \in A$. $A, B \subset S$ are *separated* if $\exists s \in S$ such that $A \ll s \ll B$ or $B \ll s \ll A$.

A subset $A \subset S$ is an *interval* if there are $1 \leq i, j \leq n$ such that $A = \{s_k \in S | i \leq k \leq j\}$. In this case, A will also be denoted simply by $[s_i, s_j]$.

Unless otherwise stated, we will assume that $\succsim$ satisfies A.1–A.5 and refer to u and v provided by Schmeidler's theorem. Furthermore, without loss of generality, we assume that $\sup\{u(y)|y \in Y\} > 1$ and $\inf\{u(y)|y \in Y\} < 0$, and for each $\alpha \in [0,1]$, we choose $y_\alpha \in Y$ such that $u(y_\alpha) = \alpha$.

For convenience, extend any act f to the domain $S \cup \{s_0, s_{n+1}\}$ by $f(s_0) = f(s_{n+1}) = y_0$ for all $f \in F$. (We assume also that $s_{n+1} \gg S \gg s_0$.)

We may finally formulate:

A.6 Variation-Preserving Sure-Thing Principle: *Suppose that* $A = [s_i, s_j]$ *with* $1 \leq i \leq j \leq n$, *and that* $f, f', g, g' \in F$ *satisfy*

$$f(s) = g(s), \quad f'(s) = g'(s) \quad \textit{for all } s \in A,$$
$$f(s) = f'(s), \quad g(s) = g'(s) \quad \textit{for all } s \in A^c,$$

and

$$f(s_k) = g(s_k) = f'(s_k) = g'(s_k) \quad \textit{for} \quad k = i-1,\ j+1.$$

Then $f \succsim g$ *iff* $f' \succsim g'$.

The Main Theorem: $\succsim$ *satisfies A.6 iff there are* p, δ: $S \to R$ *such that*

(i) $$p(s_i) \geq |\delta(s_i)| + |\delta(s_{i+1})| \quad \textit{for } i < n,$$
$$p(s_n) \geq |\delta(s_n)|, \quad \textit{and } \delta(s_i) = 0,$$

and

(ii) $$\int u(f)\, dv = \sum_{i=1}^{n} \left[p(s_i) u(f(s_i)) + \delta(s_i) |u(f(s_i)) - u(f(s_{i-1}))| \right]$$

for all $f \in F$.

Moreover, if A.6 holds then p and δ *are unique. (It will also be clear from the ensuing analysis that A.6 is independent of the other axioms.)*

2.3. *Proof of the Theorem*

Let us first assume A.6 holds. The main steps in the proof are the following: First we show that the nonadditive measure, provided by Schmeidler's theorem, has some additive measure properties with respect to the union of separated and overlapping intervals. Next we show that, using these properties, one has only $(2n-1)$ degrees of freedom in determining v, as opposed to n degrees of freedom for an additive measure on the one hand, and $2^n - 2$ degrees of freedom for a general nonadditive measure on the other hand. We then provide a relatively concise representation of the nonadditive measure v. Finally, we prove that the Choquet integral with respect to it also assumes a simple form which is, basically, the functional form we axiomatize.

We begin with the following lemma.

LEMMA 1: *Suppose $A, B \subset S$ are separated. Then*

$$v(A \cup B) = v(A) + v(B).$$

PROOF: Suppose, without loss of generality, that $A \ll s \ll B$. Now assume that there exists $C \subset S$ such that: (i) $C \gg s$; (ii) $C \cap B = \phi$; and (iii) $v(B \cup C) > v(B)$.

Let $\alpha = v(B)/v(B \cup C)$ and define $f_1, f_2, f_3, g_1, g_2, g_3 \in F$ as follows:

$$f_1(t) = \begin{cases} y_1, & t \in B, \\ y_0 & \text{otherwise}, \end{cases} \quad g_1(t) = \begin{cases} y_\alpha, & t \in B \cup C, \\ y_0 & \text{otherwise}, \end{cases}$$

$$f_2(t) = \begin{cases} y_1, & t \in B, \\ y_\alpha, & t \in A, \\ y_0 & \text{otherwise}, \end{cases} \quad g_2(t) = \begin{cases} y_\alpha, & t \in A \cup B \cup C, \\ y_0 & \text{otherwise}, \end{cases}$$

and

$$f_3(t) = \begin{cases} y_1, & t \in B \cup A, \\ y_0 & \text{otherwise}, \end{cases} \quad g_3(t) = \begin{cases} y_1, & t \in A, \\ y_\alpha, & t \in B \cup C, \\ y_0 & \text{otherwise}. \end{cases}$$

Since $\int u(f_1)\,dv = \int u(g_1)\,dv$, we obtain $f_1 \sim g_1$. By A.6, $f_2 \sim g_2$ and $g_3 \sim g_3$ must also hold. Hence $\int u(f_2)\,dv = \int u(g_2)\,dv$ and $\int u(f_3)\,dv = \int u(g_3)\,dv$. The first equality implies

$$(1-\alpha)v(B) + \alpha v(A \cup B) = \alpha v(A \cup B \cup C)$$

and the second one yields

$$v(A \cup B) = (1-\alpha)v(A) + \alpha v(A \cup B \cup C).$$

Hence

$$v(A \cup B) = (1-\alpha)v(A) + (1-\alpha)v(B) + \alpha v(A \cup B),$$

whence

$$v(A \cup B) = v(A) + v(B).$$

We now turn to the case in which there does not exist a subset C as required. We define $S' = S \cup \{s^*\}$ and $\gg'$ on $S' \cup \{s_0, s_{n+1}\}$ by $s_{n+1} \gg' s^* \gg' s_n \gg' \cdots \gg' s_1 \gg' s_0$.

For $A \subset S'$, let $v'(A) = v(A \cap S) + \varepsilon 1_{\{s^* \in A\}}$ for a fixed $\varepsilon > 0$. Now let $F' = \{f\colon S' \to Y\}$ and define $\succsim'$ on F' by $\int_{S'} u(\cdot)\,dv'$. By Schmeidler's theorem, $\succsim'$

on F' satisfies Axioms A.1–A.5. However, it also satisfies A.6 since

$$\int_{S'} u(f)\,dv' = \int_S u(f)\,dv + u(f(s^*))\cdot\varepsilon \quad \text{for} \quad f\in F'.$$

Considering A and B as subsets of S', there exists $C=\{s^*\}$ which satisfies our conditions. Therefore $v'(A\cup B)=v'(A)+v'(B)$. But $s^*\in(A\cup B)^c$ and our conclusion follows. *Q.E.D.*

By Lemma 1 we know that v is completely determined by its value on the intervals (since any $A\subset S$ is the disjoint union of finitely many separated intervals). As there are $\binom{n+1}{2}$ intervals, there are no more than $\binom{n+1}{2}$ degrees of freedom in specifying v. However, the next lemma proves that this upper bound is not the best one one may obtain:

LEMMA 2: *Let A and B be two intervals such that $A\cap B\neq\varnothing$. Then $v(A\cup B)+v(A\cap B)=v(A)+v(B)$.*

PROOF: If $A\subset B$ or $B\subset A$, the lemma is trivial. Assume, then, without loss of generality, that $A=[s_i,s_j]$ and $B=[s_k,s_l]$ where $1\le i<k<j<l\le n$. As in the previous lemma, we first assume that there exists a subset $C\subset[s_{l+1},s_n]$ such that $v(B\cap C)>v(B)$. In this case, let $\alpha\in[0,1)$ satisfy $v(B)=(1-\alpha)v(A\cap B)+\alpha v(B\cup C)$ and define $f_1,f_2,f_3,g_1,g_2,g_3\in F$ by:

$$f_1(t)=\begin{cases} y_1, & t\in B,\\ y_0 & \text{otherwise,}\end{cases}\qquad g_1(t)=\begin{cases} y_1, & t\in A\cap B,\\ y_\alpha, & t\in(B-A)\cup C,\\ y_0 & \text{otherwise,}\end{cases}$$

$$f_2(t)=\begin{cases} y_1, & t\in B,\\ y_\alpha, & t\in A-B,\\ y_0 & \text{otherwise,}\end{cases}$$

$$g_2(t)=\begin{cases} y_1, & t\in A\cap B,\\ y_\alpha, & t\in(B-A)\cup(A-B)\cup C,\\ y_0 & \text{otherwise,}\end{cases}$$

and

$$f_3(t)=\begin{cases} y_1, & t\in B\cup A,\\ y_0 & \text{otherwise,}\end{cases}\qquad g_3(t)=\begin{cases} y_1, & t\in A,\\ y_\alpha, & t\in(B-A)\cup C,\\ y_0 & \text{otherwise.}\end{cases}$$

Since $\int u(f_1)\,dv=v(B)=(1-\alpha)v(A\cap B)+\alpha v(B\cup C)=\int u(g_1)\,dv$, $f_1\sim g_1$ and A.6 implies that $f_2\sim g_2$ and $f_3\sim g_3$. By $\int u(f_2)\,dv=\int u(g_2)\,dv$ we obtain

$$(1-\alpha)v(B)+\alpha v(A\cup B)=(1-\alpha)v(A\cap B)+\alpha v(A\cup B\cup C)$$

and the equality $\int u(f_3)\,dv = \int u(g_3)\,dv$ yields

$$v(A \cup B) = (1-\alpha)v(A) + \alpha v(A \cup B \cup C).$$

Combining the equalities we get

$$(1-\alpha)v(A) + (1-\alpha)v(B) = (1-\alpha)v(A \cap B) + (1-\alpha)v(A \cup B)$$

where $\alpha < 1$.

In case no such event exists, one may proceed as in Lemma 1 to complete the proof. *Q.E.D.*

Note that in view of this last lemma, v is completely determined by its value on intervals of length 1 and 2. Hence there are no more than $(2n-1)$ degrees of freedom in specifying v. We will now proceed to represent v in a simple way which will suggest an intuitive explanation of the $(2n-1)$ parameters.

LEMMA 3: *There are functions $\hat{p}, \hat{\delta}$: $S \to R$ such that*:

(i) $\hat{p}(s_i) \geq 0, \quad \forall i \leq n,$

(ii) $\hat{\delta}(s_1) = 0,$

(iii) *for any $1 \leq i \leq n$ and $l \geq 0$ such that $i + l \leq n$,*

$$v([s_i, s_{i+l}]) = \hat{\delta}(s_i) + \sum_{k=0}^{l} \hat{p}(s_{i+k}).$$

Furthermore, these two functions are unique.

PROOF: Let us first define the functions: set $\hat{\delta}(s_1) = 0$, $\hat{p}(s_1) = v(\{s_1\})$, and for $2 \leq i \leq n$ define

$$\hat{p}(s_i) = v([s_{i-1}, s_i]) - v(\{s_{i-1}\})$$

and

$$\hat{\delta}(s_i) = v(\{s_i\}) - \hat{p}(s_i).$$

It is obvious that $\hat{p}$ and $\hat{\delta}$ satisfy conditions (i) and (ii), and that they are the only pair of functions satisfying:

(1) $v(\{s_i\}) = \hat{\delta}(s_i) + \hat{p}(s_i), \quad \forall i \leq n,$

(2) $v([s_i, s_{i+1}]) = \hat{\delta}(s_i) + \hat{p}(s_i) + \hat{p}(s_{i+1}), \quad \forall i \leq n-1.$

We need only show that $\hat{p}$ and $\hat{\delta}$ also satisfy condition (iii). We use induction on l. For $l = 1$ and $l = 2$ we use (1) and (2), respectively. Assuming correctness for $l-1$, Lemma 2 yields

$$\begin{aligned} v([s_i, s_{i+l}]) &= v([s_i, s_{i+l-1}]) + v([s_{i+l-1}, s_{i+l}]) - v(\{s_{i+l-1}\}) \\ &= \hat{\delta}(s_i) + \sum_{k=0}^{l-1} \hat{p}(s_{i+k}) + \hat{\delta}(s_{i+l-1}) + \hat{p}(s_{i+l-1}) + \hat{p}(s_{i+l}) \\ &\quad - \hat{\delta}(s_{i+l-1}) - \hat{p}(s_{i+l-1}) \\ &= \hat{\delta}(s_i) + \sum_{k=0}^{l} \hat{p}(s_{i+k}). \end{aligned}$$

Q.E.D.

Now we have the following lemma.

LEMMA 4: *For any* $f \in F$,

$$\int u(f)\, dv = \sum_{i=1}^{n} \left\{ \hat{p}(s_i) u(f(s_i)) + \hat{\delta}(s_i)[u(f(s_i)) - u(f(s_{i-1}))]^+ \right\}$$

(*where* $x^+ = \max\{x, 0\}$ *for* $x \in R$).

PROOF: For a given $f \in F$, let π: $\{1, \dots, n\} \to \{1, \dots, n\}$ be a permutation such that $u(f(s_{\pi(i)})) \geq u(f(s_{\pi(i+1)}))$ for $1 \leq i \leq n-1$. By the definition of the Choquet integral:

$$\begin{aligned} \int u(f)\, dv &= \sum_{i=1}^{n} \left[u(f(s_{\pi(i)})) - u(f(s_{\pi(i+1)})) \right] v(\{s_j | \pi(j) \leq \pi(i)\}) \\ &= \sum_{i=1}^{n} \left[u(f(s_{\pi(i)})) - u(f(s_{\pi(i+1)})) \right] \\ &\quad \cdot \left[\sum_{\{j|\pi(j) \leq \pi(i)\}} \hat{p}(s_{\pi(j)}) \right. \\ &\quad \left. + \sum_{\{j|\pi(j) \leq \pi(i)\}} \hat{\delta}(s_{\pi(j)}) 1_{\{u(f(s_{\pi(j)-1})) < u(f(s_{\pi(i)}))\}} \right] \\ &= \sum_{i=1}^{n} \hat{p}(s_i) u(f(s_i)) \\ &\quad + \sum_{\{k|u(f(s_k)) > u(f(s_{k-1}))\}} \hat{\delta}(s_k)[u(f(s_k)) - u(f(s_{k-1}))] \\ &= \sum_{i=1}^{n} \left\{ \hat{p}(s_i) u(f(s_i)) + \hat{\delta}(s_i)[u(f(s_i)) - u(f(s_{i-1}))]^+ \right\}. \end{aligned}$$

Q.E.D.

Now we may also prove the following lemma.

LEMMA 5: *For any* $1 \geq 2$, $\hat{p}(s_{i-1}) \geq \hat{\delta}(s_i) \geq -\hat{p}(s_i)$ *and for* $i \leq n-1$ $\hat{\delta}(s_i) + \hat{p}(s_i) \geq \hat{\delta}(s_{i+1})$.

PROOF: This result follows from the monotonicity axiom (A.4) and Lemma 4.

We will now prove the main theorem. Let us define the functions p and δ by

$$\delta(s_i) = (1/2)\,\hat{\delta}(s_i) \quad \text{for} \quad i \leq n$$

and

$$p(s_i) = \hat{p}(s_i) + (1/2)\big(\hat{\delta}(s_i) - \hat{\delta}(s_{i+1})\big) \quad \text{for} \quad i \leq n$$

(with $\hat{\delta}(s_{n+1}) = 0$ by definition).

Let us first show that these functions satisfy our conditions. Consider condition (i). Obviously, $\delta(s_1) = (1/2)\hat{\delta}(s_1) = 0$. To see that $p(s_i) \geq |\delta(s_i)| + |\delta(s_{i+1})|$, one only has to use the definition of p and δ and Lemma 5. Next consider condition (ii). Since $x^+ = (1/2)(x + |x|)$ for all $x \in R$, Lemma 4 completes the proof.

Conversely, we have to assume that there are p and δ as required, and prove that A.6 holds. However, this is quite easy.

3. EXTENSION TO AN INFINITE HORIZON

Let us now suppose that $S = \{s_i | i \in N\}$ where $s_i \ll s_{i+1}$, and retain all other assumptions and definitions.

In the case of an infinite S, questions of continuity quite naturally arise. If Σ is a σ-algebra, we will say that a measure v is *continuous* if, whenever $B_n \subset B_{n+1} \subset S$, $\lim_{n \to \infty} v(B_n) = v(\bigcup_{n \geq 1} B_n)$ and whenever $S \supset B_n \supset B_{n+1}$ we have $\lim_{n \to \infty} v(B_n) = v(\bigcap_{n \geq 1} B_n)$.

In our case, $\Sigma = 2^S$ is a σ-algebra, and it makes sense to ask when v is continuous. Our interest in this problem is not merely a matter of curiosity. We cannot expect to have a "neat" presentation of the Choquet integral as an infinite series—unless v is continuous.

So let us define a topology on the sets of acts F. We define it by the following notion of convergence: Let $\{f_n\}_{n \geq 1} \subset F$ and $f \in F$. We say that $\{f_n\}_{n \geq 1}$ *monotonically converges* to f if the following two conditions hold:

(i) There is a sequence $\{A_n\}_{n \geq 1} \subset \Sigma$ for which $A_n \subset A_{n+1}$ and $\bigcup_{n \geq 1} A_n = S$, such that $f_n(s) = f(s)$ for $s \in A_n$.

(ii) Either $f_n(s) \succsim f_{n+1}(s) \succsim f(s)$ for all $n \geq 1$ and $s \in S$, or $f(s) \succsim f_{n+1}(s) \succsim f_n(s)$ for all $n \geq 1$ and $s \in S$.

We now introduce another axiom:

A.7 (TIME CONTINUITY): *Suppose that* $\{f_n)$ *monotonically converges to* f *and that* $f \succ g$ $(g \succ f)$. *Then there exists an* $n \geq 1$ *such that* $f_n \succ g$ $(g \succ f_n)$.

The following lemma applies to Schmeidler's model whenever Σ is a σ-algebra (and does not depend upon the denumerability of S or the strict order ($\gg$) defined on it):

LEMMA 6: *Suppose A.1–A.5 hold. Then A.7 is satisfied iff v is continuous.*

PROOF: First assume A.7 holds. Suppose that $B_n \subset B_{n+1}(B_n \in \Sigma)$ and let $B = \bigcup_{n\geq 1} B_n$. Let $A_n = B_n \cup B^c$, and

$$f_n(s) = \begin{cases} y_1, & s \in B_n, \\ y_0 & \text{otherwise}, \end{cases} \qquad f(s) = \begin{cases} y_1, & s \in B, \\ y_0 & \text{otherwise}. \end{cases}$$

By A.7, $\int u(f_n)\,dv \to_{n\to\infty} \int u(f)\,dv$, hence $v(B_n) \to v(B)$.

Now, consider the case $B_n \supset B_{n+1}(B_n \in \Sigma)$ and denote $B = \bigcap_{n\geq 1} B_n$. Let $A_n = B \cup B_n^c$ and define $\{f_n\}_n$ and f as above. Again, $\{f_n\}_n$ monotonically converges to f and the result follows.

Now assume v is continuous, and that there are f, $\{A_n\}_{n\geq 1}$ and $\{f_n\}_{n\geq 1}$ as required by A.7. (I.e., $\{f_n\}_{n\geq 1}$ monotonically converges to f and $f_n = f$ on A_n.) We need only show that $\int u(f_n)\,dv \to_{n\to\infty} \int u(f)\,dv$, that is, that the Choquet integral is continuous with respect to monotonic convergence.

Since f and f_1 are bounded, the whole sequence $\{f_n\}_{n\geq 1} \cup \{f\}$ is uniformly bounded. Without loss of generality we may assume that it is bounded by y_1 and y_0, hence $\int u(f_n)\,dv = \int_0^1 v(\{s \mid u(f_n(s)) > t\})\,dt$ for all $n \geq 1$ and $\int u(f)\,dv = \int_0^1 v(\{s \mid u(f(s)) > t\})\,dt$.

Suppose $f(s) \succsim f_{n+1}(s) \succsim f_n(s)$ for all $n \geq 1$ and $s \in S$. (The other case, namely $f_n(s) \succsim f_{n+1}(s) \succsim f(s)$, is proved symmetrically.) For every $t \in [0,1]$,

$$\{s \mid u(f_n(s)) > t\} \subset \{s \mid u(f_{n+1}(s)) > t\} \subset \{s \mid u(f(s)) > t\}$$

and

$$\bigcup_{n\geq 1} \{s \mid u(f_n(s)) > t\} = \{s \mid u(f(s)) > t\}.$$

Hence, $v(\{s \mid u(f_n)) > t\}) \to_{n\to\infty} v(\{s \mid u(f(s)) > t\})$ monotonically. Since $[0,1]$ is compact, $v(\{s \mid u(f_n(s)) > t\})$ uniformly converges (as a function of t) to $v(\{s \mid u(f(s)) > t\})$. This implies that $\int u(f_n)\,dv \to_{n\to\infty} \int u(f)\,dv$. *Q.E.D.*

We may now prove the following Theorem.

THEOREM 2: *Assume $\succsim$ satisfies A.1–A.5. Then A.6 and A.7 hold iff there are p,δ: $S \to R$ such that:*

(i) $p(s_i) \geq |\delta(s_i)| + |\delta(s_{i+1})|$ *for* $i \geq 1$ *and* $\delta(s_1) = 0$.

(ii) *For any* $f \in F$,

$$\int u(f)\,dv = \sum_{i=1}^{\infty} \left[p(s_i)u(f(s_i)) + \delta(s_i) |u(f(s_i)) - u(f(s_{i-1}))| \right].$$

PROOF: For the "only if" part, let p and δ be defined as in the proof of the main theorem. Let there be given $f \in F$ and assume, without loss of generality, that $y_1 \succsim f(s) \succsim y_0$ for all $s \in S$. Define $A_n = \{s_i | i \leq n\}$ and

$$f_n(s) = \begin{cases} f(s), & s \in A_n, \\ y_0 & \text{otherwise.} \end{cases}$$

By A.7, $\int u(f_n)\, dv \to_{n\to\infty} \int u(f)\, dv$. But $\int u(f_n)\, dv = \Sigma_{i=1}^{n}[p(s_i)u(f(s_i)) + \delta(s_i)|u(f(s_i)) - u(f(s_{i-1}))|]$ and (ii) follows. Hence (i) is also valid as in Lemma 5.

Now let us prove the "if" part. A.6 is proved as in the main theorem. To see that A.7 holds as well, one only has to notice that since the series in (ii) converges for all $f \in F$, v is continuous. *Q.E.D.*

4. DEFINITION AND CHARACTERIZATION OF VARIATION AVERSION

In this section we will assume that $n \geq 3$ (or $n = \infty$) and that on top of A.1–A.7, the following strong monotonicity axiom is satisfied:

A.5* (STRONG MONOTONICITY): *For $f, g \in F$, if $f(s) \succsim g(s)$ for all $s \in S$ and $f(s) \succ g(s)$ for some $s \in S$, then $f \succ g$.*

Note that A.5* implies that $p(s_i) > 0$ for all i.

We will say that $\succsim$ is *variation averse* if the following condition holds: for all $f_1, f_2, g_1, g_2 \in F$ and $i \geq 2$, if:

(i) $f_2(s_i) = g_2(s_i) \succ f_1(s_i) = g_1(s_i)$,

(ii) $f_1(s_j) = f_2(s_j)$ and $g_1(s_j) = g_2(s_j)$ for all $j \neq i$,

(iii) $f_1 \sim g_1$, and

(iv) $f_1(s_i) \succsim f_1(s_{i-1}), f_1(s_{i+1})$; $g_1(s_i) \succsim g_1(s_{i+1})$, and $g_1(s_{i-1}) \succsim g_2(s_i)$,

then $g_2 \succ f_2$.

That is to say, if $f_1 \sim g_1$ and we improve both of them on s_i (to the level $f_2(s_i) = g_2(s_i)$), but f_1's variation has increased while that of g_1 has remained constant, then the modified f_1 (namely, f_2) is less preferred than the modified g_1 (which is g_2).

THEOREM 3: *Let $\succsim$ satisfy A.1–A.7 and A.5*. Then $\geq$ is variation averse iff $\delta(s_i) < 0$ for all $i \geq 2$.*

PROOF: First suppose that $\succsim$ is variation averse. Let us use the functional form of Lemma 4 (rather than that of the main theorem—or Theorem 2—itself) and show that $\hat{\delta}(s_i) < 0$. For a fixed $i \geq 2$, choose $0 < \gamma < \alpha < \beta < 1$ such that

$(\beta-\alpha)(\hat{\delta}(s_{i-1})+\hat{p}(s_{i-1}))=\gamma\hat{p}(s_{i+1})$. Now define

$$f_1(s_j)=\begin{cases} y_\alpha, & j=i,i-1,\\ y_\gamma, & j=i+1,\\ y_0 & \text{otherwise,}\end{cases} \qquad g_1(s_j)=\begin{cases} y_\beta, & j=i-1,\\ y_\alpha, & j=1,\\ y_0 & \text{otherwise,}\end{cases}$$

and

$$f_2(s_j)=\begin{cases} y_\alpha, & j=i-1,\\ y_\beta, & j=i,\\ y_\gamma, & j=i+1,\\ y_0 & \text{otherwise,}\end{cases} \qquad g_2(s_j)=\begin{cases} y_\beta, & j=i-1,i,\\ y_0 & \text{otherwise.}\end{cases}$$

The numbers were chosen in such a way that $\int u(f_1)\,dv=\int u(g_1)\,dv$. Hence, by variation aversion, $g_2 \succ f_2$. However, $\int u(g_2)\,dv-\int u(f_2)\,dv=-(\beta-\alpha)\hat{\delta}(s_i)>0$. Hence, $\hat{\delta}(s_i)<0$, which also implies $\delta(s_i)<0$.

On the other hand, if $\delta(s_i)<0$ for all $i\geq 2$, $\succsim$ is obviously variation averse, and the proof is complete. *Q.E.D.*

The definitions and characterizations of variation liking and variation neutrality are, of course, very similar and will not be given here in detail.

5. AN EXAMPLE

Consider a zero-sum two-person game played infinitely many times by two players who are identical as regards their assessments of future payoffs. That is to say, there exists a single functional $U(u_1,u_2,\ldots)$ such that $U(u^I(z_1),u^I(z_2),\ldots)$ represent player I's utility if the outcome of the ith stage is z_i, and $U(u^{II}(z_1),u^{II}(z_2),\ldots)$ represents player II's utility.

In the classical model, $U(u_1,u_2,\ldots)=\sum_{i=1}^{\infty}p_iu_i$. Hence the super-game itself is also zero sum and any pair of strategies is Pareto optimal. However, if the two players are not variation neutral, U is no longer a linear functional and this claim is no longer true. Since $|u^I(z_i)-u^I(z_{i-1})|=|u^{II}(z_i)-u^{II}(z_{i-1})|$ for any stage i and outcome vector $(z_1,z_2,\ldots)$, it may be the case that replacing $(z_1,z_2,\ldots)$ by $(z_1',z_2',\ldots)$ will strictly increase or decrease both players' utility levels. Similarly, two identical agents with linear instantaneous utility function in a single commodity economy (without production) may benefit from trade.

J. L. Kellogg Graduate School of Business, Northwestern University, Evanston, IL 60201, U.S.A.

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