"THE UTILITY OF INFINITE MENUS"

by

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Abstract

It is often argued that the St. Petersburg paradox shows that von Neumann–
Morgenstern utility functions must be bounded. Shapley (1977a,b) has ar-
gued that even ordinal utility functions must be bounded. By implication,
von Neumann–Morgenstern utility functions must be bounded, but the
boundedness issue is independt of the considerations surrounding gambling
and the St. Petersburg paradox. That view is challenged in the present
paper.

1 Introduction

The St. Petersburg paradox, as generalized by Menger (1934), is an example of a gamble with infinite expected utility and infinite certain equivalent, which can be constructed whenever the utility function is unbounded above. See Samuelson (1977) for a survey and further references.

It is often argued on the basis of the St. Petersburg paradox that von Neumann–Morgenstern utility functions must be bounded. Shapley (1977a,b) has carried the argument a step further. He argues that even ordinal utility functions must be bounded. By implication, von Neumann–Morgenstern utility functions must be bounded, but the boundedness issue is independt of the considerations surrounding gambling and the St. Petersburg paradox. That view is challenged in the present paper.

Shapley's argument goes as follows. A blank check, which the recipient can exchange for any amount of money he wishes, will be preferred to any fixed amount. So, any finite-valued utility function which ranks not only fixed amounts but also the blank check must be bounded above (by the utility of the check). Shapley extends the argument from blank checks to more general "infinite menus."

I challenge this argument on the grounds that infinite menus are not necessarily ranked along with other prospects, that boundedness of an ordinal utility function implies nothing about ordinal preferences, and that the assumption that the infinite menu has finite utility is arbitrary.

The point about finite utility is elaborated by nesting Shapley's model of choice under certainty in a model of choice under uncertainty. The usual axiom systems for expected utility yield a finite-valued von Neumann–Morgenstern utility function. However, I demonstrate that in the presence of an infinite menu (a most preferred outcome), a reasonable alternative axiom system may yield a von Neumann–Morgenstern utility function which is not finite-valued because it assigns the value plus infinity to the infinite menu.

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2 Infinite Menus

In the opinion of Aumann (1977) and others, the resolution of the St. Petersburg paradox lies in the conclusion that utility must be bounded. This conclusion is not only a statement about the mathematical modeling of preferences or choice under uncertainty. Boundedness of the von Neumann–Morgenstern utility function has substantive implications for the choices predicted. Aumann shows how the question of bounded versus unbounded utility is equivalent to a simple question about choice among lotteries.

Shapley (1977a,b) distinguishes between an empirical and a logical version of the St. Petersburg paradox and argues that the real issue in the empirical paradox is not whether utility is bounded. The issue is whether utility is sufficiently bounded to lead to a certain equivalent of the St. Petersburg game which is not only finite but also small enough to be consistent with empirical and introspective evidence. The issue in the logical paradox is whether unbounded utility is consistent with the logic of (axiomatic) expected utility theory. According to Shapley, the mere boundedness of utility is forced on us even where only ordinal utility is concerned, and before gambling and cardinality enter the picture. The boundedness issue is independent of the considerations surrounding the St. Petersburg paradox.

Shapley's argument goes as follows. A blank check, which the recipient can exchange for any amount of money he wishes, will be preferred to any fixed amount. So, any finite-valued utility function which ranks not only fixed amounts but also the blank check must be bounded above (by the utility of the check).

Shapley generalizes this argument to situations with an abstract set of prospects including some "menus." A menu is the prospect of choosing among a given set of prospects. It may be assumed that no prospect in a menu is strictly preferred to the menu. If a finite-valued utility function ranks both prospects and menus, then the utility of a menu must be at least as large as the supremum of the utilities of the prospects in the menu. Shapley imposes the further requirement that the utility of the menu is equal to the supremum. If there is a menu which is "infinite" in the specific sense that no prospect is preferred to all the prospects in the menu, then the utility function is bounded above (by the utility of this menu).

Shapley argues that

> "the case for allowing infinite menus, once finite menus are admitted, is at least as strong as the case for taking the step from finite to infinite lotteries."

This line of argument does not succeed in showing that von Neumann–Morgenstern utility functions must be bounded.

Firstly, it is not necessary to "allow infinite menus," i. e., to insist that infinite menus be ranked along with other prospects. Consumer theory, for example, gets along without them (as do consumers) and without imposing boundedness on the ordinal utility functions.

Secondly, boundedness of the ordinal utility function implies nothing about ordinal preferences, since every preference relation represented by an unbounded ordinal utility function can also be represented by a bounded one. By contrast, boundedness of the cardinal utility function in expected-utility theory does place substantive restrictions on preferences among gambles, as pointed out by Aumann.

Thirdly, if infinite menus are indeed allowed, then there is no strong reason not to permit the utility function to assign them infinite utility, since they are, by definition, preferred to all other prospects. It is, however, an important premise in Shapley's argument that the utility function is finite-valued. Only if the utility function is arbitrarily assumed to assign finite values also to infinite menus, does it follow that it will be bounded. This requirement of finiteness should be contrasted to the situation in expected-utility theory, where finiteness of the values of the utility function is not arbitrary but is a necessary consequence of the specific axioms that are usually imposed.

Shapley's argument does not bear on the decision-maker's attitudes toward choice under uncertainty. It addresses only the mathematical boundedness issue, not the attendant substantive issue about choice behavior.

For the argument to bear on choice under uncertainty, Shapley's model of choice under certainty has to be nested in a model of choice under uncertainty. When that is done, the utility function is derived from an axiom system, and it may or may not be finite-valued depending on the axioms. The standard axiom systems imply a finite-valued utility function, but I shall demonstrate how to construct a reasonable list of axioms which yield a utility function which may take the value plus infinity.

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Additional properties of the preference relation are necessary to ensure a finite-valued utility function and thus necessary to complete Shapley's argument. These properties have to do with choice under uncertainty and attitudes to gambles. Thus, boundedness of the utility function, as well as Shapley's argument to that effect, is not prior to and independent of cardinality and gambling.

3 Axioms for Infinite Utility

Let us try to nest Shapley's model of choice under certainty in a model of choice under uncertainty and use his argument to conclude that the expected utility of prospects is bounded, so that the cardinal utility of outcomes is bounded by implication.

For simplicity, take the set of *outcomes* to be $A = [0, \infty]$. The set A may be equipped with the structure of a "selection space" as defined by Shapley. This means that certain subsets of A (called menus) are identified with points in A via a mapping. The interpretation is that the prospect of having to choose from one of those subsets (menus) is represented by the corresponding point in A. Specifically take the mapping

$$\mathrm{Sel} : S \mapsto \sup S$$

which maps any subset S of $[0, \infty]$ to its supremum. The finite elements in $[0, \infty)$ may represent levels of consumption, in which case ∞ represents the possibility of choosing among all finite levels of consumption.

Let P be the set of simple *probability distributions* on A (those concentrated on finite subsets of A). Then A can be considered as a subset of P, and menus will, in particular, be represented by points in P.

Suppose $\succ$ is a preference relation on P.

Axiom 1 *The preference relation $\succ$ is an asymmetric weak order.*

Axiom 2 *If p, q, r belong to P, $p \succ q$ and $0 < \lambda < 1$, then $\lambda p + (1 - \lambda)r \succ \lambda q + (1 - \lambda)r$.*

Axiom 3 *If p, q, r belong to P, $p \succ q$ and $q \succ r$, then there exist α, β in $(0, 1)$ such that $\alpha p + (1 - \alpha)r \succ q$ and $q \succ \beta p + (1 - \beta)r$.*

Given these axioms, it follows from the standard result, see Fishburn (1970), that there exists a finite-valued utility functional V on P which represents $\succ$ and is linear. A utility functional V is *linear* if for all $\lambda \in [0, 1]$ and all p, q in P,

$$V(\lambda p + (1 - \lambda)q) = \lambda V(p) + (1 - \lambda)V(q).$$

The utility functional V *represents* the prefererence relation $\succ$ if for all p, q in P,

$$p \succ q \text{ if and only if } V(p) > V(q).$$

Moreover, there is a finite-valued von Neumann–Morgenstern utility function u on $A = [0, \infty]$ which corresponds to $\succ$ and V. Specifically, $V(p) = E_p u$ for any distribution p in P, and so for any two distributions p and q in P, $p \succ q$ if and only if $E_p u > E_q u$.

Shapley suggests that the utility of a menu should be assumed to equal the supremum of the utilities of its elements. Actually, it is more natural (and it is sufficient in Shapley's argument) to require only that the utility of the menu be no less than the supremum of the utilities of its elements. This property of the von Neumann–Morgenstern utility function can be derived from the following axiom about the preference relation.

Axiom 4 *If $s, t \in [0, \infty]$ and $t > s$, then $t \succ s$.*

If u is a von Neumann–Morgenstern utility function such that the associated utility functional V represents $\succ$ on P, then Axiom 4 holds if and only if u is strictly increasing, in which case

$$u(Sel(S)) \geq \sup u(S)$$

for all $S \subset A$.

Now, Shapley's argument is that $u(t) \leq u(\infty)$ for all $t \in [0, \infty)$, and $u(\infty)$ is finite. Hence, u is bounded even on $[0, \infty)$.

I shall argue that a different axiom system will yield a utility function u with values in $\Re \cup \{\infty\}$ and possibly with $u(\infty) = \infty$, in which case u is not bounded on $[0, \infty)$. Whether $u(\infty)$ is finite or infinite depends on the preference relation and is not independent of considerations involving risky choice.

To construct an example of an axiom system which may yield an unbounded and infinite-valued utility function, adapt Axioms 2 and 3 as follows. Let P_f (f for finite) be the set of simple probability distributions on $[0, \infty)$, *i.e.*,

$$P_f = \{p \in P : p(\infty) = 0\}.$$

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Axiom 5 *If p, q belong to P, r belongs to P_f, $p \succ q$ and $0 < \lambda < 1$, then $\lambda p + (1 - \lambda)r \succ \lambda q + (1 - \lambda)r$.*

Axiom 6 *If p, q, r belong to P_f and $p \succ q \succ r$, then there exist α, β in $(0, 1)$ such that $\alpha p + (1 - \alpha)r \succ q \succ \beta p + (1 - \beta)r$.*

Note that Axiom 5 is identical to Axiom 2, except that r is restricted to lie in P_f. Similarly, Axiom 6 is a version of the Archimedian axiom, Axiom 3, where p, q and r are restricted to lie in P_f. Even though Shapley (1977b) calls the Archimedian axiom "indispensable," I shall show here that it is indeed possible to dispense with it in the present setting in so far as prospects with positive probability of the outcome ∞ are concerned.

Axiom 7 *If p belongs to P_f, q belongs to P, $0 < \lambda \le 1$, and $\lambda \infty + (1 - \lambda)p \succ q$, then there exists $t \in [0, \infty)$ such that $\lambda t + (1 - \lambda)p \succ q$.*

Theorem 1 *Axioms 1 and 4-7 hold if and only if there exists a linear utility functional V on P with values in $\Re \cup \{\infty\}$, representing the relation $\succ$, strictly increasing on $[0, \infty]$, and with $V(\infty) = \sup V([0, \infty))$.*

The definitions, given above, of what it means that V is linear and represents $\succ$, remain valid when V may take the value ∞. The proof of Theorem 1 is in a separate section.

In the situation of Theorem 1, there is a von Neumann–Morgenstern utility function u on $[0, \infty]$ (the restriction of V to $[0, \infty]$), which may take the value $u(\infty) = \infty$, and which corresponds to V in the sense that $V(p) = E_p u$ for all $p \in P$. If indeed $u(\infty) = \infty$, then u is not bounded, not even on $[0, \infty)$, the existence of the infinite menu $\mathrm{Sel}([0, \infty)) = \infty$ notwithstanding. If, on the other hand, $u(\infty) < \infty$, then u is bounded. Whether $u(\infty) = \infty$ or $u(\infty) < \infty$ depends on the preference relation $\succ$ and thus on the individual's attitudes to gambles. Boundedness of the utility function is not forced on us a priori.

Aumann's test can be used to decide whether $u(\infty) = \infty$ or $u(\infty) < \infty$. Pick a fixed probability λ with $0 < \lambda < 1$. Then u is unbounded if and only if for every $s \in [0, \infty)$ there is some $t \in [0, \infty)$ such that $\lambda t + (1 - \lambda)0 \succ s$.

4   Conclusion

Specific unbounded functional forms of von Neumann–Morgenstern utility functions, such as logarithmic utility, are often used in economic and financial theory. It would be inconvenient if the logic of the considerations surrounding infinite menus were to force us to stop using such functions. I have argued here that this is not the case, as I have argued in Nielsen (1989) that the logical version of the St. Petersburg paradox does not lead to the conclusion that utility must be bounded.

Shapley's point, that a finite-valued utility function which ranks both ordinary prospects and infinite menus must be bounded, is irrelevant because infinite menus generally are not available to decision-makers, and if they are, then the utility function need not be finite-valued.

Like the St. Petersburg gamble, infinite menus may lead to an empirical paradox, which will involve many of the same arguments that have been made in relation to the empirical version of the St. Petersburg paradox. For example, "reasonable men" will probably not be willing to pay an unlimited amount for a blank check, because they do not believe the check will be honored. Such issues aside, the logic of the model says that the blank check will be preferred to any fixed amount. This is consistent with an unbounded as well as a bounded utility function, the utility of the blank check being infinite or finite in the two cases, respectively.

The logical version of the St. Petersburg paradox disappears when we rely on a consistent axiom system for expected utility. Most axiomatic theories cover only cases where the expected utility is finite. However, even the theory presented in the present paper, which involves an infinite menu and allows infinite expected utility as well as an infinite value of the utility function, does not lead to an inconsistency. Thus, the logical paradox of infinite menus and unbounded utilities is resolved.

5 Proof

PROOF OF THEOREM 1: It is easily shown that the axioms do hold if the utility functional V exists. Conversely, assume that the axioms hold. By the standard result, see Fishburn (1970), there exists a finite-valued linear utility functional V on P_f, representing the restriction to P_f of the relation $\succ$. Extend V to P as follows. Firstly, set

$$V(\infty) = \sup_{t \in [0,\infty)} V(t).$$

Secondly, any $q \in P$, $q \neq \infty$, can be written uniquely in the form

$$q = \lambda \infty + (1 - \lambda)p,$$

where $0 \leq \lambda < 1$ and $p \in P_f$. Set

$$V(q) = V(\lambda \infty + (1 - \lambda)p) = \lambda V(\infty) + (1 - \lambda)V(p).$$

It is clear from this definition that V is linear. To show that V represents the relation $\succ$ on all of P, let $0 \leq \lambda \leq 1$ and $0 \leq \mu \leq 1$, and let p and q belong to P_f. It has to be shown that

$$\lambda \infty + (1 - \lambda)p \succ \mu \infty + (1 - \mu)q \tag{1}$$

if and only if

$$\lambda V(\infty) + (1 - \lambda)V(p) > \mu V(\infty) + (1 - \mu)V(q) \tag{2}$$

Assume (1). By Axiom 7, there is $t \in [0, \infty)$ such that

$$\lambda t + (1 - \lambda)p \succ \mu \infty + (1 - \mu)q.$$

By Axioms 4 and 5,

$$\mu \infty + (1 - \mu)q \succ \mu s + (1 - \mu)q$$

for all $s \in [0, \infty)$, so

$$\lambda V(t) + (1 - \lambda)V(p) > \mu V(s) + (1 - \mu)V(q)$$

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for all s. Consequently,

$$\begin{aligned} \lambda V(\infty) + (1 - \lambda)V(p) \quad &> \quad \lambda V(t) + (1 - \lambda)V(p) \\ &\geq \quad \mu V(\infty) + (1 - \mu)V(q). \end{aligned}$$

Conversely, if (1) does not hold, then for every $t \in [0, \infty)$,

$$\mu\infty + (1 - \mu)q \succ \lambda t + (1 - \lambda)p,$$

and so there is some $s \in [0, \infty)$ with

$$\mu s + (1 - \mu)q \succ \lambda t + (1 - \lambda)p$$

and

$$\begin{aligned} \mu V(\infty) + (1 - \mu)V(q) \quad &\geq \quad \mu V(s) + (1 - \mu)V(q) \\ &> \quad \lambda V(t) + (1 - \lambda)V(p) \end{aligned}$$

Hence,

$$\mu V(\infty) + (1 - \mu)V(q) \geq \lambda V(\infty) + (1 - \lambda)V(p),$$

and (2) does not hold. $\square$

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