

Subjective Expected Utility Theory without States of the World

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Abstract

This paper develops an axiomatic theory of decision making under uncertainty that dispenses with the state space. The results are subjective expected utility models with unique, action-dependent, subjective probabilities, and a utility function defined over wealth-effect pairs that is unique up to positive linear transformation.

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1 Introduction

The distinguishing characteristic of decision making under uncertainty is that the choice of a course of action, by itself, does not always determine a unique outcome. To formalize this indeterminacy, or lack of advance knowledge of the outcome of alternative courses of action, Savage (1954) introduced the concept of states of the world, that is, “a description of the world so complete that, if true and known, the consequences of every action would be known” (Arrow [1971], p. 45). In the wake of Savage’s seminal work, the state space (that is, the set of all states of the world) became a cornerstone of modern theories of decision making under uncertainty. However, careful examination of the concept of state of the world reveals that the depiction of the relevant state space is often unintuitive and too complex to be compatible with decision makers’ perception of choice problems. Doubt about the relevance of state of the world as a general analytical concept and its applicability is the main motivation behind this work.

In this paper I introduce an alternative analytical framework and a new subjective expected utility theory of decision making under uncertainty that avoid the use of a state space. Moreover, within the new analytical framework I develop a theory of decision making under uncertainty that is capable of accommodating considerations of moral hazard and effect-dependent utility of wealth in individual choice-behavior.¹

The case against the general applicability of the notion of states of the world is detailed in

¹The meaning of the term effect is made clear below.

the next section. The formal theory is presented in Section 3. Section 4 contains a discussion of the meaning of subjective probabilities. Concluding remarks appear in Section 5. The proofs are given in Section 6.

2 On the Meaning of States of the World

Following Savage (1954) it is customary to formulate the problem of decision making under uncertainty invoking states and consequences as primitive concepts and acts, that is, functions from the set of states to the set of consequences, as a derived concept. Once the framework is fixed, however, states of the world may be interpreted, consistently with Arrow's (1981) definition, as mappings from the set of acts, to the set of consequences.

By definition the states of the world are mutually exclusive and jointly exhaustive. Moreover, the states must be defined in a way that their likely realization must not be affected by the decision maker's choice of action, and the valuation of the consequences be independent of the state in which they may be received. Finally, for it to be a meaningful scientific concept, the state space must be independently observable. In other words, it should be possible to reconstruct, on the basis of a decision maker's observed choices, the unique state-space underlying his decisions.² Note that the notion of the state space, advocated by Savage (1954), presumes that decision makers believe that they know the world in which they live.³

²Machina (2003) offers a detailed discussion of this and related issues.

³That is what is meant by the requirement that states be jointly exhaustive.

As a result, no amount of evidence, with Bayesian updating, would lead the decision maker to conclude that his original image of the world was incomplete.⁴

There are situations in which the relevant states of the world correspond to observable physical phenomena and have a natural, intuitive, and, most important, objective meaning. For example, the uncertainty regarding the consequences of installing or not installing a lightning rod is resolved once it is known whether the house is struck by lightning. Thus a lightning strike may be regarded as a state of the world (or a state of nature) whose likely occurrence is independent of whether or not a lightning rod is installed. In this instance, the portrayal of the state space has a clear, objective interpretation, and it makes sense to treat it as a primitive concept.

Situations in which the state space lends itself to such straightforward interpretations are rare. Often the distinction between states and consequences is blurred and frequently the likely realization of what seems like a natural definition of states for the problem at hand is not independent of the choice of the action. Moreover, in many instances, the state space is too large and complex to be compatible with the limited cognitive ability of decision makers to grasp, let alone be invoked in the decision-making process. In such instances, as the following examples illustrate, the notion of states of the world as an uncertainty-resolving device seems unintuitive, non-compelling, and outright useless, for the purpose of obtaining

⁴Gilboa (2003) illustrates this point with Newcombe's paradox. The same issue is discussed in Machina (2003).

a behavioral definition of subjective probabilities.⁵

Example 1. In a letter to Savage, from January 1971, Aumann questions "the very possibility of defining this notion [subjective probability] – in any way – via preference." (Drèze [1987], p. 77) To make his point Aumann describes a man who loves his wife very much and without whom his life is less "worth living." The wife falls ill and, if she is to survive, she must undergo a routine yet dangerous operation. Suppose that the husband is offered a choice between betting \$100 on his wife's survival or on the outcome of a coin flip. In this scenario, there are four states, corresponding to the different possible combinations of outcomes of the operation and those of the coin flip. However, even if the husband believed that his wife has an even chance of surviving the operation he may still rather bet (that is, strongly prefer to bet) on her survival. This is because winning \$100 if she does not survive is somehow worthless. Betting on the outcome of a coin flip means that he might win in a situation in which he will not be able to enjoy it. Aumann's objection is based on the presumption, that seems quite compelling in the situation described, that the valuation of the consequences is not independent of the states. In fact, Aumann argues that the notion of states and consequences are confounded to the point that there is nothing that one may call a consequence, that is, something whose value is state independent.

Savage responded to Aumann's criticism in these words:

"The difficulties that you mention are all there; ... I believe that they are serious

⁵For additional examples and comments, see Gilboa and Schmeidler (2001), Ch. 2.

but am prepared to live with them until something better comes along. The theory of personal probability and utility is, as I see it, a sort of framework into which I hope to fit a large class of decision problems. In this process, a certain amount of pushing, pulling, and departure from common sense may be acceptable and even advisable.... To some - perhaps to you - it will seem grotesque if I say that I should not mind being hung so long as it be done without damage to my health or reputation, but I think it desirable to adopt such language so that the danger of being hung can be contemplated in this framework.” (Drèze [1987], p. 78)

And to the specific example of Aumann Savage responds by saying: “In particular, I can contemplate the possibility that the lady dies medically and yet is restored in good health to her husband.” (Drèze [1987], p. 80). Even if such contemplation is possible, it is unnatural and, hence, not likely to be invoked in the decision making process.

Consider next an amendment to Aumann’s example. Suppose that, in addition to choosing between betting on the survival of his wife and on heads in a coin toss, the husband may also choose the hospital in which the surgery is to take place and the surgeon who performs it. If the likely outcome depends, as it often does, on the hospital and the surgeon, the husband’s choice affects the chances of his wife’s survival. In other words, contrary to Savage’s concept of a state space, the likely realization of the events depends on the action taken by the husband.

This discussion suggests that the possible outcomes of the operation are not states, or events, in the sense of Savage's theory. Yet they seem both natural and intuitive when contemplating the proposed bets.

Example 2. To go from here to there, a passenger must choose between flying, driving, or taking the bus.⁶ Suppose that the purpose of the trip is a week-long vacation, then the consequences, namely, the actual duration of his vacation, depend on whether the passenger arrives at his destination on time, arrives after delays of various durations, or does not arrive at all.

The factors affecting the duration of the trip include the, unknown, traffic conditions (which depends on choices of other people), the weather conditions, the mechanical state of the different means of transportation, and so forth. These factors have different implications for the duration of the trip depending on the choice of mean of transportation. The relevant state space, in this case, is large and complex and to suppose that decision makers invoke such a state space when choosing a mean of transportation strains credulity. Moreover, even if the passenger invokes, in his deliberations, a state-space image of the world, being a state of mind, it is impossible for others to infer it from his choice behavior. Clearly, different decision makers facing the same choices, may invoke distinct state-spaces.

In short, the exacting nature of Savage's analytical framework – its insistence that the realization of the states be independent from the actions, that states be separated from con-

⁶This is a variation on a decision problem described in Luce and Krantz (1971).

sequences, and that the state space be observable – makes it inadequate for the formulation and analysis of some important decision situations. To suppose that decision makers always invoke depictions of the world that qualify as states in the sense of Savage seems farfetched. The upshot of this discussion is that a general positive theory of decision making under uncertainty must not rely on the use of states of the world.

In the next section I explore an alternative theory that dispenses the state space. The main idea is that decision makers directly assess the likelihood of different outcomes, or effects, conditional on their choice of action. Consequently, this theory accommodates, in a intuitive and natural way, the presence of moral hazard considerations in individual decisions as well as the possibility that the valuation of the monetary payoffs of these decisions are effect-dependent.

3 Subjective Expected Utility Theory

3.1 The analytical framework

Let Θ be a finite set of *effects* and let A be a set whose elements represent courses of action, or *actions* for short. A *bet*, b , is a mapping from Θ into \mathbb{R} , the set of real numbers.⁷ Bets have the interpretation of monetary payoffs contingent on the effects. Let $B := \mathbb{R}^\Theta$ denote the

⁷The use of the reals is intended to simplify the exposition. It could easily be replaced by \mathbb{R}^n or, more generally, by a connected separable topological space.

set of all bets and assume that it is endowed with the $\mathbb{R}^{|\Theta|}$ topology. Denote by $(b_{-\theta}, r)$ the bet obtained from $b \in B$ by replacing the θ -coordinate of b , that is, $b(\theta)$, with r . Similarly, for each $T \subset \Theta$ and $b, b' \in B$, let $b_{\Phi} b'$ be the bet in B defined by $(b_T b')(\theta) = b(\theta)$ for all $\theta \in T$ and $(b_T b')(\theta) = b'(\theta)$ for all $\theta \in \Theta - T$. Two bets, say b and b' , are said to *agree* on T if $b(\theta) = b'(\theta)$ for all $\theta \in T$.

Decision makers are supposed to be able to choose actions and place bets on the effects. The idea is that a choice of action, a , results in the realization of an effect in Θ ; which particular effect obtains is uncertain, and the effect that obtains determines the payoff of the chosen bet. For example, a decision maker may adopt an exercise and diet regimen to reduce the risk of heart attack and at the same time take out health insurance and life insurance policies. The health implications of the diet and exercise regimen correspond to the effects while the financial terms of the insurance policies constitute a bet. Similarly, a store owner can choose the location of his store, his weekly work schedule and, within limits, the equity that he has in the business. The revenue represents the effects of his management decisions (actions) and the financial decision represents his bet. Formally, the *choice set*, \mathbb{C} , consists of all the action-bet pairs (that is, $\mathbb{C} = A \times B$). A choice of an action a and a bet b results, ultimately, in an effect-payoff pair, $(\theta, b(\theta))$. I refer to effect-payoff pairs as *consequences* and denote by C the set of all consequences (that is, $C = \Theta \times \mathbb{R}$).

Decision makers are characterized by binary relations, \succsim , on \mathbb{C} , that have the interpretation of preference relations. The strict preference relation, \succ , and the indifference relation, \sim , are the asymmetric and symmetric parts of \succsim , respectively. For each $a \in A$, the prefer-

ence relation \succsim on \mathbb{C} induces a conditional preference relation on B defined as follows: For all $b, b' \in B$, $b \succsim_a b'$ if and only if $(a, b) \succsim (a, b')$.

A decision maker may believe that if he were to select a particular course of action, certain effects are impossible to obtain. It is tempting to suppose that this belief manifests itself in indifference among all the bets that agree on the set of all other effects. Conceivably, however, there may be effects that the decision maker believes to be possible and yet, if any of these effects obtain, the decision maker would be indifferent among all the monetary payoffs. For example, a decision maker with no dependents who is about to board a flight, may decline offers to take out a flight insurance policy, regardless of how favorable are the terms of the policy. This does not mean that the decision maker regards the effect “dying in a plane crash” to be impossible. In what follows I assume that no such effects are present in the model. Formally, an effect θ is said to be *nonnull given the action a* if $(a, (b_{-\theta}, r)) \succ (a, (b_{-\theta}, r'))$, for some $b \in B$ and $r, r' \in \mathbb{R}$. Assume that every effect is nonnull for some action a . An effect θ is said to be *null given the action a* if $(a, (b_{-\theta}, r)) \sim (a, (b_{-\theta}, r'))$ for all $r, r' \in \mathbb{R}$. Given a preference relation \succsim , denote by $\Theta(a; \succsim)$ the subset of effects that are nonnull given a according to \succsim . To simplify the notations, when there is no risk of confusion, I shall write $\Theta(a)$ instead of $\Theta(a; \succsim)$.

Two effects, θ and θ' are said to be *elementarily linked* if there are actions $a, a' \in A$ such that $\theta, \theta' \in \Theta(a) \cap \Theta(a')$. Two effects are said to be *linked* if there exists a sequence of effects $\theta = \theta_0, \theta_1, \dots, \theta_n = \theta'$ such that every θ_j is elementarily linked with θ_{j+1} . I assume throughout that the set of actions is rich enough so that every pair of effects is linked.

3.2 Constant valuation bets

Intuitively speaking, a constant valuation bet is a bet that, once accepted, leaves the decision maker indifferent among all the actions. For example, a full insurance policy is a constant valuation bet since, by definition, a decision maker who takes out a homeowner policy that provides full insurance is indifferent to whether or not his house is damaged by storm, consumed by fire, or remains intact.⁸ The idea is that, the decision maker believes that by choosing alternative actions he may affect the likely realization of different effects. This, in turn, determines the relative desirability of the alternative bets. In particular, with sufficiently large number of variations of the likely realization of alternative effects there are no two bets that are equally desirable under all such variations. Let $I(a; b) = \{b' \in B \mid (a, b') \sim (a, b)\}$ then the idea of constant valuation bets is formalized as follows:

Definition 1: A bet \bar{b} is said to be a *constant-valuation bet on Θ* if $(a, \bar{b}) \sim (a', \bar{b})$ for all

$$a, a' \in A, \text{ and } \bigcap_{a \in A} I(a; \bar{b}) = \{\bar{b}\}.$$

The last requirement implies that if b^* is a constant valuation bet then no other $b \in \bigcap_{a \in A} I(a; \bar{b})$ satisfies $(a, b) \sim (a', b)$ for all $a, a' \in A$. The set of all constant valuation bets is denoted by B^{cv} . If b^{**} and b^* are constant valuation bets satisfying $(a', b^{**}) \succ (a', b^*)$ then transitivity of \succ implies $(a, b^{**}) \succ (a, b^*)$ for all $a \in A$. Since transitivity will be assumed, I

⁸The concept of constant valuation bets is analogous to constant valuation acts in Karni (1993, 2003). The idea of constant valuation acts is similar to Drèze's (1987) notion of "omnipotent" acts. A similar concept appears in Skiadas (1997).

write $b^{**} \succ b^*$ instead of $(a, b^{**}) \succ (a, b^*)$.

The following assumption is maintained throughout.

(A.0) *Every pair of effects is linked, there exist constant-valuation bets b^{**} and b^* such that $b^{**} \succ b^*$ and, for every $(a, b) \in \mathbb{C}$, there is $\bar{b} \in B^{cv}$ satisfying $(a, b) \sim \bar{b}$.*

3.3 Axioms

The structure of the preference relations on \mathbb{C} is depicted axiomatically. The first two axioms are standard and require no commentary.

(A.1) (**Weak order**) \succcurlyeq on \mathbb{C} is a complete and transitive binary relation.

(A.2) (**Continuity**) For all $(a, b) \in \mathbb{C}$ the sets $\{(a, b') \in \mathbb{C} \mid (a, b') \succcurlyeq (a, b)\}$ and $\{(a, b') \in \mathbb{C} \mid (a, b) \succcurlyeq (a, b')\}$ are closed.

The third axiom requires that the “intensity of preferences” for monetary payoffs contingent on any given effect be independent of the action that resulted in that effect. It invokes Wakker’s (1987) idea of cardinal consistency and, in its present form, it is an adaptation of Karni’s (2004) cardinal coherence.

(A.3) (**Action-independent betting preferences**) For all $a, a' \in A$, $b, b', b'', b''' \in B$, $\theta \in \Theta(a) \cap \Theta(a')$, and $r, r', r'', r''' \in \mathbb{R}$, if $(a, (b_{-\theta}, r)) \succcurlyeq (a, (b'_{-\theta}, r'))$, $(a, (b'_{-\theta}, r'')) \succcurlyeq (a, (b_{-\theta}, r'''))$, and $(a', (b''_{-\theta}, r')) \succcurlyeq (a', (b'''_{-\theta}, r))$ then $(a', (b''_{-\theta}, r'')) \succcurlyeq (a', (b'''_{-\theta}, r'''))$.

To grasp the meaning of action-independent betting preferences think of the preferences $(a, (b_{-\theta}, r)) \succ (a, (b'_{-\theta}, r'))$ and $(a, (b'_{-\theta}, r'')) \succ (a, (b_{-\theta}, r'''))$ as indicating that, given action a and effect θ , the intensity of the preferences of r'' over r''' is sufficiently larger than that of r over r' as to reverse the preference ordering of the effect-contingent payoffs $b_{-\theta}$ and $b'_{-\theta}$. The axiom requires that these intensities not be contradicted when the action is a' instead of a .

Figure 1 illustrates the axiom and the structure it imposes on the preference relations. Suppose, for the sake of simplicity that there are only two effects so that $(b_{-\theta}r) = (y', r)$ is a point in a two dimensional plane. The lower plane in Figure 1 corresponds to action-bet pairs in which the action is a while the upper plane corresponds to action-bet pairs in which the action is a' . The axiom, depicted for expositional convenience in terms of the indifference relations instead of weak preferences, requires that if $(a; (y', r)) \sim (a; (y, r'))$, $(a; (y', r'')) \sim (a; (y, r'''))$, and $(a'; (y''', r)) \sim (a'; (y'', r'))$ (these indifference relations are depicted by the corresponding point on the solid indifference curves), then $(a'; (y''', r'')) \sim (a; (y'', r'''))$ (an indifference depicted by points on the dashed indifference curve). Clearly, if $a = a'$ then this condition collapse to the Redmeister condition (see Wakker [1989]). Figure 1 also clarifies the idea of the intensity of preferences discussed above. The intensity of preferences of r' over r is measured by the compensating variation $y' \rightarrow y$ if the action is a and $y''' \rightarrow y''$ when the action is a' . Next the compensating variation $y' \rightarrow y$ is used to measure the intensity of preference of r''' over r'' . In particular, in this illustration intensity of preferences of r' over r is the same as that of r''' over r'' as they both require the same compensating variation,

namely, $y' \rightarrow y$. If, in addition, the compensating variation $y''' \rightarrow y''$ is a measure of the intensity of preferences of r' over r when the action a' is then the axiom requires that it also be a measure of the intensity of preference of r''' over r'' . In other words, the intensity of preference of r' over r relative to that of r''' over r'' do not change either when the action changes or when the payoff of the bet on the other effect varies.

In addition, for every given act, axiom (A.3) embodies the independence of preferences for the payoff conditional on any given effect from the payoffs of the bet associated with the other effects. This independence property implies the well-known Sure Thing Principle and, in the case of two effects, the hexagon condition (for more details see Lemmas 4 and 5 in Section 5.1). To grasp the last claim, suppose that $a = a'$, $y'' = y'$, and $r' = r''$ then Figure 1 collapses to Figure 2, which is the customary depiction of the hexagon condition.

3.4 The main representation theorem

The main result of this paper is the assertion that a preference relation on \mathbb{C} has the structure described by axioms (A.1) – (A.3) if and only if there is a continuous utility function, u , on the set of consequences, a family of action-dependent probability measures, $\{\pi(\cdot; a) \mid a \in A\}$, on the set of effects, and a family of continuous increasing functions $\{f_a : \mathbb{R} \rightarrow \mathbb{R} \mid a \in A\}$, such that the assignment $(a, b) \rightarrow f_a(\sum_{\theta \in \Theta} u(b(\theta); \theta) \pi(\theta; a))$ represents the preference relation. Furthermore, for each $a \in A$, the probability measure $\pi(\cdot; a)$ is unique, satisfying $\pi(\theta; a) = 0$ if and only if θ is null given a , and the utility functions $\{u(\cdot; \theta)\}_{\theta \in \Theta}$ and the

functions $\{f_a\}_{a \in A}$ are jointly unique in the following sense: If $\{u(\cdot; \theta)\}_{\theta \in \Theta}$ are transformed by a cardinal unit-comparable affine transformation, then the functions f_a are unique up to a corresponding affine translation.

Theorem 1 *Suppose that there are at least two effects and that assumption (A.0) is satisfied, then:*

(a) *The following conditions are equivalent:*

(a.i) *The preference relation, \succsim on \mathbb{C} , satisfies (A.1) – (A.3).*

(a.ii) *There exist continuous function $u : C \rightarrow \mathbb{R}$, a family of probability measures $\{\pi(\cdot; a)\}_{a \in A}$ on Θ , and a family of continuous increasing functions $\{f_a : \mathbb{R} \rightarrow \mathbb{R}\}_{a \in A}$ such that, for all $(a, b), (a', b') \in \mathbb{C}$,*

$$(a, b) \succsim (a', b') \Leftrightarrow f_a \left(\sum_{\theta \in \Theta} u(b(\theta); \theta) \pi(\theta; a) \right) \geq f_{a'} \left(\sum_{\theta \in \Theta} u(b'(\theta); \theta) \pi(\theta; a') \right).$$

(b) *v and $\{g_a\}_{a \in A}$ is another utility function and a family of increasing continuous functions that represent the preference relation in the sense of (a.ii) if and only if, for all $\theta \in \Theta$, $v(\cdot, \theta) = \lambda u(\cdot, \theta) + \varsigma(\theta)$, $\lambda > 0$, and $g_a(\lambda x + \varsigma) = f_a(x)$, for all $x \in \{\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a) \mid \bar{b} \in B^{cv}\}$, where $\varsigma = \sum_{\theta \in \Theta} \varsigma(\theta)$.*

(c) *For each $a \in A$, $\pi(\cdot; a)$ is unique and $\pi(\theta; a) = 0$ if and only if θ is null given a .*

The proof of Theorem 1 is given in Section 5.1. A sketch of the argument that (a.i) \rightarrow (a.ii), which is the difficult part of the proof, is in order. For every given $a \in A$, (A.1),

(A.2) and (A.3) imply the existence of jointly cardinal continuous additive representation of \succsim_a , (that is, for every given a , \succsim_a is represented by $(a, b) \mapsto \sum_{\theta \in \Theta} w_a(b(\theta), \theta)$, and the $w_a(\cdot; \theta)$ are unique up to multiplication by a positive, common, number and the addition of numbers that may depend on θ). Axiom (A.3) also implies that, for all $a, a' \in A$, and $\theta \in \Theta$, $w_a(\cdot; \theta) = \beta(a, a'; \theta) w_{a'}(\cdot; \theta) + \gamma(a, a'; \theta)$ where $\beta(a, a'; \theta) \geq 0$ and $\beta(a, a'; \theta) > 0$ if $\theta \in \Theta(a) \cap \Theta(a')$. Next for each the probabilities $\{\pi(\theta; a) \mid a \in A, \theta \in \Theta\}$ are defined by $\pi(\theta; a) = 0$ if $\theta \notin \Theta(a)$ and by the solution to the system of equations $\pi(\theta; a) = \beta(a, a'; \theta) \pi(\theta; a')$ and $\sum_{\theta \in \Theta} \pi(\theta; a) = 1$, $a, a' \in A$, $\theta \in \Theta(a) \cap \Theta(a')$. The utility of the consequences $(\theta; r)$, $r \in \mathbb{R}$, $u(\theta; r)$, is defined by $w_a(\theta; r)/\pi(\theta; a)$, which is shown to be independent of a . Finally, fixing $\bar{a} \in A$ and invoking the constant valuation bets, define f_a for all $a \in A$ by $\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; \bar{a}) \geq f_a (\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a))$. This links the representations across actions.

3.5 Effect-independent preferences on bets

If the decision maker bets on the effect of the next turn of a roulette wheel, it is reasonable to suppose that he does not care about the effect except insofar as it determines his monetary payoff. This example is typical of situations in which the decision maker's betting preferences are effect independent. The following axiom, which is similar to Wakker's (1987) cardinal consistency, captures this idea:

(A.4) (**Effect-independent betting preferences**) For all $a \in A$, $b, b', b'', b''' \in B$, $\theta, \theta' \in$

$\Theta(a)$, and $r, r', r'' r''' \in \mathbb{R}$, if $(a, (b'_{-\theta}, r)) \succ (a, (b_{-\theta}, r'))$, $(a, (b_{-\theta}, r'')) \succ (a, (b'_{-\theta}, r'''))$,
and $(a, (b''_{-\theta'}, r')) \succ (a, (b'''_{-\theta'}, r))$ then $(a, (b''_{-\theta'}, r'')) \succ (a, (b'''_{-\theta'}, r'''))$.

The interpretation of (A.4) is analogous to that of action-independent betting preferences. The preferences $(a, (b'_{-\theta}, r')) \succ (a, (b_{-\theta}, r))$ and $(a, (b_{-\theta}, r'')) \succ (a, (b'_{-\theta}, r'''))$ indicate that the “intensity” of the preference for r'' over r''' in given the effect θ is sufficiently greater than that of r over r' as to reverse the order of preference between the payoffs $b'_{-\theta}$ and $b_{-\theta}$. Outcome independence requires that these intensities not be contradicted by the preferences between the same payoffs given any other effect θ .

Theorem 2 *Suppose that there are at least two effects and that assumption (A.0) is satisfied, then:*

(a) *The following conditions are equivalent:*

(a.i) *The preference relation, \succ on \mathbb{C} , satisfies (A.1)–(A.4).*

(a.ii) *There exist continuous function $u : \mathbb{R} \rightarrow \mathbb{R}$ and, for all $\theta \in \Theta$, there are numbers $\sigma(\theta) > 0, \kappa(\theta)$, a family of probability measures $\{\pi(\cdot; a)\}_{a \in A}$ on Θ , and a family of increasing continuous functions $\{f_a : \mathbb{R} \rightarrow \mathbb{R}\}_{a \in A}$ such that for all $(a, b), (a', b') \in \mathbb{C}$, $(a, b) \succ (a', b')$ if and only if*

$$f_a \left(\sum_{\theta \in \Theta} [\sigma(\theta) u(b(\theta)) + \kappa(\theta)] \pi(\theta; a) \right) \geq f_{a'} \left(\sum_{\theta \in \Theta} [\sigma(\theta) u(b'(\theta)) + \kappa(\theta)] \pi(\theta; a') \right).$$

(b) v and $\{g_a\}_{a \in A}$ is another utility function and a family of increasing continuous functions that represent the preference relation in the sense of (a.ii) if and only if, for all $\theta \in \Theta$, $v(\cdot) = \lambda u(\cdot) + \varsigma$, $\lambda > 0$, and $g_a(\lambda x + \varsigma) = f_a(x)$, for all $x \in \{\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a) \mid \bar{b} \in B^{cv}\}$.

(c) For each $a \in A$, $\pi(\cdot; a)$ is unique and $\pi(\theta; a) = 0$ if and only if θ is null given a .

A *constant-payoff bet* is a bet satisfying $b(\theta) = b$ for all θ . If all constant-payoff bets are constant-valuation bets then both the preference relation and the utility functions display effect independence.⁹ The following is an immediate implication of Theorem 2.

Corollary 3 *Suppose there are at least two effects, that assumption (A.0) is satisfied, and constant-valuation bets are constant payoff bets. Then the following conditions are equivalent:*

(i) *The relation \succsim on \mathbb{C} satisfies (A.1) – (A.4).*

(ii) *There exist a continuous real-valued function u on Θ , unique up to positive linear transformation, a unique family of probability measures $\{\pi(\cdot; a) \mid a \in A\}$ on Θ , and a family of increasing continuous functions $\{f_a : \mathbb{R} \rightarrow \mathbb{R}\}_{a \in A}$ such that, for all $(a, b), (a', b) \in \mathbb{C}$,*

$$(a, b) \succsim (a', b) \Leftrightarrow f_a \left(\sum_{\theta \in \Theta} u(b(\theta)) \pi(\theta; a) \right) \geq f_{a'} \left(\sum_{\theta \in \Theta} u(b'(\theta)) \pi(\theta; a') \right),$$

⁹Effect-independent preferences are analogous to state-independent preferences, effect-independent utility function is analogous to state-independent utility function in the traditional formulations of subjective expected utility theory (see Karni [1996]).

where $\pi(\theta; a) = 0$ if and only if θ is null given a . Furthermore, v and $\{g_a\}_{a \in A}$ is another utility function and a family of increasing continuous functions that represent the preference relation in the sense of (a.ii) if and only if, for all $\theta \in \Theta$, $v(\cdot) = \lambda u(\cdot) + \varsigma$, $\lambda > 0$, and $g_a(\lambda x + \varsigma) = f_a(x)$, for all $x \in \{\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a) \mid \bar{b} \in B^{cv}\}$.

The proof of the corollary is as follows: If b^* is a constant valuation bet then, by the normalization, $\sigma(\theta) u(b^*(\theta)) + \kappa(\theta) = \sigma(\theta') u(b^*(\theta')) + \kappa(\theta') = 0$ for all $\theta, \theta' \in \Theta$. But if constant-valuation bets are constant-payoff bets then $u(r) \sum_{\theta \in \Theta} [\sigma(\theta) + \kappa(\theta)] \pi(\theta, a) = u(r) \sum_{\theta \in \Theta} [\sigma(\theta) + \kappa(\theta)] \pi(\theta, a')$, where $r \in \{b^*, b^{**}\}$. Hence $\sum_{\theta \in \Theta} [\sigma(\theta) + \kappa(\theta)] \pi(\theta, a) = \sum_{\theta \in \Theta} [\sigma(\theta) + \kappa(\theta)] \pi(\theta, a') \neq 0$. Consequently, $u(b^*(\theta')) = u(b^*(\theta)) = 0$. Hence $\kappa(\theta) = \kappa(\theta') = 0$ and, by the definition of constant valuation bets, $\sigma(\theta) = \sigma(\theta') = \sigma$ for all $\theta, \theta' \in \Theta$. The corollary then follows from Theorem 2.

4 Beliefs and Probabilities

Following the seminal work of Ramsey (1931), it is now commonplace to infer the degree of belief a decision maker holds about the likely realization of an event by his willingness to bet on that event. Presently the issue is the degree of belief of a decision maker regarding the likely realization of effects. However, effects may have implications for the decision maker's well-being that are independent of the payoff of the bet, and his beliefs regarding the likely realization of effects may depend on his choice of action. This means that the application of

Ramsey's method must be approached with care. First, the bets that figure in the definition of beliefs must be chosen in a way that neutralizes the influence of the effects, that is, by replacing the constant monetary payoffs in Ramsey's definition with constant utility payoffs. Second, the bets must be defined conditional on the action.

4.1 Constant utility bets

A bet b is said to be a *constant utility bet* if $u(b(\theta), \theta) = u(b(\theta'), \theta')$ for all $\theta, \theta' \in \Theta$. It is tempting to suppose that constant valuation bets are constant utility bets. However, because of possible variations in direct influence of the actions on the valuation of the bets (that is, because it is possible that $f_a \neq f_{a'}$ for some $a, a' \in A$) it is not true, in general, that constant valuation bets are constant utility bets. The following example illustrates this point.

Example: Let $\Theta = \{\theta, \theta'\}$, $A = \{a, a'\}$, and suppose that $\pi(\theta, a) = \pi(\theta', a) = 1/2$ and $\pi(\theta, a') = 2/3$, $\pi(\theta', a') = 1/3$. Let the range of payoffs to the bets under the two effects be the closed unit interval (that is, $\{b(\theta) \mid b \in B\} = \{b(\theta') \mid b \in B\} = [0, 1]$). Let $V : \mathbb{C} \rightarrow \mathbb{R}$ be defined by:

$$V(j, b) = f_j(\pi(\theta, j)b(\theta) + \pi(\theta', j)b(\theta')), \quad j \in \{a, a'\},$$

where f_a is the identity function and $f_{a'}(x) = (1 + 3x - \sqrt{1 + 3x})/2$.

Define a preference relation \succsim on \mathbb{C} by $(j, b) \succsim (i, b')$ if and only if $V(j, b) \geq V(i, b')$, $i, j \in \{a, a'\}$. Let $b^{**} = (1, 1)$, $b^* = (0, 0)$. Then it is easy to verify that (A.0), (A.1), (A.2)

and (A.3) are satisfied.

For every $r \in [0, 1]$, $\bar{b}_r := (\bar{b}_r(\theta), \bar{b}_r(\theta')) = (r, r^2)$, is a constant valuation bet. Thus $B^{cv} = \{\bar{b}_r \mid r \in [0, 1]\}$, while the set of constant utility bets is $B^{cu} = \{b \in B \mid b(\theta) = b(\theta')\}$.

■

A constant valuation bet is a constant utility bet if and only if the utility functions f_a are action independent. Formally, $B^{cv} = B^{cu}$ if and only if $f_a = f_{a'}$, for all $a, a' \in A$. Notice that because the utility functions that figure in the representation are deduced from individual choice behavior, it is possible to verify, within the framework of revealed preference methodology, whether constant valuation bets are constant utility bets.

4.2 Beliefs and their representation

Invoking the notion of constant utility bets and using Ramsey's approach, it is natural to define decision makers' conditional beliefs as follows:

Definition 2: For every given $a \in A$, a binary relation \succeq_a on 2^Θ is a decision maker's

beliefs conditional on a if, for all constant utility bets \tilde{b} and \tilde{b}' , such that $\tilde{b}' \succ \tilde{b}$, $S \succeq_a T$ if and only if $(a, \tilde{b}'\tilde{b}) \succ (a, \tilde{b}'\tilde{b})$.

The interpretation of $S \succeq_a T$ is that the decision maker believes that if action a were chosen then it is more likely that the effect that obtains is in S than that it is in T . The definition of beliefs is choice-theoretic (that is, all the conditions in the hypothesis of Definition

2 are potentially refutable within the revealed-preference methodological framework). Moreover, it is easy to verify that the probability measures that figure in the representation in Theorem 1 are the only probability measures representing the decision maker's conditional beliefs. In other words, $\{\pi(\cdot; a)\}_{a \in A}$ is the sole family of probability measures satisfying $S \succeq_a T$ if and only if $\pi(S; a) \geq \pi(T; a)$, where $\pi(H, a) = \sum_{\theta \in H} \pi(\theta; a)$, for all $H \subset \Theta$ and $a \in A$.

This is, as far as I know, the only *behavioral* definition of subjective probabilities that truly represent the decision makers' beliefs. Moreover, it is possible now to define a binary relation \succeq on $A \times 2^\Theta$ representing a decision maker's *beliefs* as $(a, S) \succeq (a', T)$ if and only if $\pi(S; a) \geq \pi(T; a')$. The interpretation of $(a, S) \succeq (a', T)$ is that the decision maker believes that if action a would be chosen then it is more likely that the effect that obtains is in S than that it is in T if the action a' is chosen instead.

5 Concluding Remarks

The representation Theorems 1, 2, and Corollary 3 give necessary and sufficient conditions for the decision-making process to be decomposed into two cognitive subprocesses. The first is the assessment of the likely realization of different effects conditional on the decision-maker's actions. The second is the evaluation of the consequences, that is, effect-payoff pairs, that may result from the implementation of those actions. The two processes are integrated to produce a value that is action-dependent function of a subjective expected

utility corresponding to each action-bet pairs. If the value depends on the action solely through its effect on the probabilities then the result of this work is a new subjective expected utility theory that, unlike traditional theories, does not invoke Savage's notion of states of the world to resolve uncertainty. This theory may better describe how decision makers actually perceive and assess their options. *It does not rule out that decision makers mentally construct a state space to help organize their thoughts, but it does not require that they do.* In other words, when the state space is objectively observable and the likely realization of the states is independent of the decision maker's choice of actions, so that traditional subjective utility theory is relevant, there is no contradiction between the theory developed here and the traditional approach. The traditional theory may easily be embedded in the present framework by defining the actions-bet pairs as random variables on the state space and, for every given action, assigning to the effects the probabilities of the events in the state space in which these effects are realized under the given action. Note, however, that even if decision makers do construct a mental state space to help organize their thoughts, the states are not always independently observable, and using them, in such cases, is not a good scientific procedure.

The quest to extend subjective expected utility theory to accommodate moral hazard and state-dependent preferences was pioneered by Drèze (1961,1987). Invoking the analytical framework of Anscombe and Aumann (1963), Drèze relaxes their "reversal of order" axiom to allow decision makers to strictly prefer knowing the outcome of a lottery before, rather than after, the state of nature becomes known. This is taken to imply that knowing the payoff

ahead of time would allow the decision maker to influence the probabilities of the states. How this may be done is not model explicitly, and the representation entails the maximization of subjective expected utility over a convex set of subjective probability measures. The theory developed in this paper differ from that of Drèze in several important respects. First, the analytical framework is different. Unlike Drèze I avoid the state space formulation and do not use probabilities as a primitive concept. Second, in this paper actions are modeled explicitly as part of the choice set. Drèze's presumed motive for not dealing with actions explicitly is that, in the context of principal-agent relationships action may be unobservable by the principal. The position taken here is that, whether or not actions are observable by a second party, decision makers are aware of the actions they may take and have well-defined preference relations on action-bet pairs.

A different approach to modeling subjective distributions without relying on a state space is pursued in Gilboa and Schmeidler (2004). They model preferences over acts conditional on what, in this paper, I referred to as bets. Instead of deriving the utility, Gilboa and Schmeidler assume that an outcome-independent (that is effect-independent in the terminology of this paper) linear utility on bets is given and derive subjective probabilities on the outcome, consistent with expected value maximizing behavior.¹⁰

Recognizing the ability of the decision makers to influence, by their actions, the likeli-

¹⁰Note that Gilboa and Schmeidler assume, without calling them by these names, that constant-payoff bets are constant-valuation bets. Thus they implicitly assume not only that the preferences but also the utility functions are effect independent.

hoods of alternative effects creates a natural link between the present work and the literature dealing with principal-agent relationship in the presence of moral hazard. A principal-agent relationship is governed by a contract specifying the agent's payoff as a function of the observed effect. Let $W := \{w : \Theta \rightarrow \mathbb{R}\}$ denote the set of contracts, where Θ has the interpretation of output. Clearly, contracts are bets on the output, and the agent's choice of action affect the likely realization of alternative levels of output. The modeling of the behaviors of the principal and the agent in the context of agency theory admits alternative formulations, including the state-space formulation and the parameterized distribution formulation (see, for example, Hart and Holmstrom [1979], Chambers and Quiggin [2000]). The latter formulation, pioneered and popularized by Mirrlees (1974, 1976), is analytically convenient and is often used in applications. If the constant valuation bets are constant utility bets then the decision theory developed here depicts, axiomatically, the principal's conduct in parameterized distribution formulation of agency theory.

In many applications of agency theory the choice of action is supposed to affect the agent's well-being directly and *independently* of its influence on the desirability of alternative bets. A development of a full fledge axiomatic model of the agent's behavior, that takes into account the direct effect of the actions on the agent's well-being, is the subject matter of a companion paper Karni (2004a).

There are decision situations in which the decision maker is aware that he may not be aware of all the relevant effects. The degree of his belief in these unknown effects reflects itself in his choice of actions and bets. In particular, suppose that one of the effects, say $\hat{\theta}$, is

interpreted as “none of the above” and the bets specify the payoff to each one of the effects in $\Theta - \{\hat{\theta}\}$ and also the payoff if non of these effects obtains. Then, applying the results of this paper it is possible to obtain a utility $u(\cdot; \hat{\theta})$ representing the valuation of the payoff in case non of the effects of which the decision maker is aware obtains and also the corresponding action-dependent probabilities $\{\pi(\hat{\theta}; a)\}_{a \in A}$.

6 Proofs

6.1 Proof of Theorem 1.

As a preliminary step I prove two results that are of interest in their own right.

Coordinate independence requires that, for every given action, the preference between any two bets be independent of the payoffs contingent on effects on which the two bets agree. For every given action, this condition is analogous to Savage’s (1954) Sure Thing Principle. Like it, it implies the separability of the valuation of the monetary payoffs across effects.

(Coordinate independence) For all $a \in A, b, b' \in B, \theta \in \Theta$, and $r, r' \in \mathbb{R}$, $(a, (b_{-\theta}, r)) \succcurlyeq (a, (b'_{-\theta}, r))$ if and only if $(a, (b_{-\theta}, r')) \succcurlyeq (a, (b'_{-\theta}, r'))$.

Lemma 4 *Let there be at least three nonnull effects. If \succcurlyeq on \mathbb{C} satisfies (A.3) then it satisfies coordinate independence.*

Proof. Suppose that $\left(a, \left(\tilde{b}_{-\theta}, \tilde{r}\right)\right) \succcurlyeq \left(a, \left(\hat{b}_{-\theta}, \tilde{r}\right)\right)$ and $\left(a, \left(\hat{b}_{-\theta}, \hat{r}\right)\right) \succ \left(a, \left(\tilde{b}_{-\theta}, \hat{r}\right)\right)$ for some $a \in A, \tilde{b}, \hat{b} \in B, \theta \in \Theta(a)$, and $\tilde{r}, \hat{r} \in \mathbb{R}$. In (A.3), let $r = r' = \tilde{r}, r''' = r'' = \hat{r}$, $a = a', b = b'' = \tilde{b}$, and $b' = b''' = \hat{b}$. Then, (A.3) implies that $\left(a, \left(\tilde{b}_{-\theta}, \hat{r}\right)\right) \succcurlyeq \left(a, \left(\hat{b}_{-\theta}, \hat{r}\right)\right)$ which is a contradiction. Hence $\left(a, \left(\tilde{b}_{-\theta}, \tilde{r}\right)\right) \succcurlyeq \left(a, \left(\hat{b}_{-\theta}, \tilde{r}\right)\right)$ if and only if $\left(a, \left(\tilde{b}_{-\theta}, \hat{r}\right)\right) \succcurlyeq \left(a, \left(\hat{b}_{-\theta}, \hat{r}\right)\right)$. ■

The well-known Hexagon condition implies additive separable representation for actions that the decision maker believes have exactly two nonnull effects:

(Hexagon condition) For all $a \in A, b \in B$, and $r, r', r'' \in \mathbb{R}$, if $\Theta(a) = \{\theta, \theta'\}$ then $(a, (b_{-\theta}, r)_{-\theta'}, r') \sim (a, (b_{-\theta}, r')_{-\theta'}, r)$ and $(a, (b_{-\theta}, r)_{-\theta'}, r'') \sim (a, (b_{-\theta}, r')_{-\theta'}, r') \sim (a, (b_{-\theta}, r'')_{-\theta'}, r)$ imply $(a, (b_{-\theta}, r')_{-\theta'}, r'') \sim (a, (b_{-\theta}, r'')_{-\theta'}, r')$.

Lemma 5 Let there be exactly two nonnull effects. If \succcurlyeq on \mathbb{C} satisfies (A.3) then it satisfies the Hexagon condition.

Proof. Suppose that \succcurlyeq on \mathbb{C} satisfies (A.1) and (A.3). Suppose that $(a, (b_{-\theta'}, r')_{-\theta}, r) \sim (a, (b_{-\theta'}, r)_{-\theta}, r')$ and $(a, (b_{-\theta'}, r)_{-\theta}, r'') \sim (a, (b_{-\theta'}, r')_{-\theta}, r') \sim (a, (b_{-\theta'}, r'')_{-\theta}, r)$. Apply (A.3) with $a = a', r''' = r', b'''_{-\theta} = b_{-\theta} = (b_{-\theta'}, r')_{-\theta}, b'_{-\theta} = (b_{-\theta'}, r)_{-\theta}$, and $b''_{-\theta} = (b_{-\theta'}, r'')_{-\theta}$. Then, apply (A.3) twice to obtain $(a, (b_{-\theta'}, r')_{-\theta}, r'') \sim (a, (b_{-\theta'}, r'')_{-\theta}, r')$. ■

The following additional terminology will be used in the proof below: An array of real-valued functions $(v_s)_{s \in S}$ is said to be a *jointly cardinal additive representation* of a binary relation \succeq on a product set $D = \prod_{s \in S} D_s$ if, for all $d, d' \in D$, $d \succeq d'$ if and only if

$\sum_{s \in S} v_s(d_s) \geq \sum_{s \in S} v_s(d'_s)$, and the class of all functions that constitute an additive representation of \succeq consists of those arrays of functions, $(\hat{v}_s)_{s \in S}$, for which $\hat{v}_s = \lambda v_s + \zeta_s$, $\lambda > 0$ for all $s \in S$. The representation is continuous if the functions $v_s, s \in S$ are continuous.

I turn next to the proof of Theorem 1.

(a.i) \Rightarrow (a.ii). Since \succcurlyeq satisfies (A.1)-(A.3), Lemma 4, Lemma 5 above and Theorem III.4.1 of Wakker [1989] imply that, for every $a \in A$ such that $\Theta(a)$ contains at least two nonnull effects, there exist array of functions $\{w_a(\cdot; \theta) : \mathbb{R} \rightarrow \mathbb{R}\}_{\theta \in \Theta}$ that constitute jointly cardinal continuous additive representation of \succcurlyeq_a on B .¹¹

Observe that, for all $a, a' \in A$ and $\theta \in \Theta(a) \cap \Theta(a')$, $w_a(\cdot; \theta)$ and $w_{a'}(\cdot; \theta)$ are ordinally equivalent.

Claim 1: For all $a, a' \in A$, $\theta \in \Theta(a) \cap \Theta(a')$, and $r', r \in \mathbb{R}$, $w_a(r'; \theta) \geq w_a(r; \theta)$ if and only if $w_{a'}(r'; \theta) \geq w_{a'}(r; \theta)$.

Proof. Let $(a', (b_{-\theta}, r')) \succcurlyeq (a', (b_{-\theta}, r))$. But $(a', (b_{-\theta}, r')) \succcurlyeq (a', (b_{-\theta}, r'))$, $(a', (b_{-\theta}, r')) \succcurlyeq (a', (b_{-\theta}, r))$, and $(a, (b_{-\theta}, r')) \succcurlyeq (a, (b_{-\theta}, r'))$. Thus, by (A.3), $(a, (b_{-\theta}, r')) \succcurlyeq (a, (b_{-\theta}, r))$. The conclusion is implied by the representation of \succcurlyeq . ■

By assumption (A.0) there are $b^{**}, b^* \in B^{cv}$ such that $b^{**} \succ b^*$. Invoking the uniqueness of the jointly cardinal representation normalize $\{w_a(\cdot; \theta)\}_{\theta \in \Theta}$ so that for all $a \in A$ and $\theta \in \Theta$

¹¹If $a = a^x (\succcurlyeq)$, (that is $X(a) = \{x\}$) then the fact that \succcurlyeq_a is a continuous weak order implies that there exist continuous real-valued function $w_{a^x}(\cdot; x)$ representing \succcurlyeq_{a^x} on \mathbb{R} (Debreu [1954] Theorem I).

set $w_a(b^*(\theta); \theta) = 0$.

Let \hat{A} be the subset of that consists of all actions that have at least two nonnull effects (that is, $\hat{A} = \{a \in A \mid |\Theta(a)| \geq 2\}$). Next I show that, for all $a, \bar{a} \in \hat{A}$ and $\theta \in \Theta(a) \cap \Theta(\bar{a})$, $w_a(\cdot; \theta)$ is either constant or is positive linear transformation of $w_{\bar{a}}(\cdot; \theta)$.

Lemma 6 *The following conditions are equivalent:*

(i) *The relation \succsim on \mathbb{C} satisfies (A.1) – (A.3).*

(ii) *For every $a, \bar{a} \in \hat{A}$ and $\theta \in \Theta(a) \cap \Theta(\bar{a})$ there exist $\beta_{(a, \bar{a}, \theta)} > 0$ such that $w_a(\cdot; \theta) = \beta_{(a, \bar{a}, \theta)} w_{\bar{a}}(\cdot; \theta)$, where $\{w_j(\cdot; \theta) : \mathbb{R} \rightarrow \mathbb{R}\}_{\theta \in \Theta}$, $j = a, \bar{a}$ constitute a jointly cardinal continuous additive representation of \succsim_j on B .*

Proof. (i) \Rightarrow (ii). Let $a, \bar{a} \in A$ be such that the number of nonnull effects in each set $\Theta(a)$ and $\Theta(\bar{a})$ is, at least, two. Suppose that \succsim satisfies (A.1) – (A.3). Theorem III.4.1. of Wakker (1989) implies that, for every given $a \in A$, there exist continuous functions $\{w_a(\cdot; \theta) : \mathbb{R} \rightarrow \mathbb{R} \mid \theta \in \Theta\}$ that constitute a jointly cardinal additive representation of \succsim_a on B .

If $\Theta(a) \cap \Theta(\bar{a}) \neq \emptyset$, then, by the representation, for every $\theta' \in \Theta(a) \cap \Theta(\bar{a})$ there exist $b, b', b'', b''' \in B$ such that

$$\sum_{\theta \in \Theta - \{\theta'\}} [w_{\bar{a}}(b(\theta); \theta) - w_{\bar{a}}(b'(\theta); \theta)] = \zeta > 0, \quad (1)$$

and

$$\sum_{\theta \in \Theta - \{\theta'\}} [w_a(b''(\theta); \theta) - w_a(b'''(\theta); \theta)] = \varepsilon > 0. \quad (2)$$

By continuity of the additive valued functions $w_a(\cdot; \theta)$ and the connectedness of \mathbb{R} , for every $\hat{\zeta} \in [-\zeta, \zeta]$, $\hat{\varepsilon} \in [-\varepsilon, \varepsilon]$, and $\theta' \in \Theta(a) \cap \Theta(\bar{a})$ there exist $\bar{b}, \bar{b}', \bar{b}'', \bar{b}''' \in B$ such that

$$\sum_{\theta \in \Theta - \{\theta'\}} [w_{\bar{a}}(\bar{b}(\theta); \theta) - w_{\bar{a}}(\bar{b}'(\theta); \theta)] = \hat{\zeta} \quad (3)$$

and

$$\sum_{\theta \in \Theta - \{\theta'\}} [w_a(\bar{b}''(\theta); \theta) - w_a(\bar{b}'''(\theta); \theta)] = \hat{\varepsilon}. \quad (4)$$

Define $\phi_{(a, \bar{a}, \theta)}$ by $w_a(\cdot; \theta) = \phi_{(a, \bar{a}, \theta)} \circ w_{\bar{a}}(\cdot; \theta)$, $\theta \in \Theta(a) \cap \Theta(\bar{a})$, then, by Claim 1, $\phi_{(a, \bar{a}, \theta)}$ is a continuous increasing function. To show that $\phi_{(a, \bar{a}, \theta)}$ is linear, fix $\theta' \in \Theta(a) \cap \Theta(\bar{a})$ and let $I_{\theta'} = w_{\bar{a}}(\mathbb{R}; \theta')$. Then, by the continuity of $w_{\bar{a}}(\cdot; \theta')$, $I_{\theta'}$ is an interval in \mathbb{R} . Take $\alpha, \beta, \gamma, \delta \in I_{\theta'}$ such that $-\zeta \leq \alpha - \beta = \gamma - \delta \leq \zeta$ and $-\varepsilon \leq \phi_{(a, \bar{a}, \theta')}(\alpha) - \phi_{(a, \bar{a}, \theta')}(\beta) \leq \varepsilon$. Let $r, r', r'', r''' \in \mathbb{R}$ satisfy $w_{\bar{a}}(r; \theta') = \alpha$, $w_{\bar{a}}(r'; \theta') = \beta$, $w_{\bar{a}}(r''; \theta') = \gamma$ and $w_{\bar{a}}(r'''; \theta') = \delta$. Take $b, b' \in B$ such that

$$\sum_{\theta \in \Theta - \{\theta'\}} [w_{\bar{a}}(b(\theta); \theta) - w_{\bar{a}}(b'(\theta); \theta)] = \alpha - \beta. \quad (5)$$

Then, by the representation, $(\bar{a}, (b_{-\theta'}; r)) \sim (\bar{a}, (b'_{-\theta'}; r'))$ and $(\bar{a}, (b_{-\theta'}; r'')) \sim (\bar{a}, (b'_{-\theta'}; r'''))$.

Take $b'', b''' \in B$ such that

$$\sum_{\theta \in \Theta - \{\theta'\}} [w_a(b''(\theta); \theta) - w_a(b'''(\theta); \theta)] = \phi_{(a, \bar{a}, \theta')}(\alpha) - \phi_{(a, \bar{a}, \theta')}(\beta). \quad (6)$$

Since $w_a(\cdot; \theta') = \phi_{(a, \bar{a}, \theta')} \circ w_{\bar{a}}(\cdot; \theta')$ this implies $(a, (b''_{-\theta'}, r)) \sim (a, (b'''_{-\theta'}, r'))$. Applying (A.3) twice yields $(a, (b''_{-\theta'}, r'')) \sim (a, (b'''_{-\theta'}, r'''))$. Thus

$$\phi_{(a, \bar{a}, \theta')}(\gamma) - \phi_{(a, \bar{a}, \theta')}(\delta) = \sum_{\theta \in \Theta - \{\theta'\}} [w_a(b''(\theta); \theta) - w_a(b'''(\theta); \theta)] = \phi_{(a, \bar{a}, \theta')}(\alpha) - \phi_{(a, \theta')}(\beta). \quad (7)$$

By Wakker (1987) Lemma 4.4 this implies that $\phi_{(a, \bar{a}, \theta')}$ is affine. But, by Claim 1, $\phi_{(a, \bar{a}, \theta')}$ is increasing. Hence there exist $\beta_{(a, \bar{a}, \theta)} > 0$ and $\alpha_{(a, \bar{a}, \theta)}$ such that, for all $r \in \mathbb{R}$ and nonnull $\theta \in \Theta(a)$, $w_a(r; \theta) = \beta_{(a, \bar{a}, \theta)} w_{\bar{a}}(r; \theta) + \alpha_{(a, \bar{a}, \theta)}$. By (A.3) and the normalization, $w_{\bar{a}}(b^*(\theta); \theta) = 0 = w_a(b^*(\theta); \theta)$, for all $\theta \in \Theta$. Hence

$$\sum_{\theta \in \Theta} [\beta_{(a, \bar{a}, \theta)} w_{\bar{a}}(b^*(\theta); \theta) + \alpha_{(a, \bar{a}, \theta)}] = \sum_{\theta \in \Theta} \alpha_{(a, \bar{a}, \theta)} = 0,$$

and $w_a(r; \theta) = \beta_{(a, \bar{a}, \theta)} w_{\bar{a}}(r; \theta)$, where $\beta_{(a, \bar{a}, \theta)} \geq 0$ for all $\theta \in \Theta$. Thus (i) \rightarrow (ii).

(ii) \Rightarrow (i). That (ii) implies Axioms (A.1) and (A.2) is immediate. To prove that (ii) implies (A.3) assume that for all $a, \bar{a} \in A$ and $\theta' \in \Theta(a)$ there exist positive linear or constant transformations $\phi_{(a, \bar{a}, \theta')}$ such that $w_a(\cdot; \theta') = \phi_{(a, \bar{a}, \theta')} \circ w_{\bar{a}}(\cdot; \theta')$. Let $\theta' \in \Theta(a) \cap \Theta(\bar{a})$. Suppose that $(\bar{a}, (b_{-\theta'}, r)) \succ (\bar{a}, (b'_{-\theta'}, r'))$, $(\bar{a}, (b'_{-\theta'}, r'')) \succ (\bar{a}, (b_{-\theta'}, r'''))$ and $(a, (b''_{-\theta'}, r')) \succ (a, (b'''_{-\theta'}, r))$. By the representation, $(\bar{a}, (b_{-\theta'}, r)) \succ (\bar{a}, (b'_{-\theta'}, r'))$ if and only if

$$w_{\bar{a}}(r; \theta') + \sum_{\theta \in \Theta - \{\theta'\}} w_{\bar{a}}(b(\theta); \theta) \geq w_{\bar{a}}(r'; \theta') + \sum_{\theta \in \Theta - \{\theta'\}} w_{\bar{a}}(b'(\theta); \theta) \quad (8)$$

and $(\bar{a}, (b'_{-\theta'}, r'')) \succ (\bar{a}, (b_{-\theta'}, r'''))$ if and only if

$$w_{\bar{a}}(r'''; \theta') + \sum_{\theta \in \Theta - \{\theta'\}} w_{\bar{a}}(b(\theta); \theta) \leq w_{\bar{a}}(r''; \theta') + \sum_{\theta \in \Theta - \{\theta'\}} w_{\bar{a}}(b'(\theta); \theta). \quad (9)$$

Hence

$$w_{\bar{a}}(r'; \theta') - w_{\bar{a}}(r; \theta') \leq \sum_{\theta \in \Theta - \{\theta'\}} [w_{\bar{a}}(b(\theta); \theta) - w_{\bar{a}}(b'(\theta); \theta)] \leq w_{\bar{a}}(r''; \theta') - w_{\bar{a}}(r'''; \theta'). \quad (10)$$

By positive linearity or constancy of $\phi_{(a, \bar{a}, \theta')}$ these inequalities imply

$$w_a(r'; \theta') - w_a(r; \theta') \leq w_a(r''; \theta') - w_a(r'''; \theta'). \quad (11)$$

Next observe that $(a, (b''_{-\theta'}, r')) \succcurlyeq (a, (b'''_{-\theta'}, r))$ if and only if

$$\sum_{\theta \in \Theta - \{\theta'\}} w_a(b''(\theta); \theta) + w_a(r'; \theta') \geq \sum_{\theta \in \Theta - \{\theta'\}} w_a(b'''(\theta); \theta) + w_a(r; \theta'). \quad (12)$$

Thus

$$w_a(r'; \theta') - w_a(r; \theta') \geq \sum_{\theta \in \Theta - \{\theta'\}} [w_a(b'''(\theta); \theta) - w_a(b''(\theta); \theta)]. \quad (13)$$

But inequality (11) implies

$$\sum_{\theta \in \Theta - \{\theta'\}} w_a(b''(\theta); \theta) + w_a(r''; \theta') \geq \sum_{\theta \in \Theta - \{\theta'\}} w_a(b'''(\theta); \theta) + w_a(r'''; \theta'). \quad (14)$$

Hence $(a, (b''_{-\theta'}, r'')) \succcurlyeq (a, (b'''_{-\theta'}, r'''))$. Thus (ii) \rightarrow (i). ■

Probabilities: Set $\pi(\theta; a) = 0$ for all $\theta \notin \Theta(a)$ and $\pi(\theta; a) = 1$ if $\Theta(a) = \{\theta\}$. For every $\theta \in \Theta$ and $a \in \hat{A}$, let $A(\theta) = \{a \in \hat{A} \mid \theta \in \Theta(a)\}$. For every $\theta \in \Theta$, fix $a \in A(\theta)$ and let $\{\pi(\cdot; a)\}_{a \in A}$ on Θ be a solution of the equations

$$\pi(\theta; a) - \beta_{(a, a', \theta)} \pi(\theta; a') = 0, \text{ for all } a' \in A(\theta) - \{a\}, \quad (15)$$

and

$$\sum_{\theta \in \Theta} \pi(\theta; a) = 1 \text{ for all } a \in A. \quad (16)$$

Next I show that $\{\pi(\cdot; a)\}_{a \in A}$ on Θ are well-defined.

Claim 2: There exists a unique solution to the system of equations (15) and (16).

Proof. Let $A = \{a_1, \dots, a_n\}$ and $\Theta(a) = \{\theta_{1(a)}, \dots, \theta_{m(a)}\}$. Write equations (15) and (16)

in matrix notation as follows: $\mathbf{M}\boldsymbol{\pi}^t = \boldsymbol{\beta}$, where

$$\boldsymbol{\pi} = (\pi(\theta_{1(a_1)}, a_1), \dots, \pi(\theta_{m(a_1)}, a_1), \dots, \pi(\theta_{1(a_n)}, a_n), \dots, \pi(\theta_{m(a_n)}, a_n))$$

t denotes the transpose of $\boldsymbol{\pi}$, and $\boldsymbol{\beta}$ is a $\sum_{i=1}^n m(a_i)$ column vector whose last n coordinates are 1 and all the other coordinates are 0 and \mathbf{M} is the $(\sum_{i=1}^n m(a_i)) \times (\sum_{i=1}^n m(a_i))$ matrix of coefficients of corresponding to the system of equations (15) and (16). The Matrix \mathbf{M} is of the following form:

$$\begin{pmatrix} 1 & 0 & 0 & 0 & -\beta(a_1, a_k; \theta) & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & -\beta(a_l, a_n; \theta) \\ 0 & 0 & 0 & 1 & 0 & 0 & -\beta(a_i, a_j; \theta) & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 1 & 0 & -\beta(a_s, a_h; \theta) & 0 & 0 & 0 & 0 & 0 \\ 1 & \dots & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & \dots & 1 & 0 & 0 & 0 \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot & \cdot \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & \dots & 1 \end{pmatrix}$$

To show that \mathbf{M} is non-singular suppose, by way of negation, that \mathbf{M} is singular. Take

$\bar{b} \in B^{cv}$ such that \bar{b} and define $\xi_a := \sum_{\theta \in \Theta} w_a(\bar{b}(\theta); \theta)$, for all $a \in A$. Let

$$\mathbf{w}^t = (w_{a_i}(\bar{b}(\theta_{1(a_i)}), \theta_{1(a_i)}), \dots, w_{a_i}(\bar{b}(\theta_{m(a_i)}), \theta_{m(a_i)}))_{i=1}^n.$$

Then, by Lemma 6 and the normalization, $\mathbf{M}\mathbf{w}^t = \gamma$, where γ a $\sum_{i=1}^n m(a_n)$ column vector whose last n coordinates are ξ_{a_i} and all the other coordinates are 0. Since \mathbf{M} is singular and \mathbf{w}^t exists, there is $\hat{b} \neq \bar{b}$ such that

$$\hat{\mathbf{w}}^t = (w_{a_i}(\hat{b}(\theta_{1(a_i)}), \theta_{1(a_i)}), \dots, w_{a_i}(\hat{b}(\theta_{m(a_i)}), \theta_{m(a_i)}))_{i=1}^n$$

satisfies $\mathbf{M}\hat{\mathbf{w}}^t = \gamma$. Thus $\hat{b} \in B^{cv}$ and, for every $a \in \hat{A}$,

$$\sum_{\theta \in \Theta} w_a(\bar{b}(\theta); \theta) = \xi_a = \sum_{\theta \in \Theta} w_a(\hat{b}(\theta), \theta),$$

implying $(a, \hat{b}) \sim (a, \bar{b})$. But this contradicts the uniqueness of constant valuation bets in Definition 1. Hence \mathbf{M} is non-singular and the system of equations (15) and (16) has a unique solution. ■

Utilities: For any given $r \in \mathbb{R}$, $\theta \in \Theta$, and $a \in \hat{A}$ define $u(r; \theta, a) = w_a(r; \theta) / \pi(\theta; a)$ if $\pi(\theta; a) > 0$ and $u(r; \theta, a) = \bar{u}$ otherwise. Note that, for all $a \in \hat{A}$ and $\theta \in \Theta(a') \cap \Theta(a)$,

$$u(r; \theta, a') = \frac{w_{a'}(r; \theta)}{\pi(\theta; a')} = \frac{w_a(r; \theta)}{\beta_{(a', a, \theta)} \pi(\theta; a')} = \frac{w_a(r; \theta)}{\pi(\theta; a)} = u(r; \theta, a), \quad (17)$$

where the third inequality is implied by (15). Hence $u(r; \theta, a) = u(r; \theta, a') := u(r; \theta)$ for all $a, a' \in \hat{A}$ and $\theta \in \Theta(a) \cap \Theta(a')$. Since any two effects are linked it follows that $u(r; \theta, a) = u(r; \theta)$ for all $a \in \hat{A}$ and $\theta \in \Theta(a)$. For all a and θ such that $\pi(\theta, a) = 1$ (that is, $a \in A - \hat{A}$) set let $u(r; \theta)$ to be an increasing continuous function of r .

By definition, $w_a(r; \theta) = \pi(\theta; a) u(r; \theta)$ for all $a \in A, \theta \in \Theta$, and $r \in \mathbb{R}$. Observe that, for each $a \in A$, \succsim_a is represented by the subjective expected utility functional

$$(a, b) \mapsto \sum_{\theta \in \Theta} u(b(\theta); \theta) \pi(\theta; a). \quad (18)$$

Representation: Fix $\bar{a} \in A$ and, for each $a \in A$ define a function $f_a : \mathbb{R} \rightarrow \mathbb{R}$ by

$$\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; \bar{a}) = f_a \left(\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a) \right), \quad \forall \bar{b} \in B^{cv}. \quad (19)$$

Then f_a is well-defined and strictly increasing continuous function.

For all (a, b) and (a', b') in \mathbb{C}

$$(a, b) \succsim (a', b') \Leftrightarrow f_a \left(\sum_{\theta \in \Theta} u(b(\theta), \theta) \pi(\theta; a) \right) \geq f_{a'} \left(\sum_{\theta \in \Theta} u(b'(\theta), \theta) \pi(\theta; a') \right). \quad (20)$$

(To see this observe that there is a constant valuation bet \hat{b} such that $(a, b) \succsim (a, \hat{b}) \sim (a', \hat{b}) \succsim (a', b')$. Hence,

$$(a, b) \succsim (a, \hat{b}) \Leftrightarrow \sum_{\theta \in \Theta} u(b(\theta), \theta) \pi(\theta; a) \geq \sum_{\theta \in \Theta} u(\hat{b}(\theta), \theta) \pi(\theta; a)$$

and

$$(a', \hat{b}) \succsim (a', b') \Leftrightarrow \sum_{\theta \in \Theta} u(\hat{b}(\theta), \theta) \pi(\theta; a') \geq \sum_{\theta \in \Theta} u(b'(\theta), \theta) \pi(\theta; a').$$

But

$$(a, \hat{b}) \sim (a', \hat{b}) \Leftrightarrow f_a \left(\sum_{\theta \in \Theta} u(\hat{b}(\theta), \theta) \pi(\theta; a) \right) = f_{a'} \left(\sum_{\theta \in \Theta} u(\hat{b}(\theta), \theta) \pi(\theta; a') \right).$$

The conclusion follows by transitivity of \succsim .) This completes the proof that $(a.i) \Rightarrow (a.ii)$.

(a.ii) \Rightarrow (a.i). That (a.ii) implies (A.1) – (A.2) is well known. That (a.ii) implies (A.3)

is implied by Lemma 6.

(b) Suppose that, for all $\theta \in \Theta$, $v(\cdot, \theta) = \lambda u(\cdot, \theta) + \varsigma(\theta)$, $\lambda > 0$, and $g_a(\lambda x + \varsigma) = f_a(x)$,

where $\varsigma = \sum_{\theta \in \Theta} \varsigma(\theta)$. Then, for all $a \in A$,

$$g_a \left(\sum_{\theta \in \Theta} v(b(\theta), \theta) \pi(\theta; a) \right) = f_a \left(\sum_{\theta \in \Theta} u(b(\theta), \theta) \pi(\theta; a) \right)$$

Hence, (20) implies that

$$(a, b) \succcurlyeq (a', b') \Leftrightarrow g_a \left(\sum_{\theta \in \Theta} v(b(\theta), \theta) \pi(\theta; a) \right) \geq g_{a'} \left(\sum_{\theta \in \Theta} v(b'(\theta), \theta) \pi(\theta; a') \right).$$

Let v and $\{g_a\}_{a \in A}$ be a representation of \succcurlyeq in the sense of (a.ii). Then, by the uniqueness of the jointly cardinal additive representation of \succcurlyeq_a , for all $a \in A$ and $\theta \in \Theta$, $v(\cdot; \theta) \pi(\theta; a) = \lambda(a) u(\cdot, \theta) \pi(\theta; a) + \zeta(\theta; a)$, $\lambda(a) > 0$. But, by the normalization, $v(b^*(\theta); \theta) \pi(\theta; a) = \zeta(\theta; a)$. Hence $v(b^*(\theta); \theta) = \zeta(\theta; a) / \pi(\theta; a) = \varsigma(\theta)$. Let $\varsigma = \sum_{\theta \in \Theta} \varsigma(\theta)$.

Next observe that, $v(b(\theta), \theta) = \lambda(a) u(b(\theta), \theta) + \varsigma(\theta)$. But the left hand side is independent of a . Thus $\lambda(a) = \lambda$ for all $a \in A$. Hence

$$g_a \left(\sum_{\theta \in \Theta} v(b(\theta), \theta) \pi(\theta; a) \right) = g_a \left(\lambda \sum_{\theta \in \Theta} u(b(\theta), \theta) \pi(\theta; a) + \varsigma \right) \quad \forall (a, b) \in \mathbb{C}.$$

But for all $a, a' \in A$ and $\bar{b} \in B^{cv}$,

$$f_a \left(\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a) \right) = f_{a'} \left(\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a') \right)$$

and

$$g_a \left(\sum_{\theta \in \Theta} \lambda u(\bar{b}(\theta); \theta) \pi(\theta; a) + \varsigma \right) = g_{a'} \left(\sum_{\theta \in \Theta} \lambda u(\bar{b}(\theta); \theta) \pi(\theta; a') + \varsigma \right).$$

Thus $g_a(\lambda x + \varsigma) = f_a(x)$, for all $x \in \{\sum_{\theta \in \Theta} u(\bar{b}(\theta); \theta) \pi(\theta; a) \mid \bar{b} \in B^{cv}\}$ and $a \in A$.

(c) The uniqueness of $\{\pi(\cdot; a)\}_{a \in A}$ and the fact that $\pi(\theta; a) = 0$ if and only if θ is null given a follows from the definition of the probabilities and Claim 2. \square

6.2 Proof of Theorem 2.

The proof of Theorem 2 follows from that of Theorem 1 and the following Lemma.

Lemma 7 *If $|\Theta(a)| \geq 2$ then the following conditions are equivalent:*

(i) *The relation \succsim on \mathbb{C} satisfies (A.1), (A.2), and (A.4).*

(ii) *There exist a real-valued function, f , on \mathbb{R} and positive affine functions $\varphi_{(\theta, a)} : f(\mathbb{R}) \rightarrow \mathbb{R}$, for every $\theta \in \Theta$, such that, for all $a \in A$ and $b, b' \in B$,*

$$(a, b) \succsim (a, b') \Leftrightarrow \sum_{\theta \in \Theta} \varphi_{(\theta, a)} \circ f(b(\theta)) \geq \sum_{\theta \in \Theta} \varphi_{(\theta, a)} \circ f(b'(\theta)).$$

Lemma 7 is implied by Wakker (1989) Theorem IV.2.7 and the assumption that every effect is nonnull for some $a' \in A$.

(a.i) \rightarrow (a.ii) Suppose that (a.i) holds. Lemma 7 and (A.3) imply the representation in Theorem 1 where $w_a(\cdot, \theta) = u(\cdot, \theta) \pi(\theta; a) = \varphi_{(\theta, a)} \circ f(\cdot)$ for every $a \in A$ and $\theta \in \Theta$. Define $u(\cdot) = f(\cdot)$. Then, by Lemma 7 and Theorem 1, for every $\theta \in \Theta$, $u(\cdot, \theta) \pi(\theta; a) = \varphi_{(\theta, a)} u(\cdot)$.

Hence if $\pi(\theta; a) > 0$ then $\varphi_{(\theta,a)}/\pi(\theta; a) > 0$ is independent of a . Let $(\sigma(\theta), \kappa(\theta))$ be, respectively, the multiplicative and additive coefficients characterizing $\varphi_{(\theta,a)}/\pi(\theta; a)$ if $\pi(\theta; a) > 0$. But $\pi(\theta; a) > 0$ for some $a \in A$. Thus, $\sigma(\theta) > 0$. Hence $u(\cdot, \theta) \pi(\theta; a) = [\sigma(\theta) u(\cdot) + \kappa(\theta)] \pi(\theta; a)$. Substitute this in (a.ii) in Theorem 1 to obtain (a.ii).

The proof that (a.ii) implies (a.i) as well as that of parts (b) and (c) are implied by the corresponding arguments in Theorem 1. □

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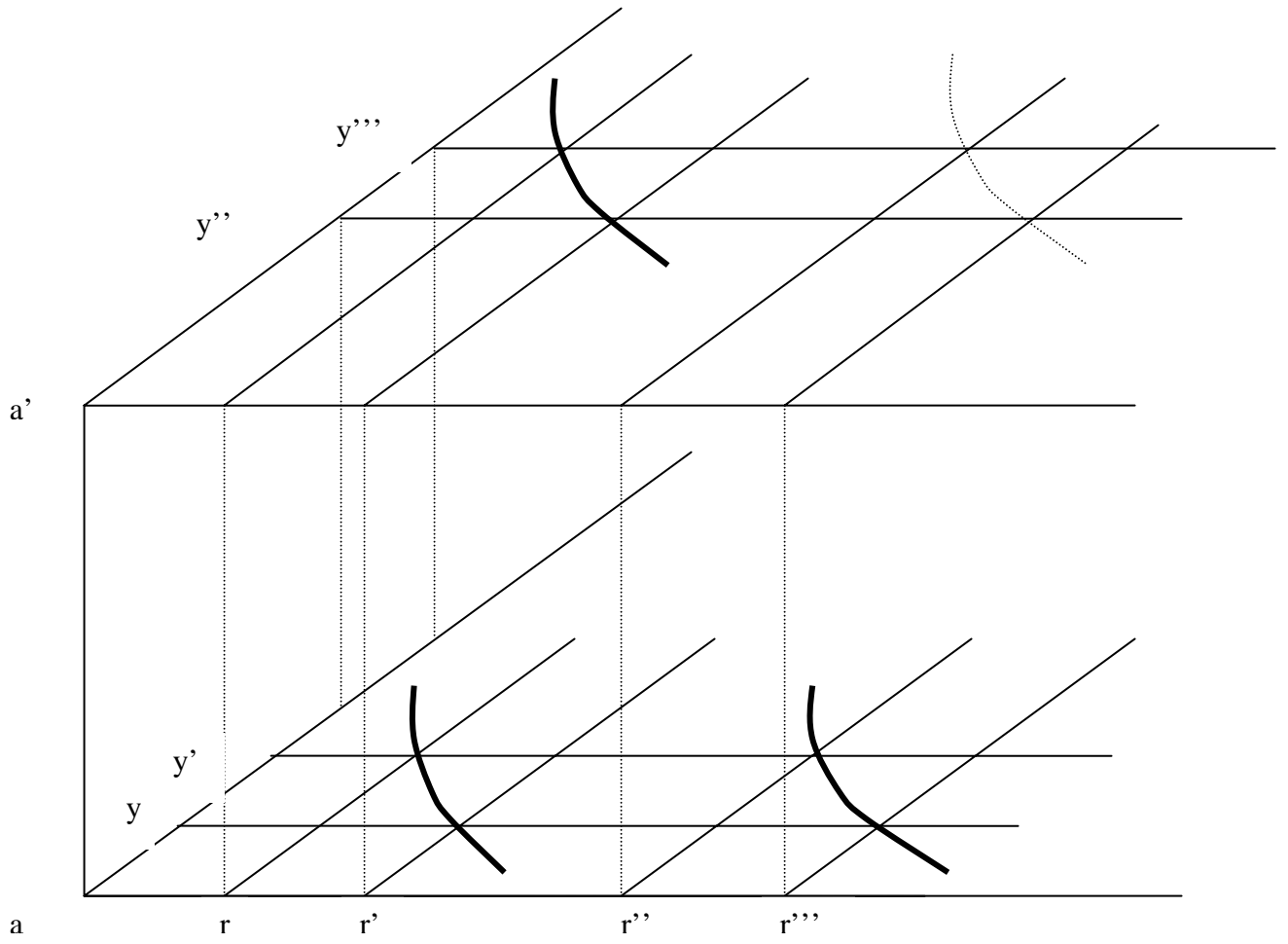


FIGURE 1

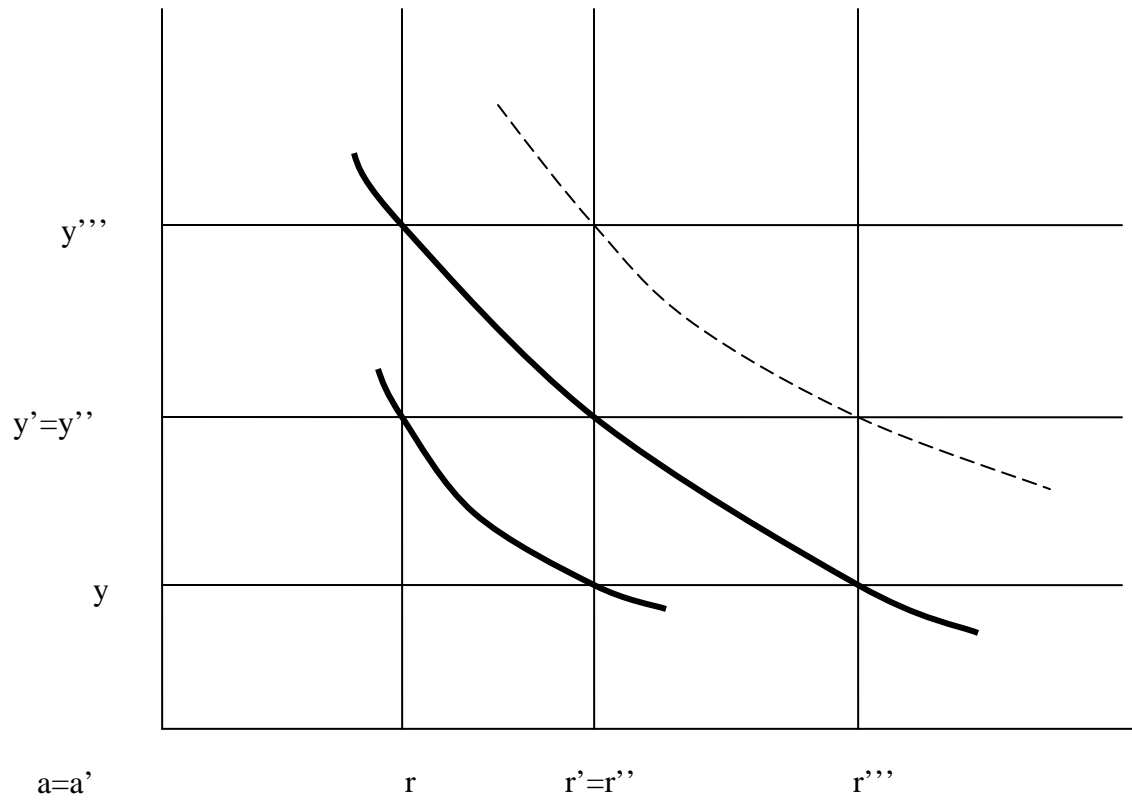


FIGURE 2