

Coarse Contingencies

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Abstract

The paper considers an agent who must choose an action today under uncertainty about the consequence of any chosen action but without having in mind a complete list of all the contingencies that could influence outcomes. She conceives of some relevant (subjective) contingencies but she is aware that these contingencies are coarse - they leave out some details that may affect outcomes. Though she may not be able to describe these finer details, she is aware that they exist and this may affect her behavior.

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1. INTRODUCTION

1.1. Outline

Consider an agent who must choose an action today under uncertainty about the consequence of any chosen action but without having in mind a complete list of all the contingencies that could influence outcomes. She conceives of some relevant (subjective) contingencies or states of the world but she is aware that these contingencies are coarse - they leave out some details that may affect outcomes. Though she may not be able to describe these finer details, she is aware that they exist and this may affect her behavior. How does one model such an agent?

The reason for addressing this question seems clear. Outside of artificial laboratory-style settings, it would seem impossible for any decision-maker to identify all relevant and finely detailed contingencies. A sophisticated agent would be aware of her limited foresight and admit the possibility that her conceptualization of the future is incomplete, and then she would take this into account in her decision-making. Think, for example, of a portfolio choice setting. An investor may identify some factors that are likely to influence returns to financial securities. However, few sophisticated investors would be confident that they have identified all relevant factors. Awareness that her conceptualization is missing some details would presumably influence an investor's choice of portfolio.

The standard Savage approach to modeling uncertainty, using a primitive state space, does not capture the agents we have in mind. It is inappropriate for two reasons. First, each Savage-style state is a complete description of the world - it determines a unique outcome for any chosen action. Second, even if we knew how to model a "coarse or incomplete state" and we redefined the Savage state space accordingly, the resulting approach would still be unsatisfactory if, as in Savage, the state space were adopted as a primitive and thus presumed observable by the modeler. Ideally, the agent's conceptualization of the future should be taken to be subjective - it should be derived from preference, that is, from in principle observable behavior.

Kreps [14, 15] was the first to raise the modeling problem posed above. He, and also subsequent authors, refer to "unforeseen contingencies", but it seems that they have in mind what we prefer to call "coarse contingencies." Kreps' seminal idea was that demand for flexibility is indicative of an individual's awareness of the coarseness of her conception. In order to capture demand for flexibility, his model postulates preference over menus. Nehring [21] and Dekel, Lipman and Rustichini [4] provide alternative extensions. In the models of Kreps and

Nehring, menus consist of alternatives from an abstract (typically finite) set. We focus primarily on the model of Dekel, Lipman and Rustichini (henceforth DLR), where menus consist of lotteries over alternatives. The richer domain permits, given suitable assumptions, the derivation of a (unique) subjective state space as part of the representation of preference. But are these states coarse? DLR describe (p. 893) the agent they view themselves as modeling: “... she sees some relevant considerations, but knows there may be others that she cannot specify. For simplicity, we assume henceforth that the agent conceives of only one situation, ‘something happens,’ but knows that her conceptualization is incomplete.” Later (pp. 919-20), they describe what is needed for a critique of their model: “... just as Ellsberg identified the role of the sure-thing-principle in precluding uncertainty-averse behavior, we believe that one must first find a concrete example of behavior that is a sensible response to unforeseen contingencies but that is precluded by our axioms. An important direction for further research is to see if there is such an Ellsbergian example for this setting and, if so, to explore relaxations of our axioms.” This is the direction we pursue here.

Our central argument is that an agent who is aware of, and averse to, the coarseness of her conceptualization of the future will have an incentive to randomize, and thus will violate Independence. As an example, suppose that her subjective conceptualization is trivial - “something happens”. Suppose further that she is indifferent between committing ex ante to lottery β or to lottery β' . She is aware ex ante that there are unforeseen (finer, or back-of-the-mind) contingencies that could affect the desirability of any action. Though she does not understand these finer details and is not able to describe them, she is nevertheless aware that they exist, and she may feel that some may make β' more desirable ex post and some may make β more desirable. As explained in the next section, randomization may hedge this uncertainty and thus the mixture might be strictly preferable to either lottery.

DLR assume the Independence axiom only in their most restrictive model (the EU additive representation). We focus also on their weakest Independence-style axiom, called Indifference to Randomization (IR), which they adopt (either explicitly or implicitly) in all of their representation theorems.¹ We argue that the case for IR is not clear-cut, at least given a particular conception of coarse perceptions. Thus we are led to explore two alternative directions: one which

¹DLR (p. 911) mention the case where ex post utilities are not vNM in the context of establishing a result regarding minimality of the subjective state space. But such violations are not described as germane to the issue of coarse contingencies.

continues to assume IR and relaxes DLR's Independence axiom, and a second model which differs more substantially from DLR - not only is IR dropped, but the domain of preference is expanded to include *random menus*.² In both cases, we describe axioms for preference that arguably capture coarse perceptions and that characterize functional forms for utility representing preference. The two alternative axiomatic models of preference are the main results of the paper.

1.2. Utility Functions and Interpretations

In DLR's most restrictive model, the utility of any menu x has the form

$$W^{DLR}(x) = \int \max_{\beta \in x} u(\beta) d\mu(u),$$

where μ is a probability measure on ex post vNM utility functions u . (More precise statements will be given below.) Given u , then choice out of x will maximize $u(\beta)$, but ex ante, the agent does not know which preference will prevail ex post. The support of μ , corresponding to the set of ex post preferences that she views as possible, constitutes her subjective state space. To evaluate x , she computes its expected payoff assuming an optimal choice of lottery in each subjective state. Taken literally, the representation suggests that subjective states are foreseen by the agent. They are distinguished rather by being uncontractable, that is, by the fact that we cannot observe the agent's ranking of Savage-style acts over these states. Kreps [15] suggests that one can interpret the functional form alternatively as an "as if" representation for an agent who does not foresee the states, and that it is impossible to distinguish between these two interpretations by observing only choice between menus. However, as sketched above, where menus consist of lotteries then awareness that some states are unforeseen should lead to a preference for randomization, contradicting Independence and hence also representation by W^{DLR} . Therefore, we interpret the DLR model as one where states are foreseen.

For ease of comparison, we describe informally also the two generalization of W^{DLR} axiomatized below. In the model where IR is satisfied, utility of a menu is given by

$$W^{MP}(x) = \min_{\pi \in \Pi} \int \max_{\beta \in x} u(\beta) d\pi(u),$$

where Π is a set of probability measures on the set of ex post vNM utility functions u . (DLR is the special case where Π is a singleton.) As in the interpretation of

²Nehring [20, 21] also adopts the domain of random menus. For more on the connection between our second model and Nehring's work see Appendix C.2.

W^{DLR} , the agent observes the realization of some u and then chooses out of the menu x by maximizing u . In our second model, where IR is violated, utility has the form

$$W(x) = \int \max_{\beta \in x} \min_{u \in U} u(\beta) d\mu(U),$$

where μ is a probability measure over suitable sets U of vNM utilities.

Here what is foreseen is more a matter of interpretation. Regarding W , for example, one could view each U as a *foreseen* coarse state, while the details (or points u) within each U are *unforeseen*, but the agent is aware that each coarse state U leaves unspecified some relevant details. In the special case where every U is a singleton, this interpretation corresponds to the DLR model with every state foreseen; more generally, the concavity of $\min_{u \in U} u(\beta)$ as a function of β implies the incentive to randomize that is intuitive given awareness of the coarseness of U . However, a more literal interpretation of the functional form suggests that even points within each U are foreseen. In that case, the minimization over U suggests complete ignorance within U - the agent foresees and can describe the details within U but has no idea how likely they are.³ From an ex ante perspective, utility can be interpreted as reflecting the expectation of future ambiguity, due to the realization of an ambiguous signal.⁴ Similarly, W^{MP} has the multiple-priors functional form axiomatized by Gilboa and Schmeidler [10], where states are foreseen but ambiguous (in the sense of the Ellsberg Paradox).

The reinterpretation in terms of ambiguity is not surprising given the role in both of our models played by the hedging gains afforded by randomization. As argued by Gilboa and Schmeidler [10], such gains can ensue also if the agent is averse to ambiguity. Indeed, we cannot distinguish the latter story - where the agent foresees a complete set of states but is not sure of their likelihoods - from the story upon which we focus, where the agent is aware of the coarseness of her state space.⁵ Our axioms have intuitive interpretations in both cases, and

³Minimizing over U is equivalent to minimizing over all probability measures on U .

⁴If one overlooks the fact that the state space is exogenous only in [10], then our second model can be viewed as a special case of recursive multiple-priors, a multi-period extension of the Gilboa-Schmeidler model - see Epstein and Schneider [6].

⁵One apparently needs a richer framework to permit a distinction. It seems that “updating” may be one way to distinguish between the two stories. The agent in our model is not thinking explicitly in terms of the fine details within a coarse contingency. But if someone tells him “this specific detail exists”, that might change his perception and thus behavior. On the other hand, such a statement would have no effect on the ambiguity averse agent - he already foresees that

consequently, the functional forms we derive can be interpreted in either way. Thus one can view the paper in two different lights. In one, it contributes to the literature on preferences under ambiguity by deriving representations, including a counterpart of multiple-priors utility, without relying on an exogenously specified state space. The second perspective, and the one that we emphasize, is that the paper shows that the very same models can also be interpreted as capturing coarse contingencies. We emphasize this interpretation because the coarseness of subjective contingencies seems to us to be potentially at least as important as ambiguity, and arguably more basic - the nature of subjective states would seem to be logically prior to the question of their likelihoods - and also because it has not previously been shown how to model agents who are aware of the coarseness of their conceptions.

We are not the first to highlight the connection between coarse perceptions and ambiguity. Mukerji [19] and Ghirardato [9] argue that an agent who is aware that she has only a coarse perception of the state space can be thought of as using a non-additive probability measure (or capacity). Their approach, inspired by Dempster [5] and Shafer [24], is much different than ours in that they take the agent's coarse perception as a primitive, while rendering it subjective is the heart of our model. See Section 4.3 for further discussion.

The paper proceeds as follows. Next we outline the DLR model and argue that their axioms preclude coarse contingencies. Then we describe two alternative models to capture coarseness. Proofs are relegated to appendices.

2. THE DLR MODEL

The DLR model has the following primitives:

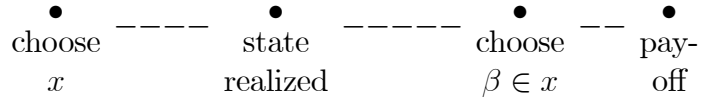
- B : finite set of actions - let $|B| = B$
- $\Delta(B)$: set of probability measures over B , endowed with the weak convergence topology; generic lotteries are $\beta, \beta', \gamma, \dots$
- \mathcal{X} : closed subsets of $\Delta(B)$, endowed with the Hausdorff metric
generic elements are denoted x, x', y, \dots and are called *menus*⁶

detail, and the statement does not give him new information about its likelihood.

⁶DLR do not restrict menus to be closed but this difference from their model is unimportant and we overlook it throughout.

- preference \succeq is defined on \mathcal{X}

The agent ranks menus at time 0 (ex ante) using \succeq with the understanding that at time 1 (ex post), she will choose a lottery from the previously chosen menu (see the time line). One can think of a menu as corresponding to an action to be taken ex ante, where the significance of an ex ante action is that it limits options



for further action ex post, that is, for the choice of β in $\Delta(B)$. There are no exogenous states of the world, but the agent may envisage some scenarios for time 1. She anticipates learning which scenario is realized before making her choice out of the menu. Thus her subjective conceptualization of the future affects her expected choices out of menus and hence also her ex ante evaluation of menus. In other words, her subjective state space underlies the preference \succeq and (under suitable assumptions) is revealed by it.

For example, the ranking

$$\{\beta, \beta'\} \succ \{\beta\} \succ \{\beta'\}$$

reveals that the agent conceives of a circumstance in which she would strictly prefer β over β' and also another circumstance in which she would strictly prefer β' over β . Under DLR's set of axioms, subjective contingencies concern only the possible ex post preference over lotteries. This is natural - payoffs rather than ex post physical states per se are ultimately all that matter.

DLR assume throughout that preference satisfies the following two axioms:

ORDER: \succeq is complete and transitive.

CONTINUITY: For every menu x , the sets $\{y \in \mathcal{X} : y \succeq x\}$ and $\{y \in \mathcal{X} : y \preceq x\}$ are closed.

They occasionally, though not universally, adopt also the next axiom.

MONOTONICITY: For all menus x' and x , $x' \supset x \implies x' \succeq x$.

The axiom states that flexibility has non-negative value. For concreteness, we restrict attention here to models satisfying this property.

The first problematic axiom that we consider is Independence.⁷ It refers to mixtures of two menus as defined by

$$\alpha x + (1 - \alpha) y = \{\alpha\beta + (1 - \alpha)\gamma : \beta \in x, \gamma \in y\}.$$

Formally, the indicated mixture of x and y is another menu and thus when the agent contemplates that menu ex ante, she anticipates choosing out of $\alpha x + (1 - \alpha) y$ ex post. It follows that one should think of the randomization corresponding to the α and $(1 - \alpha)$ weights as taking place at the end - after she has chosen some mixed lottery $\alpha\beta + (1 - \alpha)\gamma$ out of the menu.

INDEPENDENCE: For all menus x', x and y and $0 < \alpha < 1$,

$$x' \succeq x \iff \alpha x' + (1 - \alpha) y \succeq \alpha x + (1 - \alpha) y.$$

In the introduction we asserted that the axiom is not intuitive for an agent who is aware of the incompleteness of her subjective state space. Here we elaborate. The typical rationale for Independence (DLR, p. 905, for example) relies on two claims. First, is the intuitive appeal of the condition

$$x' \succeq x \implies \alpha x' \oplus (1 - \alpha) y \succeq x \oplus (1 - \alpha) y, \quad (2.1)$$

where $\alpha x \oplus (1 - \alpha) y$ denotes the lottery over menus that delivers x with probability α and y with probability $(1 - \alpha)$, and where the lottery is played out immediately, that is, before any subjective uncertainty is resolved. The second claim is that the agent should be indifferent between the mixture $\alpha x + (1 - \alpha) y$ and the two-stage object $\alpha x \oplus (1 - \alpha) y$. The difference between these two ‘mixtures’ is in the timing of the randomization (or coin toss). In the latter, the coin is tossed immediately - a specific menu is realized before the agent sees a subjective state and chooses from the menu. In contrast, in $\alpha x + (1 - \alpha) y$ the randomization is completed only at the end after choice out of the mixed menu. However, we argue that this difference in timing matters when the agent is aware of the incompleteness of her conceptualization, and that it is intuitive only that

$$\alpha x + (1 - \alpha) y \succeq \alpha x \oplus (1 - \alpha) y, \quad (2.2)$$

⁷DLR use the term Independence to refer to a weaker condition than what is stated below. However, the two axioms are equivalent given their continuity axiom.

thus refuting the case for the invariance asserted in Independence.

That the timing of randomization matters can be understood as follows: an agent who is aware of the coarseness of her conception of the future and averse to it might behave as though she were playing a game against a malevolent nature. She suspects that, after realization of a coarse contingency and after she has chosen an action (or lottery) ex post, nature will complete the missing details in a way that is unfavorable for her. Then, randomization that is completed immediately, before nature acts, does nothing to impede persecution by nature. However, when randomization is completed only after nature moves, then nature is at a disadvantage. For example, if $x = \{\beta\}$ and $y = \{\gamma\}$, nature may be able to choose underlying details that lead to a low payoff for β and other (*different*) details that lead to an equally low payoff for γ , but then, in general, she cannot be as effective in sabotaging the mixture $\alpha\beta + (1 - \alpha)\gamma$. The agent can expect this to be true in particular if states in which β leads to a high (low) payoff are those in which γ has a low (high) payoff, that is, if β hedges γ . Though the agent cannot describe these fine states, it suffices that the preceding lies beneath her coarse conception and is in the ‘back of her mind.’ Then late randomization will be preferable, consistent with (2.2), and the latter can be understood as due to the gain from hedging.⁸ The bottom line is that, because of hedging, the agent might exhibit the ranking

$$\{\alpha\beta + (1 - \alpha)\gamma\} \succ \{\beta\} \sim \{\gamma\},$$

violating Independence.

DLR show that in conjunction with completeness, transitivity and suitable continuity, Independence implies the following axiom:⁹

INDIFFERENCE TO RANDOMIZATION (IR): For every menu x ,
 $x \sim co(x)$.

⁸It is well-known in the theory of preference over lotteries, (see [17], for example), that the timing of randomization matters for the normative appeal of Independence if the agent must choose an auxiliary action before the risk is resolved. Independence is intuitive if the coin toss corresponding to the randomization is completed before the action choice, but not if it is completed only after the action must be chosen. The argument here about timing is similar except that it is nature, rather than the agent, who takes the auxiliary action.

⁹ $co(x) = \{\alpha\beta + (1 - \alpha)\beta' : \beta, \beta' \in x, 0 \leq \alpha \leq 1\}$ denotes the convex hull of x . As in the case of Independence, one should think of the randomization as occurring after choice is made out of the menu.

To evaluate this axiom, it is important to understand precisely the meaning of the time line sketched above. It describes the agent's ex ante expectations, for example, that ex post she will be able to choose from the menu that is chosen initially. The critical issue is what information she expects to have at that point. In fact, it may very well be that the true complete (Savage-like) state will be realized before she has to choose out of the menu. But since she does not conceive of them ex ante, she cannot be thinking explicitly in terms of the complete states that might be realized ex post. Rather, given her ex ante conceptualization in terms of coarse contingencies, one natural assumption is that she expects only to know which of these is true before choosing out of the menu. In that case, she expects coarseness to persist even ex post. On the other hand, she need not foresee all the complete states in order to believe that one of them will be realized ex post.¹⁰ Thus an alternative assumption is that the agent anticipates that *some* complete state will be realized ex post. The intuitive appeal of IR depends on which of these assumptions is adopted.

If the agent anticipates that some complete state will be realized ex post, then she can be certain that her ex post preference over lotteries will conform to vNM. Thus she anticipates choosing out of the previously chosen menu x in order to maximize a mixture linear utility over lotteries, which means that she will do as well choosing out of x ex post as out of $co(x)$. Being certain of this ex ante, she will be indifferent between x and $co(x)$. This is the justification for Indifference to Randomization put forth by DLR.

Suppose, however, that coarseness is expected to persist ex post. Then the agent expects to be concerned ex post not only with how any given lottery β will play out, but also with how (payoff-relevant) back-of-the-mind uncertainty will be resolved eventually. Then, just as described above in the discussion of Independence, randomization may be valuable ex post. Anticipating this ex ante, she might strictly prefer $co(x)$ to x , violating IR. Both hypotheses concerning the agent's expectations seem to us to be descriptively plausible. Thus we formulate two alternative axiomatic models - one where IR is imposed and one where the axioms reflect coarse perceptions that are expected to persist.

Finally, we describe the most restrictive utility functional form characterized by DLR - the so-called non-negative additive EU representation. To express it, note that each mixture linear $u : \Delta(B) \rightarrow \mathbb{R}^1$ can be identified with a (unique) vector in $N \subset \mathbb{R}^B$, where the role of the subset N is to normalize vNM utilities

¹⁰Nevertheless, it seems to us that this assumption presumes a higher degree of awareness of the underlying fine states than does the alternative.

so that each u corresponds to a unique ordering of lotteries. (DLR’s specification of N is not important here; later we adopt a different specification.) The utility of any menu has the form

$$W^{DLR}(x) = \int \max_{\beta \in x} u(\beta) d\mu(u), \quad (2.3)$$

where μ is a probability measure on N and $u(\beta) = \sum_{b \in B} \beta(b) u_b = u \cdot \beta$.

3. MODEL 1: SHORT-RUN COARSENESS

Here we consider an agent who has coarse contingencies in mind ex ante, but who expects to see a complete state ex post before choosing out of a menu. As in DLR, preference is defined on the set \mathcal{X} of menus, and satisfies Order, Monotonicity, and Indifference to Randomization. Other axioms are relaxed or modified as we now describe.

First exclude total indifference.

NONDEGENERACY: $x' \succ x$ for some menus x' and x .

Our principal deviation from DLR is to relax Independence. From the argument surrounding (2.1)-(2.2) regarding the gains from hedging, we are led to the following weakening of Independence:

PREFERENCE CONVEXITY: $x' \succeq x \implies \alpha x' + (1 - \alpha)x \succeq x$.

The intuition that ‘hedging’ motives may render randomization valuable recalls the intuition provided in Gilboa and Schmeidler [10] for their relaxation of Independence designed to accommodate ambiguity aversion. In their setting, there is an exogenous set of complete states, objects of choice are acts over these states, and hedging variation across states, which reduces ambiguity, is the rationale for randomization. In the present setting, states or contingencies are subjective and coarse, objects of choice are menus of actions rather than acts, and it is the hedging of variation across “missing details” that is the rationale for randomization. But the basic intuition is similar.

Since Gilboa and Schmeidler [10] work in a different setting, we verify that Preference Convexity can be understood also as arising from the ambiguity aversion of an agent who foresees a complete set of subjective states but who is not sure about their likelihoods. Suppose the agent ex ante foresees each possible

u , an ex post utility function over lotteries. Then she presumably anticipates choosing out of any given menu conditionally on the realization of each u . For example, given x , she anticipates choosing the lottery β_u if u is realized. Thus the menu x is equivalent for her to the (lottery-valued) act given by $u \mapsto \beta_u$. Similarly, x' can be identified with an act $u \mapsto \beta'_u$. Then $x' \succeq x$ translates into the weak preference for the primed act over the unprimed one. If states are ambiguous for her, then, as argued by Gilboa and Schmeidler, she may strictly prefer the α -mixture of these two acts to (β_u) . But the mixed act is feasible for her by choosing conditionally on each u if she has the menu $\alpha x' + (1 - \alpha)x$, and thus she can do at least as well with the latter menu as with x , which ‘proves’ Preference Convexity.

We adopt two additional axioms that are admittedly “excess baggage” - they express ex ante certainty about the payoffs to a specific alternative b_* in B and certainty also that it will be the worst outcome (hence also lottery) ex post.

Fix b_* in B . Define a dominance relation on lotteries by: $\beta \geq_D \beta'$

$$\text{if } \beta(b_*) \leq \beta'(b_*) \text{ and } \beta(b) \geq \beta'(b) \text{ for all } b \neq b_*.$$

Thus β may be obtained from β' by shifting probability mass from b_* to other actions. Since she is certain that b_* will be worst ex post (and that ex post preference will conform to vNM), the agent can be certain that she will prefer β to β' and hence that she would not choose β' (alone) if β is available; that is, β' has no flexibility value if β is feasible ex post. Extend this intuition by first extending the dominance relation to menus. Say that x dominates x' , written $x \geq_D x'$, if for every β' in x' there exists β in x such that $\beta \geq_D \beta'$. If $x \geq_D x'$, the agent can be certain of doing as well choosing out of x as out of $x \cup x'$. This explains the next axiom.

WORST: For all menus x' and x , if $x \geq_D x'$, then $x \sim x \cup x'$.

Given our other axioms, Worst implies that, for all menus x ,

$$\Delta(B) \sim B \succeq x \succeq \{b_*\}, \text{ and } B \succ \{b_*\}.$$

By IR and Monotonicity, $B \sim \Delta(B) \succeq x$. On the other hand, $x \geq_D \{b_*\}$ for any x . Thus Worst and Monotonicity imply that $x \sim x \cup \{b_*\} \succeq \{b_*\}$. Conclude that

$$B \succeq x \succeq \{b_*\}. \tag{3.1}$$

Finally, $B \sim \{b_*\}$ would imply total indifference, contrary to Nondegeneracy.

Though certain that b_* will be worst and $\Delta(B)$ (or B) best, the agent may nevertheless be uncertain about the cardinal payoffs to each; moreover, cardinal payoffs are important when the agent evaluates menus ex ante and must weigh payoffs across all possible contingencies. We assume that, in fact, expected cardinal payoffs to both b_* and $\Delta(B)$ are certain ex ante, where the payoff to $\Delta(B)$ refers to the payoff to the lottery chosen out of $\Delta(B)$ ex post - the chosen lottery, but not its payoff, may vary with the (back-of-the-mind) state. If the cardinal payoffs to b_* and $\Delta(B)$ are certain, then so are the payoffs to all lotteries of the form $x_p = p\Delta(B) + (1-p)b_*$, for any p in the unit interval.¹¹ Therefore, mixing with such lotteries provides no hedging gains, which suggests that the invariance required by Independence should be satisfied for such mixtures. This explains:

CERTAINTY INDEPENDENCE: For all menus x' and x , and $x_p = p\Delta(B) + (1-p)b_*$, and for all $0 < \alpha < 1$,

$$x' \succeq x \iff \alpha x' + (1-\alpha)x_p \succeq \alpha x + (1-\alpha)x_p.$$

Finally, we assume a mild form of continuity à la Herstein and Milnor [12].

MILD CONTINUITY: For all menus x , the sets $\{p \in [0, 1] : x_p \succeq x\}$ and $\{p \in [0, 1] : x_p \preceq x\}$ are closed.

To describe the implied functional form, note that any vNM ex post preference that is not degenerate and that ranks b_* as worst can be identified with a unique vector u in N , where

$$N = \left\{ u \in \mathbb{R}_+^B : u(b_*) = 0, \max_B u(b) = 1 \right\}. \quad (3.2)$$

Note also that¹²

$$\beta \geq_D \beta' \iff u \cdot \beta \geq u \cdot \beta' \text{ for all } u \text{ in } N. \quad (3.3)$$

Our first model is summarized in:

¹¹ $p\Delta(B) + (1-p)b_* = \{pq + (1-p)\delta_{b_*} : q \in \Delta(B)\}$, a menu of lotteries.

¹²If there exists $b' \neq b_*$ such that $\beta(b') < \beta'(b')$, then $u \cdot \beta < u \cdot \beta'$ for u defined by $u_{b'} = 1$ and $u_b = 0$ for $b \neq b'$.

Theorem 3.1. *Preference \succeq on \mathcal{X} satisfies Order, Monotonicity, Indifference to Randomization, Nondegeneracy, Preference Convexity, Worst, Certainty Independence and Mild Continuity, if and only if it admits a representation by $W^{MP} : \mathcal{X} \rightarrow \mathbb{R}$ of the form:*

$$W^{MP}(x) = \min_{\pi \in \Pi} \int \max_{\beta \in x} u(\beta) d\pi(u), \quad (3.4)$$

where Π is a convex and weak*-compact set of Borel probability measures on N .

Moreover, there exists Π that is smallest (in the sense of set inclusion) amongst sets satisfying the above. The set Π is a singleton (and so W^{MP} has the DLR form) if and only if, for all $x, x' \in \mathcal{X}$ and all $\alpha \in [0, 1]$,

$$x \sim x' \implies \alpha x + (1 - \alpha)x' \preceq x. \quad (3.5)$$

If preference satisfies Independence, then every menu satisfies (3.5), and the theorem yields (a variant of) the DLR representation result for the non-negative additive EU representation (2.3). We argued above that their model does not capture coarseness. More generally, on the surface the multiple-priors representation does not seem to suggest coarse contingencies as much as ambiguity. However, since we have shown that the underlying axioms, including Preference Convexity, are well motivated by coarseness, it follows that the resulting functional form can be understood as modeling coarseness.

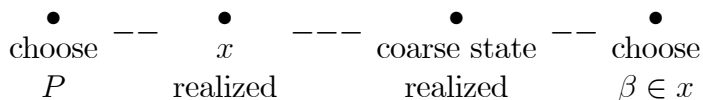
An interpretation in terms of ambiguity is also warranted. We pointed out earlier that the axioms, particularly Preference Convexity, are intuitive also for an agent who foresees complete states whose likelihoods are ambiguous. Thus the theorem can be viewed as extending Gilboa and Schmeidler's [10] multiple-priors utility model by dispensing with an exogenous state space. At a formal level, Theorem 3.1 is not a trivial variation of the representation result in [10]. Our axioms deliver a (superlinear and translation invariant) preference functional defined only on the convex cone of support functions, a meagre subset of the set of all continuous functions on N ; in particular, the cone has an empty interior under the supnorm topology. For this reason we have to use different techniques than the ones used in [10], and we exploit the notion of niveloid developed in [16]. The smallness of the domain on which the preference functional is defined results in the non-uniqueness of the set Π of the representation (3.4), the domain not being big enough to pin down a single set of priors, but only a smallest one.

4. MODEL 2: PERSISTENT COARSENESS

Section 2 argued that IR is not intuitive if ex ante coarseness is expected to persist. Here we describe a second model designed to capture this conception of coarseness. We deviate more drastically from DLR, beginning with the adoption of an expanded domain for preference - we assume that the agent ranks not only menus but all *random menus*. In this respect, and also in the nature of our central axiom called Dominance, our approach is closer to that of Nehring [20, 21], as it has been developed and generalized by Epstein and Seo [7].

The sets B , $\Delta(B)$ and \mathcal{X} are as above.

Preference \succeq is defined on $\Delta(\mathcal{X})$.¹³ Generic elements of $\Delta(\mathcal{X})$ are denoted P, P', Q, \dots and are referred to as random menus. As indicated by the time line below, for any random menu P chosen ex ante, a menu x is realized next, and then, as in DLR and in our first model, the agent expects to see some subjective



uncertainty resolved and finally to choose from the realized menu. A difference from our first model is that here, if she thinks in terms of coarse contingencies ex ante, then she expects only to see one of those coarse contingencies ex post.

4.1. Utility

There is uncertainty ex ante about ex post preferences over lotteries. Ex post payoff functions are continuous functions $v : \Delta(B) \rightarrow \mathbb{R}$ satisfying suitable normalizations. To express them, fix two actions b_* and b^* , identified with degenerate lotteries, interpreted as the worst and best lotteries ex post. This exacerbates somewhat the problem of “excess baggage” in our first model, since we now assume that not only the worst, but also the best lottery is fixed exogenously. Every vNM

¹³ \mathcal{X} is compact metric (and so Polish) under the Hausdorff metric. It is endowed with the Borel σ -algebra. Thus $\Delta(\mathcal{X})$ is the set of Borel probability measures. It is also compact Polish under the weak-convergence topology. $\Delta(X)$ has similar meaning for any metric space X .

ex post preference over lotteries that (is not total indifference and that) ranks b_* as worst and b^* as best may be represented by some u in N^* , where

$$N^* = \left\{ u \in [0, 1]^B : u(b_*) = 0, u(b^*) = 1 \right\}.$$

However, the agent does not conceive of all of these possibilities ex ante - rather she thinks in terms of subsets of N^* . Denote by $\mathcal{K}(N^*)$ the set of closed subsets of N^* , endowed with the Hausdorff metric, which renders it compact metric. Say that $U \subset N^*$ is *comprehensive* if $U = \{u' \in N^* : u' \geq u \text{ for some } u \in U\}$. Denote by $\mathcal{K}^{cc}(N^*)$ the set of closed, convex and comprehensive subsets of N^* . (Then $\mathcal{K}^{cc}(N^*)$ is also compact metric.)

The utility of any random menu P is given by

$$\mathcal{W}(P) = \int_{\mathcal{X}} \left(\int_{\mathcal{K}^{cc}(N^*)} \max_{\beta \in x} \min_{u \in U} u(\beta) d\mu(U) \right) dP(x), \quad (4.1)$$

for some Borel probability *measure* $\mu \in \Delta(\mathcal{K}^{cc}(N^*))$. Say that μ *represents* the corresponding preference.

To interpret, note first that preference conforms to vNM theory when evaluating lotteries over menus - it has the expected utility form

$$\mathcal{W}(P) = \int_{\mathcal{X}} W(x) dP(x),$$

for the vNM index $W : \mathcal{X} \rightarrow \mathbb{R}$ given by

$$W(x) = \int_{\mathcal{K}^{cc}(N^*)} \max_{\beta \in x} \min_{u \in U} u(\beta) d\mu(U), \quad x \in \mathcal{X}. \quad (4.2)$$

Since W represents the ranking of (nonrandom) menus, it can be compared with DLR's utility function (2.3), to which W reduces if μ has support on singletons.¹⁴ More generally, the functional form suggests the following interpretation: the agent foresees coarse contingencies represented by sets U in the support of μ . Since she does not think explicitly in terms of finer contingencies, she anticipates choosing out of the menu x conditionally on each of these possible coarse contingencies. But she is aware ex ante that each set U leaves out some relevant missing details. Further, she anticipates that she will continue to be aware of the

¹⁴More precisely, since μ is defined only on comprehensive sets, DLR is the special case where μ has support on sets of the form $\{u' \in N^* : u' \geq u\}$ for some u in N^* .

presence of missing details also given the realization of any particular U . This anticipation is captured by the fact that for any lottery β , its anticipated utility conditional on U is given by $\min_{u \in U} u(\beta)$. (In particular, the ex post utility function over lotteries, given by $\beta \mapsto \min_{u \in U} u(\beta)$, is not a vNM functional.) Thus, given U , it is anticipated that a lottery will be chosen from x so as to solve $\max_{\beta \in x} \min_{u \in U} u(\beta)$. This leads to the evaluation of x shown in (4.2).

Note that the restriction to sets U that are convex and comprehensive is wlog - for any closed set U , $\min_{u \in U} u(\beta)$ is unchanged if we replace U by its convex hull, or if we add to U points u' in N^* such that $u' \geq u$ for some $u \in U$. The normalization to convex and comprehensive sets will permit us to show below that the representing measure μ is unique.

As in our first model, utility can be interpreted alternatively as modeling ambiguity. The functional form (4.2) might describe an agent who conceives ex ante of the complete states in N^* , but does not expect to see the true state ex post. Rather, she expects only a “signal” U to be realized ex post. There is no prior ambiguity about the likelihoods of signals; however, each signal is “ambiguous” - it will inform the agent that the true state u lies in U , but leave her completely ignorant otherwise. This is a special case of recursive multiple-priors utility studied by Epstein and Schneider [6] (though the information structure is exogenous there and subjective here).

Finally, for perspective, consider the alternative functional form obtained by reversing the order of the *max* and *min* appearing inside the integral in (4.2), that is, consider

$$W^{rev}(x) = \int \min_{u \in U} \max_{\beta \in x} u(\beta) d\mu(U), \quad x \in \mathcal{X}. \quad (4.3)$$

In general, W^{rev} is ordinally distinct from W . This is suggested by the fact that the minimax theorem justifying such reversals of order requires that both sets x and U be convex, but menus need not be convex. Preference represented by W^{rev} satisfies all the assumptions of Theorem 3.1, including IR, and so it is a special case of that model. (Appendix B describes a “concrete” set Π that provides the multiple-priors representation.) However, preference represented by W violates IR in general.

4.2. Axioms and Representation Result

Let \succeq be a preference order on $\Delta(\mathcal{X})$. We assume that it is complete and transitive (Order), continuous in the usual sense (Continuity), and that it is not total

indifference (Nondegeneracy).

We also assume that preference satisfies a form of independence. To distinguish it from the Independence axiom in DLR, we give it another name.

FIRST-STAGE INDEPENDENCE: For all random menus P, P' and Q and for all $0 < \alpha < 1$, $P' \succeq P \iff \alpha P' + (1 - \alpha) Q \succeq \alpha P + (1 - \alpha) Q$.

Since a mixture such as $\alpha P + (1 - \alpha) Q$ is a random menu, it follows from the time line described above that a specific menu is realized before the agent sees a subjective state and chooses from the menu. In particular, therefore, all randomization in both component measures P and Q , as well as in the mixing is completed before then. As explained in our discussion of the DLR model, this difference in timing differentiates First-Stage Independence from DLR's Independence, and there are no hedging gains from immediate randomization.¹⁵

Our key axiom is adapted from [20, 21] and [7]. Its statement makes use of the fact that, by [1, Theorem 3.63], $\{x \in \mathcal{X} : x \subset G\}$ is open in \mathcal{X} for every open subset $G \subset \Delta(B)$. Therefore, for any menu y ,

$$\{x \in \mathcal{X} : x \cap y \neq \emptyset\} = \mathcal{X} \setminus \{x \in \mathcal{X} : x \subset \Delta(B) \setminus y\}$$

is closed, hence Borel measurable.

Let Y be a set of menus, each of which is interpreted as an upper contour set for some ex post preference order that the agent views as possible. We assume:

DOMINANCE: If $P'(\{x \in \mathcal{X} : x \cap y \neq \emptyset\}) \geq P(\{x \in \mathcal{X} : x \cap y \neq \emptyset\})$ for all menus y in Y , then $P' \succeq P$.

Say that P' *dominates* P if the condition in the axiom is satisfied.

Consider two implications of the axiom.¹⁶ First, when $P' = \delta_{x'}$ and $P = \delta_x$ are degenerate, then $\delta_{x'}$ dominates δ_x if $x' \supset x$. Therefore, Dominance implies Monotonicity:

$$x' \supset x \implies x' \succeq x.$$

¹⁵First-Stage Independence corresponds to, and generalizes, condition (2.1). A difference is that since only here is preference defined on random menus, then only here is the axiom formally meaningful.

¹⁶Nehring [20, 21] makes a similar observation for his setting.

It also implies (given First-Stage Independence) Kreps' second key axiom [14, condition (1.5)]: given any menus x and x' , let

$$P' = \frac{1}{2}\delta_x + \frac{1}{2}\delta_{x'} \text{ and } P = \frac{1}{2}\delta_{x \cap x'} + \frac{1}{2}\delta_{x \cup x'}. \quad (4.4)$$

Then P' dominates P , and thus Dominance implies that

$$\frac{1}{2}\delta_x + \frac{1}{2}\delta_{x'} \succeq \frac{1}{2}\delta_{x \cap x'} + \frac{1}{2}\delta_{x \cup x'}.$$

Deduce from First-Stage Independence that

$$\delta_{x'} \sim \delta_{x \cap x'} \implies \delta_x \succeq \delta_{x \cup x'}.$$

Since Monotonicity is also implied, we have finally that (in the obvious notation)

$$x \cap x' \sim x' \implies x \sim x \cup x',$$

which is equivalent to Kreps' axiom.¹⁷

To understand further the meaning of the axiom, think of each y in Y as an upper contour set for some conceivable ex post preference. Thus lotteries in y are “desirable” according to that ex post preference and $x \cap y \neq \emptyset$ indicates that x contains at least one desirable action, in which case we might refer to x as being desirable. Accordingly, P' dominates P if the probability of the realization of a desirable menu is larger under P' , **and** if this is true for every set y and hence for every conceivable definition of “desirable.” The set Y specifies which upper contour sets are relevant, or, in other words, Dominance for the given Y implies certainty that ex post upper contour sets will lie in Y .

The content of the axiom depends on the specification of Y which we now describe. Fix actions b_* and b^* , and say that β' is an *elementary improvement* of β if *either*

$$\begin{aligned} \beta' - \beta &= \kappa\delta_{b^*} - \kappa\delta_b \text{ for some } b \neq b^*, \text{ or} \\ \beta' - \beta &= -\kappa\delta_{b_*} + \kappa\delta_b \text{ for some } b \neq b_*. \end{aligned}$$

In the first case, probability mass is shifted from some outcome b to b^* and in the second mass is shifted from b_* to some other outcome. Both shifts are unambiguous improvements if b^* and b_* are the best and worst actions respectively. In particular, if that is the case, then β' dominates β in the sense of the first-order-stochastic dominance relation induced by the ranking of actions.

Assume that Y consists of all nonempty sets y satisfying the following properties:¹⁸

¹⁷The latter is usually stated in the form $x \sim x' \cup x \implies x \cup x'' \sim x' \cup (x \cup x'')$.

¹⁸ β_p denotes the lottery $(b^*, p; b_*, 1 - p)$.

Y1 y is closed and convex

Y2 If β' is an elementary improvement of β , and $\beta \in y$, then $\beta' \in y$

Y3 $[\beta^0 \notin y, \beta_q \notin y \text{ for all } q < p] \implies \alpha\beta^0 + (1 - \alpha)\beta_p \notin y \text{ for all } \alpha > 0$

To interpret these conditions in the context of Dominance, think again of Y as consisting of ex post upper contour sets that the agent thinks possible ex ante. For Y1, y being closed reflects certainty that ex post preferences will be (upper semi) continuous. Convexity expresses the certainty that randomization will be (weakly) valuable. The expectation of indifference to randomization ex post would be captured by adding the requirement that the complement y^c (a strict lower contour set) also be convex.¹⁹ The absence of this requirement permits a role for randomization ex post.

Property Y2 states that any elementary improvement of a lottery in an upper contour set y is also in y . Thus it expresses certainty that b^* and b_* are the best and worst actions respectively. An immediate implication is that

$$[\beta_q \in y \text{ and } p > q] \implies \beta_p \in y. \quad (4.5)$$

Iterating Y2 yields that

$$b^* \in y \text{ for every } y,$$

and $b_* \in y$ implies $y = \Delta(B)$.

Turn finally to Y3. Let $\beta^0 \notin y$, and suppose also that $\beta_p \notin y$, which, by (4.5), is stronger than the stated hypothesis. We argued above that randomization can be valuable to hedge coarseness. But suppose that, after realization of some coarse contingency, the agent is certain not only that b^* will be best ex post, but also that its payoff is constant across all back-of-the-mind details; and similarly for b_* . Thus there is conditional certainty about the *cardinal* payoffs to b^* and b_* , from which it follows that there should be conditional certainty also about the cardinal payoffs to all mixtures $\beta_p = (b^*, p; b_*, 1 - p)$. But then mixing with β_p (or with any β_q) should provide no hedging gains. In that case, the agent should not expect $\alpha\beta^0 + (1 - \alpha)\beta_p$ to be better than both component lotteries, each of which is undesirable (in the sense of not lying in y). In other words, $\alpha\beta^0 + (1 - \alpha)\beta_p \notin y$.

¹⁹Suppose that y^c is convex for every y in Y . Then $y \cap x = \emptyset \implies x \subset y^c \implies co(x) \subset y^c \implies y \cap co(x) = \emptyset$, and δ_x dominates $\delta_{co(x)}$. By Dominance, therefore, $x \succeq co(x)$. Thus they must be indifferent by Monotonicity.

Finally, suppose that β_p does indeed lie in y , but only barely in the sense that $\beta_q \notin y$ for all $q < p$. Since y is closed and $\beta^0 \notin y$, it falls short by a discrete amount from being desirable according to y . Since β_p is just barely in y , mixing with β_p is not enough to compensate for the deficiency in β^0 . Therefore, again we conclude that $\alpha\beta^0 + (1 - \alpha)\beta_p \notin y$.

If the cardinal payoffs to b^* and b_* are expected to be certain conditional on each coarse contingency, then not only should randomization with any β_p be of no value ex post, as just argued in connection with Y3, but also ex ante there should be no hedging gains. But hedging gains were the only reason for arguing that the timing of randomization should matter and hence that indifference in (2.2) is not intuitive. This explains the final axiom:²⁰

CERTAINTY REVERSAL OF ORDER: For every menu $x' \in \mathcal{X}$, $0 < \alpha < 1$ and $0 \leq p \leq 1$,

$$\alpha x' \oplus (1 - \alpha) \{\beta_p\} \sim \alpha x' + (1 - \alpha) \{\beta_p\}.$$

We can now state our second main result.

Theorem 4.1. *\succeq satisfies Order, Continuity, Nondegeneracy, First-Stage Independence, Dominance and Certainty Reversal of Order if and only if it has a representation of the form (4.1). Moreover, the representing measure μ in (4.1) is unique.*

Uniqueness of the representing measure may be surprising at first - as DLR point out for their model, state-dependence is inherent when the state space is subjective, and it is well-known that state dependence complicates the identification of probabilities. The problem is avoided here because of the assumption that payoffs to b_* and b^* are constant - this is enough state independence to identify probabilities. Consequently, *both* the subjective coarse state space (the support of μ) *and* ex ante beliefs about coarse contingencies are determined given preference over random menus.

If Certainty Reversal of Order is strengthened so as to apply to all pairs of menus, that is, to require indifference in (2.2) for all x' and x , then First-Stage Independence implies Independence, and all subjective states are singletons (up

²⁰In more accurate but less friendly notation, the axiom asserts that $\alpha\delta_{x'} + (1 - \alpha)\delta_{\{\beta_p\}} \sim \delta_{\alpha x' + (1 - \alpha)\{\beta_p\}}$.

to being comprehensive) as in DLR - coarseness is excluded. Alternatively, the latter model is obtained if Dominance is strengthened by shrinking Y so that, in addition to $Y1 - Y3$, every y in Y is required to have a convex complement (which leads to indifference to randomization (IR)).

4.3. Dempster and Shafer-Style Models

Finally, we relate the model (4.2) to the Dempster-Shafer-style models of Mukerji [19] and Ghirardato [9] mentioned in the introduction. They suppose that while there exists a Savage-style state space S , the agent does not conceive of all the complete states in S and has coarse perceptions. These are modeled through an auxiliary epistemic state space Ω and a correspondence Γ from Ω into S . (See the figure below.) There is a probability measure p representing beliefs on Ω .

$$\begin{array}{ccc}
 (\Omega, p) & \xrightarrow{\Gamma} & (S, \nu) \\
 & \searrow \hat{f} & \downarrow f \\
 & & X
 \end{array} \tag{4.6}$$

Unlike a Savage agent who would view each physical action as an act from S to the outcome set X , and who would evaluate it via its expected utility (using a probability measure on S), the present agent views each action as a (possibly multi-valued) act on Ω .

Ghirardato assumes that each \hat{f} is multi-valued where the nonsingleton nature of $\hat{f}(\omega)$ reflects her awareness that ω is a coarse contingency. Its utility is given by

$$V^G(\hat{f}) = \int_{\Omega} \left(\min_{x \in \hat{f}(\omega)} u(x) \right) dp.$$

In this formulation, both Ω and the acts \hat{f} are taken to be objective and hence observable to the analyst. One can view our model (4.2) as one possible way to render them subjective: take $X = \mathbb{R}^1$, $\Omega = \text{Supp}(\mu) \subset \mathcal{K}^{cc}(N^*)$, and $p = \mu$, where μ is the measure appearing in our representation; and identify each lottery β in $\Delta(B)$ with the multi-valued act $\hat{\beta}$,

$$\hat{\beta} : U \longrightarrow \{u(\beta) : u \in U\}.$$

Then

$$V^G(\hat{\beta}) = \mathcal{W}(\{\beta\}).$$

Turn to the rest of the triangle (4.6). It is commutative if $\widehat{f}(\omega) = f(\Gamma(\omega))$. This is satisfied in our model if we take $S = N^*$ and $\Gamma(U) = U \subset N^*$.

Finally, we can write

$$V^G(\widehat{f}) = \int_S u(f) d\nu(s),$$

where ν is the non-additive measure or capacity

$$\nu(A) = \mu(\{\omega : \Gamma(\omega) \subset A\}),$$

and the integral on the right is in the sense of Choquet (see Schmeidler [23]).²¹ Since Schmeidler's Choquet expected utility model was devised in order to accommodate ambiguity, this demonstrates once again the close connection between coarse perceptions and ambiguity.

Though there are differences in detail, similar remarks apply to Mukerji [19]; in particular, our model can be viewed as a way to endogenize the state spaces Ω and S , as well as the correspondence Γ , all of which are taken as primitives by Mukerji.

A. Appendix: Proof of Theorem 3.1

This appendix proves Theorem 3.1. Necessity is immediate; for example, IR is satisfied because

$$\max_{\beta \in x} u \cdot \beta = \max_{\beta \in co(x)} u \cdot \beta, \text{ for any } x.$$

The proof of sufficiency is quite long. We provide the complete argument here, including preliminary results on niveloids that are formulated for a more abstract setting and that extend some results of [16]. Proof of the minimality of the set Π is based on a result of Ergin and Sarver [8].

A.1. Preliminaries

Begin with some preliminaries. Let C be a convex subset of some normed vector space. A function $h : C \rightarrow \mathbb{R}$ is quasiconvex if

$$h(t\beta' + (1-t)\beta'') \leq \max\{h(\beta'), h(\beta'')\}, \quad \forall \beta', \beta'' \in C.$$

²¹More precisely, it corresponds to the special case where ν is a belief function.

It is quasiconcave if $-f$ is quasiconvex, and it is quasimonotone if it is both quasiconvex and quasiconcave.

The following result is due to [11, p. 1559].

Lemma A.1. *Let $h : C \rightarrow \mathbb{R}$ be continuous. Then h is quasimonotone if and only if the sets $\{\beta : h(\beta) = c\}$ are convex for all $c \in \mathbb{R}$.*

Suppose K is a compact set in some topological space, and let $h : C \rightarrow \mathbb{R}$ be given by

$$h(\beta) = \min_{y \in K} T(\beta, y), \quad (\text{A.1})$$

where $T : C \times K \rightarrow \mathbb{R}$ is continuous on K and affine on C , i.e., for each $\beta', \beta'' \in C$,

$$T(t\beta' + (1-t)\beta'', y) = tT(\beta', y) + (1-t)T(\beta'', y), \quad \forall y \in K. \quad (\text{A.2})$$

The function $h : C \rightarrow \mathbb{R}$ defined in (A.1) is easily seen to be concave.

Define

$$\Theta(\beta) = \arg \min_{y \in K} T(\beta, y), \quad \forall \beta \in C.$$

Say that h is affine on some convex subset $Q \subseteq C$ if $h(\lambda\beta_1 + (1-\lambda)\beta_2) = \lambda h(\beta_1) + (1-\lambda)h(\beta_2)$ for all $\lambda \in [0, 1]$ and all $\beta_1, \beta_2 \in Q$.

Lemma A.2. (i) *For any finite collection $\{\beta_i\}_{i \in I} \subseteq C$,*

$$h\left(\sum_{i=1}^n \lambda_i \beta_i\right) = \sum_{i=1}^n \lambda_i h(\beta_i) \quad (\text{A.3})$$

for some collection $\{\lambda_i\}_{i \in I}$ with $\lambda_i \in (0, 1)$ and $\sum_{i \in I} \lambda_i = 1$, iff $\cap_{i \in I} \Theta(\beta_i) \neq \emptyset$. In this case, $\cap_{i \in I} \Theta(\beta_i) = \Theta(\sum_{i=1}^n \lambda_i \beta_i)$.

(ii) *Let $Q \subseteq C$ be a convex set. Then h is affine on Q iff $\cap_{\beta \in Q} \Theta(\beta) \neq \emptyset$.*

(iii) *Given $c \in \mathbb{R}$, the set $h^{-1}(c) = \{\beta \in C : h(\beta) = c\}$ is convex only if $\cap_{\beta \in h^{-1}(c)} \Theta(\beta) \neq \emptyset$.*

Proof. In points (i) and (ii) we prove the “only if”, the converse being trivial.

(i) Let $\hat{y} \in \Theta(\sum_{i=1}^n \lambda_i \beta_i)$ and $\hat{y}_i \in \Theta(\beta_i)$ for $i \in I$. As $T(\cdot, \hat{y})$ is affine, by (A.3) we have:

$$\sum_{i=1}^n \lambda_i T(\beta_i, \hat{y}) = T\left(\sum_{i=1}^n \lambda_i \beta_i, \hat{y}\right) = \sum_{i=1}^n \lambda_i T(\beta_i, \hat{y}_i). \quad (\text{A.4})$$

On the other hand, $\widehat{y}_i \in \Theta(\beta_i)$ implies:

$$T(\beta_i, \widehat{y}_i) \leq T(\beta_i, \widehat{y}), \quad \forall i \in I.$$

Hence, by (A.4) we have

$$\sum_{i=1}^n \lambda_i T(\beta_i, \widehat{y}) = \sum_{i=1}^n \lambda_i T(\beta_i, \widehat{y}_i),$$

which in turn implies $T(\beta_i, \widehat{y}) = T(\beta_i, \widehat{y}_i)$ for each $i \in I$. This shows that $\Theta(\sum_{i=1}^n \lambda_i \beta_i) \subseteq \cap_{i \in I} \Theta(\beta_i)$. The converse inclusion is trivial, and we conclude that $\Theta(\sum_{i=1}^n \lambda_i \beta_i) = \cap_{i \in I} \Theta(\beta_i) \neq \emptyset$.

(ii) Suppose h is affine on Q . As Q is convex, this implies that $h(\sum_{i=1}^n \lambda_i \beta_i) = \sum_{i=1}^n \lambda_i h(\beta_i)$ for any finite collection $\{\beta_i\}_{i \in I} \subseteq Q$, and any $\{\lambda_i\}_{i \in I}$ with $\lambda_i \in [0, 1]$ and $\sum_{i \in I} \lambda_i = 1$. By the previous point, $\cap_{i \in I} \Theta(\beta_i) \neq \emptyset$. As all sets $\Theta(\beta)$ are compact, the Finite Intersection Property implies that $\cap_{\beta \in Q} \Theta(\beta) \neq \emptyset$.

(iii) Let $\beta_1, \beta_2 \in h^{-1}(c)$. As $h^{-1}(c)$ is convex,

$$h(\lambda \beta_1 + (1 - \lambda) \beta_2) = \lambda h(\beta_1) + (1 - \lambda) h(\beta_2), \quad \forall \lambda \in [0, 1].$$

By the previous point, $\cap_{\beta \in h^{-1}(c)} \Theta(\beta) \neq \emptyset$. ■

Lemma A.3. *Let $Q \subseteq C$ be a convex set and suppose h is continuous. Then h is affine on Q if and only if h is quasiconvex on Q and there exists $\gamma \in Q$ such that, for all $\lambda \in [0, 1]$ and all $\beta \in Q$,*

$$h(\beta) \geq h(\gamma) \quad \text{and} \quad h(\lambda \beta + (1 - \lambda) \gamma) = \lambda h(\beta) + (1 - \lambda) h(\gamma).$$

In this case, there exists $y \in K$ such that

$$h(\beta) = T(\beta, y), \quad \forall \beta \in Q. \tag{A.5}$$

Proof. For “only if”, take $\gamma \in \arg \min_{\beta \in \Delta(B)} h(\beta)$. Consider now the “if” part. First observe that h is quasimonotone, and so by Lemma A.1 its level sets $h^{-1}(c) = \{\beta : h(\beta) = c\}$ are convex for all $c \in \mathbb{R}$. By Lemma A.2(iii),

$$\cap_{\beta \in h^{-1}(c)} \Theta(\beta) \neq \emptyset, \quad \forall c \in \mathbb{R}. \tag{A.6}$$

Set $\widetilde{Q} = \{\beta \in Q : h(\beta) > h(\gamma)\}$. Let $\beta_1, \beta_2 \in \widetilde{Q}$, and suppose $h(\beta_1) \geq h(\beta_2)$. If $h(\beta_1) = h(\beta_2)$, then

$$h(\lambda \beta_1 + (1 - \lambda) \beta_2) = \lambda h(\beta_1) + (1 - \lambda) h(\beta_2), \quad \forall \lambda \in [0, 1]$$

since h is quasimonotone. Suppose $h(\beta_1) > h(\beta_2)$. There exists $\lambda \in (0, 1)$ such that $h(\beta_2) = \lambda h(\beta_1) + (1 - \lambda) h(\gamma) = h(\lambda\beta_1 + (1 - \lambda)\gamma)$. Set $c = h(\beta_2)$. By (A.6), there is $\hat{y} \in \Theta(\beta_2) \cap \Theta(\lambda\beta_1 + (1 - \lambda)\gamma)$. Hence,

$$\begin{aligned} h(\lambda\beta_1 + (1 - \lambda)\gamma) &= T(\lambda\beta_1 + (1 - \lambda)\gamma, \hat{y}) \\ &\geq \lambda T(\beta_1, \hat{y}) + (1 - \lambda) T(\gamma, \hat{y}) \\ &\geq \lambda h(\beta_1) + (1 - \lambda) h(\gamma) \\ &= h(\lambda\beta_1 + (1 - \lambda)\gamma), \end{aligned}$$

so that $T(\beta_1, \hat{y}) = h(\beta_1)$. Hence, $\hat{y} \in \Theta(\beta_1)$, and we conclude that $\Theta(\beta_1) \cap \Theta(\beta_2) \neq \emptyset$. By Lemma A.2(i), $h(\lambda\beta_1 + (1 - \lambda)\beta_2) = \lambda h(\beta_1) + (1 - \lambda) h(\beta_2)$ for all $\lambda \in [0, 1]$, and so the function h is affine on \tilde{Q} .

Let $\bar{\beta} \in Q$ be such that $h(\bar{\beta}) = h(\gamma)$. If $\beta^* \in Q$ is also such that $h(\beta^*) = h(\gamma)$, then $h(t\beta^* + (1 - t)\bar{\beta}) = th(\beta^*) + (1 - t)h(\bar{\beta})$ since h is quasimonotone. Suppose that $\beta^* \in \tilde{Q}$. Given $\lambda \in [0, 1]$, set $\beta_\lambda = \lambda\beta^* + (1 - \lambda)\bar{\beta}$. Since h is concave and $h(\beta^*) > h(\bar{\beta})$, we have

$$h(\beta_\lambda) \geq \lambda h(\beta^*) + (1 - \lambda) h(\bar{\beta}) > h(\bar{\beta}), \quad \forall \lambda \in (0, 1].$$

and so $\beta_\lambda \in \tilde{Q}$ for each $\lambda \in (0, 1]$. By the continuity of h , we then have:

$$\begin{aligned} th(\beta^*) + (1 - t)h(\bar{\beta}) &= \lim_{\lambda \rightarrow 0} th(\beta^*) + (1 - t)h(\beta_\lambda) \\ &= \lim_{\lambda \rightarrow 0} h(t\beta^* + (1 - t)\beta_\lambda) \\ &= h(t\beta^* + (1 - t)\bar{\beta}), \end{aligned}$$

and so we can conclude that h is affine on Q . By Lemma A.2(ii), $\cap_{\beta \in Q} \Theta(\beta) \neq \emptyset$. Any $y \in \cap_{\beta \in Q} \Theta(\beta)$ satisfies (A.5). ■

A.2. Niveloids

Let $(E, \geq, \|\cdot\|)$ be a normed Riesz space and let H be a convex cone in E containing an order unit e .²² Say that $\|\cdot\|$ is an e -norm if there exists $k > 0$ such that $|f| \leq k\|f\|e$ for all $f \in E$. Throughout we consider only e -norms.

²²That is, E is a lattice under the order \geq and the norm $\|\cdot\|$ is such that, for all $f, g \in E$, $\|f\| \leq \|g\|$ whenever $|f| \leq |g|$. Recall that $|f| = f^+ + f^- = f \vee 0 + (-f) \vee 0$, and that $e \in E_+$ is an order unit if for each $f \in E$ there is $\alpha > 0$ such that $|f| \leq \alpha e$.

Example A.4. Each normed Riesz space has a natural e -norm, called the e -uniform Riesz norm, given by

$$\|f\|_e = \inf \{k \geq 0 : |f| \leq ke\}.$$

In this case, $|f| \leq \|f\|_e e$ for all $f \in E$ (see [3, p. 103]). For example, if E is a function space and e is 1_Ω , then $\|\cdot\|_e$ is the supnorm. \blacktriangle

Lemma A.5. *If $h_1, h_2 \in H$, then $h_1 + h_2 \in H$.*

A functional $I : H \rightarrow \mathbb{R}$ with $I(0) = 0$ is an e -niveloid if it is monotone, $I(e) = 1$, and

$$I(h + \alpha e) = I(h) + \alpha \text{ for all } h \in H \text{ and } \alpha \geq 0.$$

If the preceding is true also for all $\alpha < 0$ such that $h + \alpha e \in H$, say that I is e -translation invariant.

Lemma A.6. *Any e -niveloid $I : H \rightarrow \mathbb{R}$ is Lipschitz continuous and e -translation invariant. Moreover, I is concave iff it is quasiconcave.*

Remark. Observe that Lemma A.6 applies to any e -niveloid on a convex cone.

Proof. For translation invariance, if $\alpha < 0$, then

$$I(h) + \alpha = I(h + \alpha e - \alpha e) + \alpha = I(h + \alpha e) - \alpha + \alpha = I(h + \alpha e).$$

For the Lipschitz property, argue as follows: If $f, g \in H$, then $f - g \leq |f - g|$. As $\|\cdot\|$ is an e -norm, we have $|f - g| \leq k \|f - g\| e$, and so $f \leq g + k \|f - g\| e$. By the monotonicity of I , we have $I(f) - I(g) \leq k \|f - g\|$.

Finally, suppose I is quasiconcave. Let $f, g \in H$ with $I(f) \geq I(g)$ and set $\alpha = I(f) - I(g)$. Then I is concave, because, for all $t \in [0, 1]$,

$$\begin{aligned} I(tf + (1-t)g) + (1-t)\alpha &= I(tf + (1-t)(g + \alpha e)) \\ &\geq tI(f) + (1-t)I(g + \alpha e) \\ &= tI(f) + (1-t)I(g) + (1-t)\alpha. \blacksquare \end{aligned}$$

Let $(E, \geq, \|\cdot\|)$ be a Banach lattice with topological dual E^* . Denote by E_+^* the set of all monotone elements in E^* and let $\Delta = \{L \in E_+^* : L(e) = 1\}$. Recall that a functional $I : H \rightarrow \mathbb{R}$ is superlinear if it is positively homogeneous and superadditive, i.e., $I(f + g) \leq I(f) + I(g)$ for all $f, g \in H$. Superlinearity and concavity are equivalent properties for positively homogeneous functionals.

Theorem A.7. Suppose E is a separable Banach lattice with $E = \overline{H - H}$. Let $I : H \rightarrow \mathbb{R}$ be a quasi-concave and positively homogeneous e -niveloid. Then there exists a greatest superlinear e -niveloid $\widehat{I} : E \rightarrow \mathbb{R}$ that extends I , that is, $J \leq \widehat{I}$ pointwise for any extension $J : E \rightarrow \mathbb{R}$ of I . In particular, there exists a smallest convex and weak*-compact set $\Gamma \subseteq \Delta$ such that

$$I(f) = \min_{L \in \Gamma} L(f), \quad \forall f \in H.$$

The set Γ is a singleton iff I is additive.

Proof. Define $I' : E \rightarrow \mathbb{R}$ by

$$I'(f) = \sup_{g \in H, \alpha \in \mathbb{R}} \{I(g) + \alpha : g + \alpha e \leq f\}.$$

Then I' is a superlinear e -niveloid that extends I : It is readily verified that $I' = I$ on H , and that I' is monotone and e -translation invariant. In addition:

- I' is superadditive: suppose that $f_1, f_2 \in E$ and $I'(f_1 + f_2) < I'(f_1) + I'(f_2)$. Then there exist $g_1, g_2 \in H$ and $\alpha_1, \alpha_2 \in \mathbb{R}$, with $g_1 + \alpha_1 e \leq f_1$ and $g_2 + \alpha_2 e \leq f_2$, such that

$$I'(f_1 + f_2) < I(g_1) + \alpha_1 + I(g_2) + \alpha_2 \leq I(g_1 + g_2) + \alpha_1 + \alpha_2,$$

a contradiction, because $g_1 + g_2 \in H$ and $g_1 + g_2 + (\alpha_1 + \alpha_2)e \leq f_1 + f_2$.

- I' is positively homogeneous: given any $\beta \geq 0$ and $f \in E$, then

$$\begin{aligned} I'(\beta f) &= \sup_{g \in H, \alpha \in \mathbb{R}} \{I(g) + \alpha : g + \alpha e \leq \beta f\} \\ &= \sup_{g \in H, \alpha \in \mathbb{R}} \left\{ I\left(\frac{g}{\beta}\right) \beta + \frac{\alpha}{\beta} \beta : \frac{g}{\beta} + \frac{\alpha}{\beta} e \leq f \right\} \\ &= \beta \sup_{g \in H, \alpha \in \mathbb{R}} \left\{ I\left(\frac{g}{\beta}\right) + \frac{\alpha}{\beta} : \frac{g}{\beta} + \frac{\alpha}{\beta} e \leq f \right\} \\ &= \beta \sup_{h \in H, \gamma \in \mathbb{R}} \{I(h) + \gamma : h + \gamma e \leq f\} = \beta I'(f). \end{aligned}$$

Let $\widetilde{I} : E \rightarrow \mathbb{R}$ be any superlinear e -niveloid that extends I . The superdifferential $\partial \widetilde{I}(f)$ at $f \in E$ is given by

$$\partial \widetilde{I}(f) = \left\{ L \in E^* : \widetilde{I}(g) \leq \widetilde{I}(f) + L(g - f) \quad \forall g \in E \right\}. \quad (\text{A.7})$$

Since \tilde{I} is concave and Lipschitz continuous (by Lemma A.6), $\partial\tilde{I}(f)$ is nonempty, convex and weak*-compact for each $f \in E$ (see [22, Propn. 1.11]).

Show that $\tilde{I}(f) = \min_{L \in \partial\tilde{I}(0)} L(f)$: Let $L \in \partial\tilde{I}(f)$. If we take $g = 0$ in (A.7), we get $\tilde{I}(f) \geq L(f)$, while if we take $g = 2f$, then we get $\tilde{I}(f) \leq L(f)$. Conclude that $\tilde{I}(f) = L(f)$. This implies that $\partial\tilde{I}(f) = \left\{ L \in \partial\tilde{I}(0) : L(f) = \tilde{I}(f) \right\}$ and $\tilde{I}(f) = \min_{L \in \partial\tilde{I}(0)} L(f)$.

Next we show that $\partial\tilde{I}(0) \subseteq \Delta$. Fix $f \in E$ and $L \in \partial\tilde{I}(0)$. Then $\tilde{I}(f + \alpha e) \leq L(f + \alpha e)$ for all $\alpha \in \mathbb{R}$, and so $\tilde{I}(f) \leq L(f) + \alpha (L(e) - \tilde{I}(e))$ for all $\alpha \in \mathbb{R}$. This contradicts $\tilde{I}(f) > -\infty$ unless $L(e) = \tilde{I}(e) = 1$. It remains to prove that $\partial\tilde{I}(0) \subseteq E_+^*$: $L \in \partial\tilde{I}(0) \implies L(f) \geq \tilde{I}(f) \geq 0$ for every $f \in E_+$ by the monotonicity of \tilde{I} . Therefore $\partial\tilde{I}(0) \subseteq \Delta$.

Define $I^* : E^* \rightarrow \mathbb{R}$ by $I^*(L) = \inf_{h \in H} \{L(h) - I(h)\}$. Then $I^*(L) = 0$ for $L \in \partial\tilde{I}(0)$. Therefore, for each $f \in E$,

$$\tilde{I}(f) = \min_{L \in \partial\tilde{I}(0)} L(f) = \min_{L \in \partial\tilde{I}(0)} \{L(f) - I^*(L)\}.$$

By [8, Propn. 2], there is a convex weak*-compact set Γ such that²³

$$I(h) = \min_{L \in \Gamma} \{L(h) - I^*(L)\}, \quad \forall h \in H,$$

and such that Γ is smallest in this respect, that is, $\Gamma \subseteq \Phi$ for any convex weak*-compact set Φ satisfying

$$I(h) = \min_{L \in \Phi} \{L(h) - I^*(L)\}, \quad \forall h \in H.$$

Since

$$I(h) = \tilde{I}(h) = \min_{L \in \partial\tilde{I}(0)} L(h) = \min_{L \in \partial\tilde{I}(0)} \{L(h) - I^*(L)\}, \quad \forall h \in H,$$

it follows that $\Gamma \subseteq \partial\tilde{I}(0)$. Hence the functional $\hat{I} : E \rightarrow \mathbb{R}$ given by

$$\hat{I}(f) = \min_{L \in \Gamma} L(f), \quad \forall f \in E,$$

²³Ergin and Sarver's result shows the existence of a smallest weak*-compact set. Its closed convex hull is then the smallest convex and weak*-compact set.

is the greatest superlinear e -niveloid that extends I on E , that is, $\widehat{I} \geq \widetilde{I}$ for any superlinear e -niveloid \widetilde{I} extending I .

As a result, Γ is the desired smallest set. In fact, let $\Gamma' \subseteq \Delta$ be any other convex and weak*-compact set such that $I(f) = \min_{L \in \Gamma'} L(f)$ for all $f \in H$. Define $\widetilde{I} : E \rightarrow \mathbb{R}$ by $\widetilde{I}(f) = \min_{L \in \Gamma'} L(f)$. The functional \widetilde{I} is a superlinear e -niveloid that extends I , and so $\widehat{I} \geq \widetilde{I}$, which in turn implies $\Gamma \subseteq \Gamma'$.

Finally, suppose I is additive. By Lemma A.6, I is Lipschitz and so by the Hahn-Banach Theorem it admits a unique linear extension $J : E \rightarrow \mathbb{R}$. Hence, $J \leq \widehat{I}$, and

$$J(f) = -J(-f) \geq -\widehat{I}(-f) \geq \widehat{I}(f) \geq J(f), \quad \forall f \in E,$$

which implies $J = \widehat{I}$ and $\Gamma = \{J\}$. ■

Given a convex subset G containing both 0 and e , let $\langle G \rangle$ be the vector subspace it generates.

Corollary A.8. *Let G be a convex subset containing both 0 and e of a separable Banach lattice E , with $E = \overline{\langle G \rangle}$. Let $W : G \rightarrow \mathbb{R}$ be quasiconcave and monotone, such that $W(0) = 0$ and*

$$W(tf + (1-t)\gamma e) = tW(f) + (1-t)\gamma, \quad \forall f \in G, \forall t, \gamma \in [0, 1]. \quad (\text{A.8})$$

Then there exists a smallest convex and weak-compact set $\Gamma \subseteq \Delta$ such that*

$$W(f) = \min_{L \in \Gamma} L(f), \quad \forall f \in G. \quad (\text{A.9})$$

The set Γ is a singleton iff W is affine.

Proof. Let $H = \bigcup_{\alpha > 0} \alpha G$ be the cone generated by G . For each $h \in H$, there exists $\alpha > 0$ such that $h/\alpha \in G$. Define $I : H \rightarrow \mathbb{R}$ by $I(h) = \alpha W(h/\alpha)$.

The functional I is well defined: suppose that, for a given $h \in H$, there exist $\alpha, \beta > 0$ such that $h/\alpha, h/\beta \in G$. Wlog suppose $\beta \leq \alpha$. Then

$$W\left(\frac{h}{\alpha}\right) = W\left(\frac{\beta h}{\alpha \beta}\right) = W\left(\frac{\beta h}{\alpha \beta} + \left(1 - \frac{\beta}{\alpha}\right)0\right) = \frac{\beta}{\alpha} W\left(\frac{h}{\beta}\right),$$

as desired. Observe that $h/\beta \in G$ and $\beta \leq \alpha$ imply $h/\alpha \in G$. Hence, given any $h_1, h_2 \in H$, there exists $\alpha \geq 1$ such that $h_i/\alpha \in G$ and $I(h_i) = \alpha W(h_i/\alpha)$ for each $i = 1, 2$. This property will be tacitly used in the sequel.

The functional I is clearly positively homogeneous and it is an e -niveloid. Show that I is quasiconcave on H : given any $h_1, h_2 \in H$, there exist $\alpha > 0$ such that $h_1/\alpha, h_2/\alpha \in G$. For any $t \in [0, 1]$,

$$\begin{aligned} I(th_1 + (1-t)h_2) &= I\left(t\alpha\frac{h_1}{\alpha} + (1-t)\alpha\frac{h_2}{\alpha}\right) \\ &= \alpha I\left(t\frac{h_1}{\alpha} + (1-t)\frac{h_2}{\alpha}\right) = \alpha W\left(t\frac{h_1}{\alpha} + (1-t)\frac{h_2}{\alpha}\right) \\ &\geq \alpha \min\left\{W\left(\frac{h_1}{\alpha}\right), W\left(\frac{h_2}{\alpha}\right)\right\} = \min\{I(h_1), I(h_2)\}. \end{aligned}$$

Thus I is quasiconcave. By Theorem A.7, there is a smallest convex and weak*-compact set $\Gamma \subseteq \Delta$ such that

$$I(f) = \min_{L \in \Gamma} L(f), \quad \forall f \in H.$$

In particular, Γ is a singleton iff I is additive. Hence, Γ is such that (A.9) holds, and it is the smallest such set: suppose $\Gamma' \subseteq \Delta$ is another set for which (A.9) holds. Define $\tilde{I} : E \rightarrow \mathbb{R}$ by $\tilde{I}(f) = \min_{L \in \Gamma'} L(f)$. Then $\tilde{I}(f) = I(f)$ for all $f \in H$, and by Theorem A.7 we then have

$$\min_{L \in \Gamma} L(f) \geq \min_{L \in \Gamma'} L(f), \quad \forall f \in E,$$

which implies $\Gamma \subseteq \Gamma'$. Since I is additive iff W is affine, this completes the proof. ■

A.3. Application

Let $\Delta(N)$ be the set of all Borel probability measures on N and $\mathcal{C}(N)$ be the set of all continuous functions on N . Endow $\mathcal{C}(N)$ with the supnorm $\|\cdot\|_s$ and define an order \geq on $\mathcal{C}(N)$ by $f \geq g$ if $f(u) \geq g(u)$ for all $u \in N$.

The triple $(\mathcal{C}(N), \geq, \|\cdot\|_s)$ forms a separable Banach lattice; its dual is given by the set of all bounded Borel measures and the set Δ of Theorem A.7 is given by $\Delta(N)$. Moreover, 1_N is an order unit e that makes $\|\cdot\|_s$ an e -norm, while the 0 is the function on N that is identically zero.

Denote by Σ the set of all support functions $\sigma_x : N \rightarrow \mathbb{R}$, given by $\sigma_x(u) = \max_{\beta \in x} \beta \cdot u$ for each $u \in N$ and $x \in \mathcal{X}$. Then Σ is a convex subset of $\mathcal{C}(N)$ containing both e and 0 . For the latter, note that $\sigma_{\Delta(B)} = 1_N$ and $\sigma_{\{b_*\}} = 0$.

For this setting we have the following version of a classic result of Hormander [13].

Lemma A.9. $\mathcal{C}(N)$ is the supnorm closure of $\langle \Sigma \rangle$.

Proof. Since $0 \in \Sigma$, we have $\langle \Sigma \rangle = \bigcup_{\alpha > 0} \alpha \Sigma - \bigcup_{\alpha > 0} \alpha \Sigma$. By proceeding as in [13, p. 185], we can show that $\langle \Sigma \rangle$ is a Riesz subspace of $\mathcal{C}(N)$. Moreover, given $u, u' \in N$ with $u \neq u'$ there is $\beta \in \Delta(N)$ such that $\beta \cdot u \neq \beta \cdot u'$. Hence, $\sigma_{\{\beta\}}(u) \neq \sigma_{\{\beta\}}(u')$ and so $\langle \Sigma \rangle$ separates the points of N . Since $\langle \Sigma \rangle$ also contains 1_N , application of the lattice version of the Stone-Weierstrass Theorem completes the proof. \blacksquare

The next result is an immediate consequence of Corollary A.8 and Lemmas A.3, A.6 and A.9. Observe that a weak*-compact subset of $\Delta(N)$ is weakly compact.

Corollary A.10. Let $W : \Sigma \rightarrow \mathbb{R}$ be monotone, quasiconcave, satisfying $W(0) = 0$, $W(e) = 1$, and

$$W(\alpha \sigma_x + (1 - \alpha) \gamma e) = \alpha W(\sigma_x) + (1 - \alpha) \gamma, \quad \forall \sigma_x \in \Sigma, \forall \alpha, \gamma \in [0, 1].$$

There exists a smallest convex and weakly compact subset $\Pi \subseteq \Delta(N)$ such that

$$W(\sigma_x) = \min_{\pi \in \Pi} \int_N \sigma_x(u) d\pi, \quad \forall \sigma_x \in \Sigma.$$

The set Π is a singleton iff W is quasimonotone.

Turn finally to the proof of Theorem 3.1. Adopt the hypotheses stated there.

Lemma A.11. There exists $\mathcal{W} : \mathcal{X} \rightarrow \mathbb{R}$ that represents \succeq and such that, for each $x, x' \in \mathcal{X}$, $\alpha \in [0, 1]$ and $x_p \in C$,

$$\begin{aligned} \mathcal{W}(\alpha x + (1 - \alpha) x_p) &= \alpha \mathcal{W}(x) + (1 - \alpha) p, \text{ and} \\ \mathcal{W}(\alpha x + (1 - \alpha) x') &\geq \min \{ \mathcal{W}(x), \mathcal{W}(x') \}. \end{aligned}$$

The functional \mathcal{W} is unique up to positive affine transformations.

Proof. The set $C = \{x_p \equiv p\Delta(B) + (1 - p)b_* : p \in [0, 1]\}$ is a convex subset of the vector space $\{\lambda\Delta(B) + \nu b_* : \lambda, \nu \in \mathbb{R}\}$. In fact, for all $x_p, x_q \in C$ and all $\alpha \in [0, 1]$:

$$\begin{aligned} \sigma_{\alpha x_p + (1 - \alpha) x_q} &= \alpha \sigma_{x_p} + (1 - \alpha) \sigma_{x_q} = \alpha \sigma_{p\Delta(B) + (1 - p)b_*} + (1 - \alpha) \sigma_{q\Delta(B) + (1 - q)b_*} \\ &= \alpha (p\sigma_{\Delta(B)} + (1 - p)\sigma_{b_*}) + (1 - \alpha) (q\sigma_{\Delta(B)} + (1 - q)\sigma_{b_*}) \\ &= (\alpha p + (1 - \alpha) q) \sigma_{\Delta(B)} + (1 - \alpha p - (1 - \alpha) q) \sigma_{b_*} \\ &= \sigma_{(\alpha p + (1 - \alpha) q)\Delta(B) + (1 - \alpha p - (1 - \alpha) q)b_*} = \sigma_{x_{\alpha p + (1 - \alpha) q}} \end{aligned}$$

and so $\alpha x_p + (1 - \alpha) x_q = x_{\alpha p + (1 - \alpha) q}$.

Because \succeq satisfies the vNM axioms on C (for example, Mild Continuity implies the Archimedean axiom on C), there exists an affine function $u : C \rightarrow \mathbb{R}$, unique up to positive affine transformations, such that $x_p \succeq x_{p'}$ iff $u(x_p) \geq u(x_{p'})$. Normalize u so that $u(b_*) = 0$ and $u(\Delta(B)) = 1$. Hence,

$$u(x_p) = u(p\Delta(B) + (1 - p)b_*) = pu(\Delta(B)) + (1 - p)u(b_*) = p. \quad (\text{A.10})$$

Any $x \in \mathcal{X}$ satisfies (3.1), that is, $\Delta(B) \succeq x \succeq b_*$. By Mild Continuity there exists a $p \in [0, 1]$ such that $x_p \sim x$. Such p is unique since, by (A.10), $x_p \sim x_q$ iff $p = q$.

Set $\mathcal{W}(x) = u(x_p) = p$. Clearly, $x \succeq x'$ iff $\mathcal{W}(x) \geq \mathcal{W}(x')$, and \mathcal{W} is the unique functional on \mathcal{X} representing \succeq that reduces to u on C .

Consider $x \in \mathcal{X}$ and $x_p \in C$. There exists $x_q \in C$ such that $x \sim x_q$. By Certainty Independence,

$$x \sim x_q \iff \alpha x + (1 - \alpha)x_p \sim \alpha x_q + (1 - \alpha)x_p,$$

for all $\alpha \in [0, 1]$, and so

$$\begin{aligned} \mathcal{W}(\alpha x + (1 - \alpha)x_p) &= \mathcal{W}(\alpha x_q + (1 - \alpha)x_p) = \alpha \mathcal{W}(x_q) + (1 - \alpha) \mathcal{W}(x_p) \\ &= \alpha \mathcal{W}(x) + (1 - \alpha) \mathcal{W}(x_p). \end{aligned}$$

Finally, quasiconcavity of \mathcal{W} is a direct consequence of Preference Convexity. ■

For any menu x , define its \geq_D -hull by

$$\text{hull}(x) = \{\beta' \in \Delta(B) : \beta \geq_D \beta' \text{ for some } \beta \in x\}.$$

If x is convex, then so is $\text{hull}(x)$.

Lemma A.12. (i) For any convex x and $\beta^0 \in \Delta(B) \setminus \text{hull}(x)$, there exists u in N such that

$$\sigma_x(u) < u(\beta^0). \quad (\text{A.11})$$

(ii) For any convex x and y ,

$$\begin{aligned} \sigma_y &= \sigma_x \implies y \sim x, \\ \sigma_y &\geq \sigma_x \implies y \succeq x \end{aligned}$$

Proof. (i) Define \geq_D^* on \mathbb{R}^B by $\beta \geq_D^* \beta' \iff u \cdot \beta \geq u \cdot \beta'$ for all u in N . By (3.3), \geq_D^* agrees with \geq_D on $\Delta(B)$; hence we denote both orders by \geq_D . Let

$$H = \{\beta \in \mathbb{R}^B : \sum_b \beta_b = 1\}$$

and

$$\text{hull}_H(x) = \{\beta' \in H : \beta \geq_D \beta' \text{ for some } \beta \in x\}.$$

Then $\beta^0 \notin \text{hull}_H(x)$, a closed convex set. Therefore, there exists a v in \mathbb{R}^B such that

$$\sup_{\beta \in \text{hull}_H(x)} v \cdot \beta < v \cdot \beta^0. \quad (\text{A.12})$$

Since $b_* \in \text{hull}_H(x)$, it follows that $v \cdot b_* < v \cdot \beta^0$. This implies that v is not a constant.

Wlog let $v_{b_*} = 0$, so that $v \cdot \beta^0 > 0$. It remains only to show that

$$v_b \geq 0 \text{ for all } b \neq b_*. \quad (\text{A.13})$$

In that case, we can renormalize v to obtain $u \in N$ satisfying (A.11).

To prove (A.13), given any $b \neq b_*$ and $\kappa < 0$, define

$$\gamma_\kappa \equiv \kappa \delta_b + (1 - \kappa) \delta_{b_*}.$$

If $\kappa < 0$, then $\beta \geq_D \gamma_\kappa$ for all $\beta \in \Delta(B)$, and hence $\gamma_\kappa \in \text{hull}_H(x)$. By (A.12),

$$v_b = \frac{1}{\kappa} (v_b \kappa) = \frac{1}{\kappa} (v \cdot \beta_\kappa) > \frac{1}{\kappa} (v \cdot \beta^0).$$

Since this holds for every $\kappa < 0$, $v_b \geq 0$.

(ii) We have

$$x \geq_D \text{hull}(x) \text{ and } y \geq_D \text{hull}(y).$$

By Worst,

$$x \sim \text{hull}(x) \text{ and } y \sim \text{hull}(y). \quad (\text{A.14})$$

Thus it suffices to show that

$$\sigma_x = \sigma_y \implies \text{hull}(x) = \text{hull}(y).$$

Suppose that $\beta^0 \in \text{hull}(x) \setminus \text{hull}(y)$. Then by (i) there exists u in N such that

$$\sigma_y(u) < \beta^0 \cdot u \leq \sigma_x(u), \quad (\text{A.15})$$

a contradiction. Conclude that $\text{hull}(x) = \text{hull}(y)$.

Finally, let $\sigma_y \geq \sigma_x$ on N . By (A.14), it is enough to show that $\text{hull}(x) \subseteq \text{hull}(y)$. Otherwise, there exists $\beta^0 \in \text{hull}(x) \setminus \text{hull}(y)$, which implies (A.15), contradicting our hypothesis. \blacksquare

Define $W : \Sigma \rightarrow \mathbb{R}$ by

$$W(\sigma_x) = \mathcal{W}(x) \text{ for each } x \in \mathcal{X}. \quad (\text{A.16})$$

Then W is well-defined because, by Lemmas A.11-A.12 and IR,

$$\sigma_x = \sigma_{x'} \implies \sigma_{co(x)} = \sigma_{co(x')} \implies co(x) \sim co(x') \implies$$

$$\mathcal{W}(co(x)) = \mathcal{W}(co(x')) \implies \mathcal{W}(x) = \mathcal{W}(x').$$

Also by Lemma A.12, W is monotone, with $W(0) = 0$ and $W(e) = 1$. Moreover,

$$\begin{aligned} W(\alpha\sigma_x + (1-\alpha)\gamma\sigma_B) &= W(\sigma_{\alpha x + (1-\alpha)x_\gamma}) = \mathcal{W}(\alpha x + (1-\alpha)x_\gamma) \\ &= \alpha\mathcal{W}(x) + (1-\alpha)\mathcal{W}(x_\gamma) \\ &= \alpha W(\sigma_x) + (1-\alpha)\gamma W(\sigma_B), \text{ and} \end{aligned}$$

$$\begin{aligned} W(\alpha\sigma_x + (1-\alpha)\sigma_{x'}) &= W(\sigma_{\alpha x + (1-\alpha)x'}) = \mathcal{W}(\alpha x + (1-\alpha)x') \\ &\geq \min\{\mathcal{W}(x), \mathcal{W}(x')\} = \min\{W(x), W(x')\}. \end{aligned}$$

Hence W satisfies the hypotheses of Corollary A.10, and so there exists a smallest convex and weakly compact subset $\Pi \subseteq \Delta(N)$ such that, for each $\sigma \in \Sigma$,

$$\mathcal{W}(x) = W(\sigma_x) = \min_{\pi \in \Pi} \int_N \sigma_x(u) d\pi = \min_{\pi \in \Pi} \int_N \max_{\beta \in x} u(\beta) d\pi.$$

Finally, if (3.5) holds, then Preference Convexity implies

$$x \sim x' \implies \alpha x + (1-\alpha)x' \sim x, \quad \forall x, x' \in \mathcal{X}, \forall \alpha \in [0, 1],$$

and so W is quasimonotone by Lemma A.1. By Corollary A.10, Π is a singleton.

B. Appendix: A Set of Priors for W^{rev}

Let μ be a Borel probability measure on $\mathcal{K}^{cc}(N^*)$ with support $Supp\mu = \mathcal{U}$. Say that the collection $\{p_U(\cdot) : U \in \mathcal{U}\}$ is a \mathcal{U} -conditional probability system (\mathcal{U} -cps) if μ -a.s.: (i) $p_U(\cdot) \in \Delta(U)$, and (ii) $A \mapsto p_U(A)$ is suitably measurable. Define Π by

$$\Pi = \left\{ \pi : \pi(\cdot) = \int p_U(\cdot) d\mu(U) \text{ for some } \mathcal{U}\text{-cps } \{p_U(\cdot)\} \right\}. \quad (\text{B.1})$$

Each p_U is a probability measure on U , which can be thought of as giving probability conditional on U . Measures in Π share the common ‘marginal’ μ on the sets U , but all conditionals are admitted.

With this specification for Π , the (multiple-priors) utility of any menu x is given by

$$\begin{aligned} \min_{\pi \in \Pi} \int \max_{\beta \in x} u(\beta) d\pi(u) &= \min_{\{p_U\}} \int \left(\int \max_{\beta \in x} u(\beta) dp_U(u) \right) d\mu(U) \\ &= \int \left(\min_{p_U} \int \max_{\beta \in x} u(\beta) dp_U(u) \right) d\mu(U) \\ &= \int \left(\min_{u \in U} \max_{\beta \in x} u(\beta) \right) d\mu(U) = W^{rev}(x). \end{aligned}$$

Roughly, the structure (B.1) for Π permits the minimum over Π appearing outside the integral to be taken inside.

C. Appendix: Proof of Theorem 4.1

C.1. Upper Contour Sets

Refer to the menu y as an *upper contour set* if

$$y = \{\beta \in \Delta(B) : \min_{u \in U} u \cdot \beta \geq s\} \quad (\text{C.1})$$

for some $0 \leq s \leq 1$ and some closed, convex and comprehensive $U \subset N^*$.

Proposition C.1. *y is an upper contour set iff it satisfies Y1 – Y3. Moreover, the corresponding pair (U, s) is unique.*

Thus

$$Y = \left\{ y \in \mathcal{X} : y = \{\beta \in \Delta(B) : \min_{u \in U} u \cdot \beta \geq s\}, 0 \leq s \leq 1, U \in \mathcal{K}^{cc}(N^*) \right\}. \quad (\text{C.2})$$

Since $\mathcal{K}^{cc}(N^*)$ is compact, it is straightforward to show that Y is compact (and hence also measurable).²⁴

Turn to the proof of the proposition.

Lemma C.2. *Let y satisfy Y1 – Y3. If $\beta^0 \in \Delta(B) \setminus y$, then there exists $u \in N^*$ such that*

$$u \cdot \beta^0 < s \leq u \cdot \beta \text{ for every } \beta \in y, \quad (\text{C.3})$$

where

$$s = \min\{p \in [0, 1] : \beta_p \in y\}. \quad (\text{C.4})$$

Proof. Define the partial order \geq_D on $\Delta(B)$ as the smallest transitive relation satisfying: $\beta' \geq_D \beta$ if β' is an elementary improvement of β . Note that, for all lotteries β ,

$$b^* \geq_D \beta \geq b_* \text{ for all } \beta \in \Delta(B), \text{ and} \quad (\text{C.5})$$

$$[\beta' \geq_D \beta, \beta \in y] \implies \beta' \in y. \quad (\text{C.6})$$

As a result, $\{p \in [0, 1] : \beta_p \in y\}$ is nonempty because it contains $\beta_1 = b^*$, and it is closed by Y1. Therefore, s is well-defined and $\beta_s \in y$. Moreover, by Y3,

$$\text{co}(\{\beta^0, \beta_s\}) \cap y = \{\beta_s\}, \quad (\text{C.7})$$

where $\text{co}(\{\beta^0, \beta_s\}) = \{\alpha\beta^0 + (1 - \alpha)\beta_s : \alpha \in [0, 1]\}$.

The definition of \geq_D admits the obvious extension to all of \mathbb{R}^B . Let

$$H = \{\beta \in \mathbb{R}^B : \Sigma_b \beta_b = 1\}$$

and

$$\text{Phull}_H(y) = \{\beta \in H : \beta \neq \beta_s, \beta \geq_D \beta' \text{ for some } \beta' \in y\}.$$

It follows from Y1 that $\text{Phull}_H(y)$ is convex. Define also

$$D^0 = \{\beta \in H : \beta' \geq_D \beta \text{ for some } \beta' \in \text{co}(\{\beta^0, \beta_s\})\}.$$

²⁴In Lemma C.4, we prove the continuity of $U \times s \mapsto \{\beta \in \Delta(B) : \min_{u \in U} u \cdot \beta \geq s\}$.

This set is also closed and convex, and it does not intersect $Phull_H(y)$: if $\beta \in D^0 \cap Phull_H(y)$, then there exists $\alpha > 0$ and β' in y such that

$$\alpha\beta^0 + (1 - \alpha)\beta_s \geq_D \beta \geq_D \beta'.$$

Since \geq_D is transitive, $\alpha\beta^0 + (1 - \alpha)\beta_s \geq_D \beta'$, and $\alpha\beta^0 + (1 - \alpha)\beta_s \in y$ by (C.6). But this contradicts (C.7).

Therefore, there exists a separating hyperplane v in \mathbb{R}^B such that

$$v \cdot \beta^0 < v \cdot \beta_s \leq v \cdot \beta \text{ for all } \beta \in Phull_H(y), \text{ and} \quad (\text{C.8})$$

$$v \cdot \beta \leq v \cdot \beta_s \text{ for all } \beta \in D^0. \quad (\text{C.9})$$

Since $b^* \in Phull_H(y)$, by (C.5), it follows that

$$v \cdot \beta^0 < v \cdot b^* = v_{b^*}.$$

Claim 1. $v_b \leq v_{b^*}$ for all b : Let $v_b > v_{b^*}$ for some b , and consider $\beta' \in H$ of the form

$$\beta'_b = -\kappa, \beta'_{b^*} = 1 + \kappa, \text{ and } \beta'_{b'} = 0 \text{ for } b' \neq b, b^*, \text{ where } \kappa > 0.$$

Then for any lottery β , $\beta' \geq_D b^* \geq_D \beta$. Hence $\beta' \geq_D \beta$ and $\beta' \in Phull_H(y)$. But $v \cdot \beta' = v_{b^*} + (v_b - v_{b^*})\kappa < v \cdot \beta^0$ for sufficiently large κ , contradicting (C.8).

Claim 2. $v_{b_*} \leq v_b$ for all b : Let $v_b < v_{b_*}$ for some b and consider $\beta \in H$ of the form

$$\beta_b = -\kappa, \beta_{b_*} = 1 + \kappa, \text{ and } \beta_{b'} = 0 \text{ for } b' \neq b, b_*, \text{ where } \kappa > 0.$$

Then, using (C.5), $\beta^0 \geq_D b_* \geq_D \beta$, which implies $\beta^0 \geq_D \beta$. Hence $\beta \in D^0$. However, $v \cdot \beta = (1 + \kappa)v_{b_*} - \kappa v_b > v \cdot \beta_s$ for sufficiently large κ , contradicting (C.9).

Finally, normalize v to obtain u in N^* ($u_{b_*} = 0$, $u_{b^*} = 1$). Then $u \cdot \beta_s = s$ and (C.3) is satisfied. ■

Proof of Proposition: We prove only sufficiency. Define s by (C.4), so that, by (4.5),

$$\beta_p \in y \text{ iff } p \geq s. \quad (\text{C.10})$$

Let

$$U = \{u \in N^* : u \cdot \beta \geq s \ \forall \beta \in y\}. \quad (\text{C.11})$$

Then U is closed, convex and comprehensive. We claim that s and U satisfy (C.1).

That $y \subset \{\beta \in \Delta(B) : \min_{u \in U} u \cdot \beta \geq s\}$ is immediate from the definition of U . Thus it remains to prove that

$$\min_{u \in U} u \cdot \beta \geq s \implies \beta \in y.$$

Suppose to the contrary that

$$\min_{u \in U} u \cdot \beta^0 \geq s \text{ and } \beta^0 \notin y. \quad (\text{C.12})$$

Then by the Lemma, there exists $u \in N^*$ such that

$$u \cdot \beta^0 < s \leq u \cdot \beta \text{ for every } \beta \in y. \quad (\text{C.13})$$

Because $s \leq u \cdot \beta$ for every $\beta \in y$, it follows that $u \in U$. By (C.12), $u \cdot \beta^0 \geq s$. But this contradicts (C.13).

Turn to uniqueness. Suppose that

$$y = \{\beta \in \Delta(B) : \min_{u \in U} u \cdot \beta \geq s\} = \{\beta \in \Delta(B) : \min_{u' \in U'} u' \cdot \beta \geq s'\}, \quad (\text{C.14})$$

where U and s are as above and where U' is closed, convex and comprehensive. That $s' = s$ follows from (C.10). Evidently, $U' \subset U$. To prove equality, let $u \in U \setminus U'$. Separate u and U' by some $\gamma \in \mathbb{R}^B$,

$$u \cdot \gamma < u' \cdot \gamma \text{ for all } u' \in U'.$$

Suppose that there exists $\gamma \in \Delta(B)$ satisfying the preceding (existence of such a γ follows from a separation argument in \mathbb{R}^B and from comprehensiveness of U'). Then, by mixing γ suitably with b_* and b^* , it is wlog to assume that $u \cdot \gamma < s < u' \cdot \gamma$ for all $u' \in U'$. But this is impossible: by (C.14), $\gamma \in y$ (using the U' -representation) and $\gamma \notin y$ (using the U -representation). ■

C.2. An Intermediate Result

In the sufficiency part of the proof, we use some results from Epstein and Seo [7]. They prove a representation result for preferences over random menus satisfying axioms that are collectively weaker than Order, Continuity, Nondegeneracy and First-Stage Independence, plus a form of Dominance whose formal statement is identical to the one in this paper, but where the set Y of upper contour sets is required to satisfy a much weaker set of regularity conditions rather than $Y1 - Y3$.

(One qualification is that Epstein and Seo permit $\mathcal{B} \in Y$, but this is a matter of a harmless difference in normalizations. Otherwise, their conditions are trivial implications of (C.2).)

Therefore, deduce from [7] that \succeq satisfying our axioms has a representation:

$$\mathcal{W}(P) = \int m(\{y \in \mathcal{X} : x \cap y \neq \emptyset\}) dP(x) \text{ for all } P \in \Delta(\mathcal{X}), \quad (\text{C.15})$$

for some countably additive probability measure $m \in \Delta(\mathcal{X})$, viewed as a measure over upper contour sets, such that $m(Y) = 1$.²⁵

The rationale for (C.15) can be understood roughly as follows: Order, Continuity and First-Stage Independence imply that there exists an expected utility representation for \succeq , that is,

$$\mathcal{W}(P) = \int W(x) dP(x),$$

for some continuous vNM index $W : \mathcal{X} \rightarrow [0, 1]$. The normalizations

$$W(\{b_*\}) = 0 \text{ and } W(\{b^*\}) = 1,$$

can be shown to be wlog given the remaining axioms. It is well-known that, under suitable assumptions, a set function, such as W , can be expressed in the form

$$W(x) = m(\{y \in \mathcal{X} : x \cap y \neq \emptyset\}), \text{ for all } x \in \mathcal{X}, \quad (\text{C.16})$$

for some unique countably additive probability measure on the Borel σ -algebra generated by the Hausdorff topology on \mathcal{X} (see [2, Theorems 50.1 and 51.1], as well as the more recent works surveyed in [18]). The key property of W that permits such a representation is that it is *infinitely alternating*: for any finite set of menus $\{x_i\}_{i=1}^n$,

$$W(\cap_{i=1}^n x_i) \leq \sum_{\{I: \emptyset \neq I \subseteq \{1, \dots, n\}\}} (-1)^{|I|+1} W(\cup_{i \in I} x_i). \quad (\text{C.17})$$

One way to understand the representation result (C.15) in [7] is that it shows that the axioms for preference \succeq adopted there imply that W is infinitely alternating.²⁶

²⁵They prove also uniqueness of m , but we rely on [7] only for the existence of m . In order to be as self-contained as possible, the uniqueness property that we need here is proven below - see Lemma C.7.

²⁶Nehring [20] was the first to show a connection between an ordinal property analogous to Dominance (that he calls Indirect Stochastic Dominance) and the cardinal property “infinitely alternating.” He derives a representation similar to (C.15) for his setting where menus consist of alternatives from the finite set B rather than of lotteries over B .

Finally, Dominance leads to the restriction $m(Y) = 1$ (thanks to a version of (C.16) derived in [7]). This is because, as described in the text, Dominance imposes ex ante certainty that only upper contour sets in Y will be relevant ex post.

We use (C.15), including the restriction $m(Y) = 1$, heavily below where we derive the further implications of Certainty Reversal of Order. We also use the following lemma from [1, Theorem 14.69]:

Lemma C.3. *The Borel σ -algebra on \mathcal{X} coincides with the σ -algebra generated by the sets of the form*

$$\{y \in \mathcal{X} : x \cap y \neq \emptyset\} \text{ for } x \in \mathcal{X}.$$

C.3. The Remainder of the Proof

Necessity: Only Dominance requires proof. The utility function \mathcal{W} can be rewritten in the form (C.15). (Such a representation is implied not only by the axioms, as noted above, but also by the functional form (4.1); the measure m is described in (C.25) below.) Therefore,

$$\begin{aligned} \mathcal{W}(P) &= \int_{\mathcal{X}} \int_Y \max_{\beta \in x} \mathbf{1}_y(\beta) dm(y) dP(x) = \int \int \max_{\beta \in x} \mathbf{1}_y(\beta) dP(x) dm(y) \\ &= \int_Y P(\{x : x \cap y \neq \emptyset\}) dm(y), \quad \text{and} \end{aligned}$$

$$\mathcal{W}(P') - \mathcal{W}(P) = \int_Y (P'(\{x : x \cap y \neq \emptyset\}) - P(\{x : x \cap y \neq \emptyset\})) dm(y),$$

which is non-negative if P' dominates P .

The remainder of the proof establishes *sufficiency* of the axioms, and then the asserted uniqueness.

We sometimes adopt the abbreviation

$$\mathcal{B} = \Delta(B).$$

Set

$$h_U(\beta) = \min_{u \in U} u\beta, \tag{C.18}$$

and define $\Psi : \mathcal{K}^{cc}(N^*) \times [0, 1] \rightarrow Y$ by

$$\Psi(U, s) = \{\beta : h_U(\beta) \geq s\}. \quad (\text{C.19})$$

Given $D \subset \mathcal{K}^{cc}(N^*)$, $\Psi(D, [0, s])$ is the image of $D \times [0, s]$, that is,

$$\Psi(D, [0, s]) = \{\Psi(U, s') : U \in D, s' \in [0, s]\}.$$

By Proposition C.1, Ψ is one-to-one and onto.

Lemma C.4. *For any Borel set $D \subset \mathcal{K}^{cc}(N^*)$, $\Psi(D, [0, s])$ is a Borel-measurable subset of \mathcal{X} .*

Proof : First observe that

$$(\beta, U) \longmapsto h_U(\beta) \text{ is continuous.} \quad (\text{C.20})$$

By the Maximum Theorem, it suffices to show that (i) $(\beta, u) \longmapsto u\beta$ is jointly continuous, and (ii) the correspondence $\Gamma : \mathcal{B} \times \mathcal{K}^{cc}(N^*) \rightsquigarrow N^*$ defined by

$$\Gamma(\beta, U) = U,$$

is continuous. Condition (i) is clear. For (ii), when viewed as a function from $\mathcal{B} \times \mathcal{K}^{cc}(N^*)$ into $\mathcal{K}^{cc}(N^*)$, Γ is continuous under the Hausdorff metric. Therefore, (ii) follows from [1, Theorem 14.16].

We claim that Ψ is continuous. By [1, Theorem 14.16], it suffices to show that Ψ is a continuous correspondence.

To show that Ψ is upper hemicontinuous, let $(U_n, s_n) \rightarrow (U, s)$ and $\beta_n \in \Psi(U_n, s_n)$, and prove that β_n has a limit point in $\Psi(U, s)$. Since \mathcal{B} is compact, there is a convergent subsequence β_{n_k} . Let $\beta_{n_k} \rightarrow \beta$. Then $h_{U_{n_k}}(\beta_{n_k}) \geq s_{n_k}$, for every k , which, by (C.20), implies that $h_U(\beta) \geq s$.

Now show that Ψ is lower hemicontinuous. Let $(U_n, s_n) \rightarrow (U, s)$ and $\beta \in \Psi(U, s)$. We need to show that there is a sequence $\beta_n \in \Psi(U_n, s_n)$ such that $\beta_n \rightarrow \beta$. Define

$$\begin{aligned} t_n &= \begin{cases} \min \left\{ \frac{1-s_n}{1-h_{U_n}(\beta)}, 1 \right\} & \text{if } h_{U_n}(\beta) < 1 \\ 1 & \text{if } h_{U_n}(\beta) = 1 \end{cases} \quad \text{and} \\ \beta_n &= t_n\beta + (1-t_n)b^*. \end{aligned}$$

If $h_{U_n}(\beta) < 1$, then

$$\begin{aligned} h_{U_n}(\beta_n) &= t_n h_{U_n}(\beta) + (1 - t_n) \\ &= -t_n(1 - h_{U_n}(\beta)) + 1 \\ &\geq -\frac{1 - s_n}{1 - h_{U_n}(\beta)}(1 - h_{U_n}(\beta)) + 1 \geq s_n, \end{aligned}$$

and if $h_{U_n}(\beta) = 1$, then

$$h_{U_n}(\beta_n) = h_{U_n}(\beta) = 1 \geq s_n.$$

Hence, $\beta_n \in \Psi(U_n, s_n)$. And by (C.20), $\lim_n(1 - h_{U_n}(\beta)) \leq \lim_n(1 - s_n)$ which implies $t_n \rightarrow 1$ and $\beta_n \rightarrow \beta$.

Finally, fix $s \in [0, s]$ and let \mathcal{D} be the set of measurable sets D such that $\Psi(D, [0, s])$ is Borel measurable. Since Ψ is one-to-one, \mathcal{D} is easily seen to be a σ -algebra. Moreover, when D is closed, it is compact and hence, by continuity of Ψ , $\Psi(D, [0, s])$ is also compact and hence measurable. Thus \mathcal{D} contains every closed set and thus also every Borel-measurable set. \blacksquare

Lemma C.5. *Let $m \in \Delta(\mathcal{X})$ be the probability measure satisfying (C.15). Then Certainty Reversal of Order implies that, for each measurable $D \subset \mathcal{K}^{cc}(N^*)$,*

$$m(\Psi(D, [0, s])) = s \cdot m(\Psi(D, [0, 1])).$$

Proof : Recall that $m(Y) = 1$. Therefore, by Proposition C.1, it suffices to consider upper contour sets of the form $y = \{\beta : h_U(\beta) \geq s\}$. For any such set y and $0 \leq t \leq 1$, define $t * y = \{\beta : h_U(\beta) \geq ts\}$. For $A \subset Y$ and $0 \leq t \leq 1$, let

$$t * A = \{t * y : y \in A\}.$$

Step 1.

$$t * \{y \in Y : y \cap x \neq \emptyset\} = \{y \in Y : y \cap (tx + (1 - t)\{b_*\}) \neq \emptyset\} :$$

When $t = 0$, both sets are empty. Let $0 < t \leq 1$. It suffices to show that

$$\begin{aligned} y' &\in Y \text{ and } y' = t * y, \text{ for some } y \in Y \text{ such that } y \cap x \neq \emptyset \\ &\iff [y' \in Y \text{ and } y' \cap (tx + (1 - t)\{b_*\}) \neq \emptyset]. \end{aligned}$$

\implies : Assume that $y' = t * y$ and $y \cap x \neq \emptyset$. Let $\hat{\beta} \in y \cap x$ and $\beta' = t\hat{\beta} + (1 - t)b_*$. Then,

$$\min_{u \in U} u\beta' = \min_{u \in U} u \left(t\hat{\beta} + (1 - t)b_* \right) = t \min_{u \in U} u\hat{\beta} \geq ts.$$

Hence $\beta' \in y'$. Also, $t\hat{\beta} + (1-t)b_* \in tx + (1-t)\{b_*\}$. Therefore,
 $y' \cap (tx + (1-t)\{b_*\}) \neq \emptyset$.

\Leftarrow : Let $y' \in Y$ and $y' \cap (tx + (1-t)\{b_*\}) \neq \emptyset$. By the latter condition, there exists $\hat{\beta} \in x$ such that

$$\beta' = t\hat{\beta} + (1-t)b_* \in y'.$$

Since $y' \in Y$, there exist $U \in \mathcal{K}^{cc}(N^*)$ and $s \in [0, 1]$ such that $y' = \{\beta : h_U(\beta) \geq s\}$. Moreover $s \leq t$, because

$$s \leq \min_{u \in U} u\beta' = \min_{u \in U} u \cdot (t\hat{\beta} + (1-t)b_*) = t \min_{u \in U} u\hat{\beta} \leq t.$$

Let $y = \{\beta : h_U(\beta) \geq s/t\}$. Then

$$t * y = \left\{ \beta : \min_{u \in U} u\beta \geq t \cdot (s/t) \right\} = y'.$$

Moreover, $\hat{\beta} \in y$ because

$$t \min_{u \in U} u\hat{\beta} = \min_{u \in U} u \cdot (t\hat{\beta} + (1-t)b_*) = \min_{u \in U} u\beta' \geq s.$$

Hence $\hat{\beta} \in x \cap y \neq \emptyset$. This completes the step.

Step 2. $m(t * \{y \in Y : y \cap x \neq \emptyset\}) = t \cdot m(\{y \in Y : y \cap x \neq \emptyset\})$:
 By Step 1, (C.15) and Certainty Reversal of Order,

$$\begin{aligned} & m(t * \{y \in Y : y \cap x \neq \emptyset\}) \\ &= m(\{y \in Y : y \cap (tx + (1-t)\{b_*\}) \neq \emptyset\}) \\ &= m(\{y \in \mathcal{X} : y \cap (tx + (1-t)\{b_*\}) \neq \emptyset\}) \\ &= W(tx + (1-t)\{b_*\}) \\ &= t \cdot W(x) = t \cdot m(\{y \in Y : y \cap x \neq \emptyset\}). \end{aligned}$$

Step 3. For any Borel set $A \subset Y$, we have $m(t * A) = t \cdot m(A)$:

Let Σ be the collection of all Borel sets $A \subset Y$ satisfying the noted condition. It is easy to verify that Σ is a Dynkin system: (i) $Y \in \Sigma$; (ii) if $A, A' \in \Sigma$ and $A \subset A'$, then $A' \setminus A \in \Sigma$; (iii) if a sequence $\{A_n\}$ in Σ is such that $A_n \nearrow A$, then $A \in \Sigma$. The proofs are as follows:

(i) $m(t * Y) = m(t * \{y \in Y : y \cap \mathcal{B} \neq \emptyset\}) = t \cdot m(\{y \in Y : y \cap \mathcal{B} \neq \emptyset\}) = t \cdot m(Y)$, where the second equality is by Step 2.

(ii) Since $t * (A' \setminus A) = (t * A') \setminus (t * A)$ and $t * A \subset t * A'$,

$$\begin{aligned} m(t * (A' \setminus A)) &= m(t * A') - m(t * A) \\ &= t \cdot m(A') - t \cdot m(A) = t \cdot m(A' \setminus A). \end{aligned}$$

(iii) $m(t * A) = \lim m(t * A_n) = \lim t \cdot m(A_n) = t \cdot m(A)$.

Let \mathcal{F} be the π -system generated by sets of the form $\{y \in Y : y \cap x \neq \emptyset\}$. That is, \mathcal{F} is the smallest family of subsets such that \mathcal{F} is closed under finite intersections and $\{y \in Y : y \cap x \neq \emptyset\} \in \mathcal{F}$.

Show that $\mathcal{F} \subset \Sigma$. Let $\mathcal{F}_n = \{\cap_{i=1}^n \{y \in Y : y \cap x_i \neq \emptyset\} : x_i \in \mathcal{X}\}$. It suffices to show that $\mathcal{F}_n \subset \Sigma$ for all $n \geq 1$. Argue by induction. By Step 2, $\mathcal{F}_1 \subset \Sigma$. Suppose $\mathcal{F}_n \subset \Sigma$ and show that $\mathcal{F}_{n+1} \subset \Sigma$. Let $A_n = \cap_{i=1}^n \{y \in Y : y \cap x_i \neq \emptyset\}$ and $A_{n+1} = A_n \cap \{y \in Y : y \cap x_{n+1} \neq \emptyset\} \in \mathcal{F}_{n+1}$. Then

$$\begin{aligned} m(t * A_{n+1}) &= m(t * A_n) + m(t \{y \in Y : y \cap x_{n+1} \neq \emptyset\}) \\ &\quad - m[t * (A_n \cup \{y \in Y : y \cap x_{n+1} \neq \emptyset\})]. \end{aligned}$$

The last term can be rewritten as

$$\begin{aligned} &m[t * ((\cap_{i=1}^n \{y \in Y : y \cap x_i \neq \emptyset\}) \cup \{y \in Y : y \cap x_{n+1} \neq \emptyset\})] \\ &= m[t * (\cap_{i=1}^n [\{y \in Y : y \cap x_i \neq \emptyset\} \cup \{y \in Y : y \cap x_{n+1} \neq \emptyset\}])] \\ &= m[t * (\cap_{i=1}^n \{y \in Y : y \cap (x_i \cup x_{n+1}) \neq \emptyset\})] \\ &= t \cdot m[\cap_{i=1}^n \{y \in Y : y \cap (x_i \cup x_{n+1}) \neq \emptyset\}] \quad (\text{by } \mathcal{F}_n \subset \Sigma) \\ &= t \cdot m[(\cap_{i=1}^n \{y \in Y : y \cap x_i \neq \emptyset\}) \cup \{y \in Y : y \cap x_{n+1} \neq \emptyset\}] \\ &= t \cdot m[A_n \cup \{y \in Y : y \cap x_{n+1} \neq \emptyset\}]. \end{aligned}$$

Thus

$$\begin{aligned} m(t * A_{n+1}) &= t \cdot m(A_n) + t \cdot m(\{y \in Y : y \cap x_{n+1} \neq \emptyset\}) \\ &\quad - t \cdot m[A_n \cup \{y \in Y : y \cap x_{n+1} \neq \emptyset\}] = t \cdot m(A_{n+1}). \end{aligned}$$

Hence $\mathcal{F} \subset \Sigma$.

Therefore, by Dynkin's Lemma [1, Theorem 8.10], Σ includes the σ -algebra generated by \mathcal{F} , which is the Borel σ -algebra (Lemma C.3).

Finally, note that $\Psi(D, [0, s]) = s * \Psi(D, [0, 1])$ and $\Psi(D, [0, 1]) \subset Y$. Therefore, by Lemma C.4 and Step 3, $m(\Psi(D, [0, s])) = s \cdot m(\Psi(D, [0, 1]))$. ■

The desired representation will be established using the measure $\mu \in \Delta(\mathcal{K}^{cc}(N^*))$ defined by

$$\mu(D) = m(\Psi(D, [0, 1])) \text{ for each Borel set } D \subset \mathcal{K}^{cc}(N^*). \quad (\text{C.21})$$

Lemma C.6. *The function \mathcal{W} in (C.15) satisfies*

$$\mathcal{W}(P) = \int \int \max_{\beta \in x} \min_{u \in U} u\beta d\mu(U) dP(x) \text{ for each } P \in \Delta(\mathcal{K}(\mathcal{B})).$$

Proof : First we claim that, for any $x \in \mathcal{K}(\mathcal{B})$,²⁷

$$\left\{ \Psi(U, s) : \max_{\beta \in x} h_U(\beta) \geq s \right\} = \{y \in Y : y \cap x \neq \emptyset\}. \quad (\text{C.22})$$

\subset : $\max_{\beta \in x} h_U(\beta) \geq s \implies \exists \beta \in x, h_U(\beta) \geq s \implies \Psi(U, s) \in \{y \in Y : y \cap x \neq \emptyset\}$.
 \supset : If $y \in Y$ and $y \cap x \neq \emptyset$, then $y = \Psi(U, s)$ for some $(U, s) \in \mathcal{K}^{cc}(N^*) \times [0, 1]$, and $\exists \beta \in \Psi(U, s) \cap x$. Then $h_U(\beta) \geq s$. Thus $\max_{\beta \in x} h_U(\beta) \geq s$ and $y = \Psi(U, s) \in \{\Psi(U', s') : \max_{\beta \in x} h_{U'}(\beta) \geq s'\}$.

Since $U \mapsto \max_{\beta \in x} \min_{u \in U} u \cdot \beta$ is bounded and continuous, it is μ -integrable. Thus there is a decreasing sequence of step functions $\phi_n(U) = \sum_{i=1}^n \alpha_{n,i} I_{D_{n,i}}(U)$ such that ϕ_n converges to the function $U \mapsto \max_{\beta \in x} h_U(\beta)$ and such that

$$\int \max_{\beta \in x} h_U(\beta) d\mu(U) = \lim \int \phi_n d\mu.$$

Then

$$\begin{aligned} \int \max_{\beta \in x} h_U(\beta) d\mu(U) &= \lim \sum_{i=1}^n \alpha_{n,i} \mu(D_{n,i}) \\ &= \lim \sum_{i=1}^n \alpha_{n,i} m(\Psi(D_{n,i}, [0, 1])) \quad (\text{by definition of } \mu) \\ &= \lim \sum_{i=1}^n m(\Psi(D_{n,i}, [0, \alpha_{n,i}])) \quad (\text{by Lemma C.5}) \end{aligned}$$

²⁷Recall that h_U and Ψ are defined in (C.18) and (C.19).

$$\begin{aligned}
&= \lim m \left(\bigcup_i^n \Psi(D_{n,i}, [0, \alpha_{n,i}]) \right) \quad \begin{array}{l} \text{(the sets } \Psi(D_{n,i}, [0, \alpha_{n,i}]) \\ \text{are disjoint)} \end{array} \\
&= \lim m (\{\Psi(U, s) : s \leq \phi_n(U)\}) \quad \begin{array}{l} \text{(by definition of} \\ \Psi \text{ and } \phi_n) \end{array} \\
&= m \left(\bigcap_n \{\Psi(U, s) : s \leq \phi_n(U)\} \right) \quad \text{(since } m \text{ is c.a.)}
\end{aligned}$$

Since

$$\bigcap_n \{\Psi(U, s) : s \leq \phi_n(U)\} = \left\{ \Psi(U, s) : \max_{\beta \in x} h_U(\beta) \geq s \right\},$$

we have

$$\begin{aligned}
\int \max_{\beta \in x} h_U(\beta) d\mu(U) &= m \left(\left\{ \Psi(U, s) : \max_{\beta \in x} h_U(\beta) \geq s \right\} \right) \\
&= m(\{y \in Y : y \cap x \neq \emptyset\}) \quad \text{(by (C.22)).}
\end{aligned}$$

Therefore, by (C.15),

$$\int \int \max_{\beta \in x} h_U(\beta) d\mu(U) dP(x) = \int m(\{y \in Y : y \cap x \neq \emptyset\}) dP(x) = \mathcal{W}(P). \quad \blacksquare$$

It remains to prove the uniqueness assertion.

Lemma C.7. *Given any $\mu \in \Delta(\mathcal{K}^{cc}(N^*))$ such that preference \succeq is represented by the utility function in (4.1), define $W : \mathcal{X} \rightarrow \mathbb{R}$ by*

$$W(x) = \int_{\mathcal{K}^{cc}(N^*)} \max_{\beta \in x} h_U(\beta) d\mu(U). \quad \text{(C.23)}$$

Then there exists a unique Borel probability measure m_μ on \mathcal{X} such that

$$W(x) = m_\mu(\{y : x \cap y \neq \emptyset\}), \quad \forall x \in \mathcal{X}. \quad \text{(C.24)}$$

Further, for all Borel measurable sets B ,

$$m_\mu(B) = \int_0^1 \mu(\{U : \Psi(U, s) \in B\}) d\lambda(s), \quad \text{(C.25)}$$

where λ denotes the Lebesgue measure.

Proof. The set function W is infinitely alternating, that is, it satisfies (C.17). Moreover, since μ is countably additive, the Monotone Convergence Theorem implies that $W(x_n) \downarrow W(x)$ whenever $x_n \downarrow x$. Thus the existence of a unique measure m_μ satisfying (C.24) follows from [2, Theorems 50.1, 51.1]. (In fact, existence of m_μ was asserted in Section C.2 and was used in Lemma C.5 - the new claim here is uniqueness.)

For each $s \in [0, 1]$, define $\Psi_s : \mathcal{K}^{cc}(N^*) \rightarrow Y$ by $\Psi_s(U) = \Psi(U, s)$. As a correspondence, Ψ_s is compact-valued and upper hemicontinuous. By [1, Theorem 14.11], it is a closed correspondence. Hence, by [1, Theorem 14.68] it is measurable, and so by [1, Corollary 14.70], when viewed as a function, Ψ_s is Borel measurable, that is, $\Psi_s^{-1}(B) = \{U : \Psi(U, s) \in B\}$ is Borel measurable for every measurable $B \subset \mathcal{X}$.

Therefore, $s \mapsto \mu \circ \Psi_s^{-1}(B)$ is well-defined for each measurable B ; it is also Lebesgue integrable (see [7, Lemma B.2]). Define, for every measurable B ,

$$m'_\mu(B) = \int_0^1 \mu \circ \Psi_s^{-1}(B) d\lambda(s).$$

By the Monotone Convergence Theorem, m'_μ is easily seen to be a Borel measure. Moreover, for all $x \in \mathcal{X}$,

$$\begin{aligned} W(x) &= \int_V \max_{\beta \in x} h_U(\beta) d\mu(U) = \int_0^1 \mu \left(\{U : \max_{\beta \in x} h_U(\beta) \geq s\} \right) d\lambda(s) \\ &= \int_0^1 \mu(\{U : x \cap \{\beta \in \mathcal{B} : h_U(\beta) \geq s\} \neq \emptyset\}) d\lambda(s) \\ &= \int_0^1 \mu \circ \Psi_s^{-1}(\tilde{x}) d\lambda = m'_\mu(\tilde{x}), \end{aligned}$$

where $\tilde{x} = \{y \in Y : x \cap y \neq \emptyset\}$. Therefore, by (C.24), $m'_\mu(\tilde{x}) = m_\mu(\tilde{x})$ for all $x \in \mathcal{X}$. By Lemma C.3 and the uniqueness property established in first part of the proof, we conclude that $m'_\mu(B) = m_\mu(B)$ for all measurable B . \blacksquare

Lemma C.8. *Suppose that μ and μ' represent the same preference as in (4.1). Then $\mu = \mu'$.*

Proof : Define W and W' as in (C.23). Since both W and W' are vNM indices for expected utility functions representing \succeq , they must be identical (given also that they agree on $\{b_*\}$ and $\{b^*\}$). Let m_μ and $m_{\mu'}$ be the Borel probability

measures on \mathcal{X} corresponding to μ and μ' as in Lemma C.7. Then by Lemma C.7, $m_\mu = m_{\mu'}$. Therefore, for each Borel set $D \subset \mathcal{K}^{cc}(N^*)$,

$$\begin{aligned} \mu(D) &= \int_0^1 \mu(D) ds = \int_0^1 \mu(\{U : \Psi(U, s) \in \Psi(D, [0, 1])\}) ds \\ &= m_\mu(\Psi(D, [0, 1])) = m_{\mu'}(\Psi(D, [0, 1])) = \mu'(D). \quad \blacksquare \end{aligned}$$

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