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Dominance Violations and Event Splitting in Decision under Uncertainty*

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November 29, 1999

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A standard requirement of rationality is that preferences obey stochastic dominance. In this paper, we investigate a new variety of dominance violation from the domain of uncertainty. We find that subjects systematically value a *packed prospect*, $x if one of two mutually exclusive events E_1 or E_2 obtains, less than an *unpacked and dominated* prospect, $x if E_1 obtains, and $\$x-\varepsilon$ if E_2 obtains. We account for these violations in terms of subadditivity of probability judgments (Tversky and Koehler, 1994): unpacking an event into constituent components increases the total probability assigned to that event. We discuss the implications of these dominance violations for composition rules in prospect theory.

* We thank Jason Brown and Ben Sommers for assistance in collecting data.

1. Introduction

A standard requirement of rationality is that preferences obey stochastic dominance, i.e., if *A* stochastically dominates *B*, then *A* should be preferred to *B*. This axiom is generally regarded as normatively essentially by decision theorists (e.g., Howard, 1992) as well as by subjects (*e.g.*, MacCrimmon and Larsson, 1979).[1] Indeed, systematic violations of dominance are rarely found in empirical studies of decision making. When direct violations of dominance are found, *i.e.*, when one alternative is chosen over another alternative that dominates it, these violations usually occur because the dominance is not transparent to the subject (Tversky and Kahneman, 1986; Birnbaum and Navarette, 1998; Leland, 1998).[2] In contrast, indirect violations, while rare, are more prevalent than direct violations (*e.g.*, Birnbaum 1997 and references therein). An indirect violation of dominance arises when *A* is priced lower than a stochastically dominated A', or alternatively when the dominated alternative A' is preferred to a third option *B*, while *B* is preferred over *A*.

In this paper, we investigate a new variety of indirect dominance violation. Unlike the previous demonstrations that involve risk, the domain here is uncertainty. In this domain, the analogy to stochastic dominance is cumulative dominance (Sarin and Wakker, 1992).[3] We find that subjects systematically value a *packed prospect*, \$*x* if event E_1 or event E_2 obtains (where E_1, E_2 are mutually exclusive events), less than an unpacked and dominated prospect, \$*x* if event E_1 obtains and $\$x-\varepsilon$ if event E_2 obtains. We demonstrate instances in which the packed prospect is priced lower than the unpacked prospect, as well as instances in which the percentage

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[1] MacCrimmon and Larsson found that subjects gave the rule, "If one alternative *A* has outcomes that are at least as good as the outcomes for another alternative *B*, for very possible state of the world, then alternative *A* is at least as good as *B*", an average rating of 8.1 on a 0 ("strongly disagree") to 10 ("strongly agree") scale. Two rules out of 20 rated higher, transitivity (8.8), and a "looser" form of dominance (8.5; "When two alternatives have probabilities that are in the same range, select the alternative with the larger payoff").

[2] However, direct violations of dominance also occur when individuals use rules such as "choose the option that is favored on the most states" (Paterson and Diekmann, 1988). Paterson and Diekmann found that preference for certain prospects is not invariant to permutation. Let $(x_1,...,x_6)$ represents a gamble in which x_i is the outcome obtained if the *i*-th side of the die occurs. Paterson and Diekman found that 84% of subjects preferred (20,30,40,50,60,10) to (10,20,30,40,50,60), and about 60% of subjects preferred to (20,30,40,50,60,10) to (12,22,32,42,52,62).

[3] Let $S_x(A)$ denote the set of events that give outcome *x* or better under alternative *A*. An alternative *A* cumulatively dominates *B* if $S_x(A) \supseteq S_x(B)$ for all *x*, with a strict set inclusion for some *x*.

of subjects choosing an unpacked prospect over a sure thing is higher than the percentage of subjects choosing the packed prospect over the same sure thing.

We account for these violations in terms of subadditivity of probability judgments (Tversky and Koehler, 1994): unpacking an event ($E_1 \cup E_2$) into constituent components (E_1 and E_2) increases the total probability assigned to that event. Thus, splitting an event into smaller components increases the total probability of that event and hence the attractiveness of the corresponding prospect.

The paper proceeds as follows. In Section 2, we present some examples of dominance violations in which subjects assign a lower price to a packed prospect than an unpacked and dominated prospect. In Section 3, we present some violations involving indirect choice. In Section 4, we describe some theoretical implications of these findings for the two-stage model of Tversky and Fox (1995). We conclude in Section 5.

2. Pricing

A traditional assumption of choice theories is that if *A* is preferred to *B* in direct comparison, then *A* should be priced higher than *B*. It is well-known that this assumption does not in general hold, as is best illustrated by the preference reversal demonstrations of Lichtenstein and Slovic (1973; see also, Grether and Plott, 1979; Tversky and Thaler, 1990). In this section, we document some violations of dominance that take the following form: A' is priced higher than *A*, even though *A* dominates A'. [Throughout our paper, we use dominance as a shorthand for Sarin and Wakker's (1992) cumulative dominance, the uncertainty analog to the more well-studied stochastic dominance.] In particular, *A* will be a prospect that offers \$*x* if event E_1 or event E_2 obtains (where E_1, E_2 mutually exclusive events), and A' will be a prospect that offers \$*x* if event E_1 obtains and $\$x-\varepsilon$ if event E_2 obtains. By construction, *A* dominates A'.

Example 1

Prior to the 1995 American League Championship Series of Major League Baseball, we recruited baseball fans (all undergraduates at Harvard College) to answer one of two surveys concerning the result of the 1995 World Series. The World Series is the championship of Major League Baseball and involves the winners of the American League and National League Championship Series. All subjects were given the following instructions:

> One of four teams — the Cleveland Indians or Seattle Mariners from the American League, or the Atlanta Braves or Cincinnati Reds from the National League — will win the 1995 World Series.
>
> The prospect below offers hypothetical amounts of money depending on the outcome of the World Series.

Subjects were then given one of the two prospects described below, either the "packed" alternative A or the "unpacked" alternative A':

A	If an American League team wins the World Series	*You win $220*
	Otherwise	*You win $0*

	If the Cleveland Indians win the World Series	*You win $220*
A′	If the Seattle Mariners win the World Series	*You win $200*
	Otherwise	*You win $0*

Finally, subjects were asked whether they would choose the uncertain prospect or a particular dollar amount. For example, a typical question would be: "Would you choose A or $220 for sure?" Subjects would then indicate whether they preferred the prospect or $220 by checking the appropriate box next to the preferred alternative. This question was repeated for dollar amounts that varied from $220 down to $0 in increments of $20. Under this scheme, we define the price of A to be the highest dollar amount such that A is preferred to that dollar amount for sure.

Clearly, the packed alternative, A, dominates the unpacked alternative, A'. However, Table 1 indicates that subjects priced A' $11.70 higher on average than A ($t(84) = 1.67$, $p < .10$). Note that in this example, the instructions informed subjects that the two remaining American League teams were Cleveland and Seattle. Nevertheless, the unpacked prospect is more attractive than the packed prospect.

We also asked each subject to rate his or her knowledge of baseball on a 1 ("know very little about baseball" to 9 ("know very much") scale. Subjects rated themselves as quite knowledgeable about baseball: the average rating was 6.1, and only 21% of subject rated their knowledge as 4 or lower. Although more knowledgeable fans tended to give higher prices (r=.19), the mean difference between the conditions was independent of knowledge.

Example 2

The 1995 World Series Championship featured the Cleveland Indians and the Atlanta Braves. After the two teams had won their respective league championships but prior to the start of the World Series, we recruited a second set of baseball fans (undergraduates at Harvard College) to answer one of two surveys. Subjects were given the following instructions:

> On Saturday, October 21, the 1995 World Series kicks off with the Atlanta Braves facing the Cleveland Indians. The first team to win four games will win the 1995 World Series. The prospect below offers hypothetical amounts of money depending on the outcome of the World Series.

Subjects were then given one of two prospects to price, either a "packed" alternative B, or an "unpacked" alternative B':

B	If Cleveland wins the World Series	*You win $150*
	Otherwise	*You win $0*

	If Cleveland wins the World Series in 7 games	*You win $150*
	If Cleveland wins the World Series in 6 games	*You win $145*
B′	If Cleveland wins the World Series in 5 games	*You win $140*
	If Cleveland wins the World Series in 4 games	*You win $135*
	Otherwise	*You win $0*

The procedure for pricing the prospect was identical to the procedure used in Example 1 with one exception. Dollar amounts varied from $150 to $0, in increments of $10. Table 2 shows that subjects priced the packed alternative B $7.20 lower than the unpacked but dominated alternative B' ($t(110) = 1.80, p = .07$). Clearly, the event that "Cleveland wins the World Series" is identical to the event that "Cleveland wins the World Series in 4, 5, 6, or 7 games".

Even so, unpacking the event into different components seems to increase the attractiveness of the gamble, even when the dollar amounts are shaved during the unpacking.

3. Choice

In this section, we demonstrate a second variety of indirect dominance violation. We give subjects a choice between either *A* and *B*, or A' and *B*. We find situations in which $B \succ A$ and $A' \succ B$, even though *A* dominates *A′*. Under transitivity, the two relations imply $A' \succ A$, a direct choice for the dominated alternative, a relation we do not observe.

Example 3

Example 3 was part of a survey of 25 questions administered to Harvard College undergraduates. All but one question involved risk. The source of uncertainty was the high temperature in Boston on February 1, 1996 (the survey was administered in December 1995). Subjects chose between a fixed prospect and either a packed or unpacked prospect. The fixed prospect *C* is given below:

	If 30° < Boston Temperature $\leq$ 40°	*You win $160*
C	If 40° < Boston Temperature $\leq$ 50°	*You win $120*
	Otherwise	*You win $0*

Subjects chose between the fixed prospect *C* and either an packed (*D*) or unpacked (*D′*) prospect:

	If Boston High Temperature $\leq$ 50°	*You win $120*
D		
	Otherwise	*You win $0*

	If Boston High Temperature $\leq$ 40°	*You win $120*
D¢	If 40° < Boston High Temperature $\leq$ 50°	*You win $110*
	Otherwise	*You win $0*

Thus, half of the subjects (n=58) chose between C and D (the packed prospect), while the other half (n=59) chose between C and D' (the unpacked prospect). Even though D' is dominated by C, the subjects choosing the unpacked prospect over the fixed prospect (50%) was higher than the percentage choosing the packed prospect over the fixed prospect (32%) (binomial test of proportions, p=.025).

Example 4

Example 4 was administered to University of Chicago undergraduates prior to the beginning of the 1996-97 National Basketball Association regular season. The source of uncertainty was the number of games the Chicago Bulls would win during the regular season (maximum 82). Subjects chose between $150 for sure and one of the following two prospects:

E	If the Chicago Bulls win more than 65 games	*You win $240*
	Otherwise	*You win $0*

	If the Chicago Bulls win between 65 and 69 games	*You win $240*
E′	If the Chicago Bulls win more than 70 games	*You win $220*
	Otherwise	*You win $0*

Relative to the sure $150, the unpacked prospect (E') was more popular than the packed prospect (E): 56% of subjects (n=75) chose the unpacked prospect E' over $150, whereas only 38% of subjects (n=50) chose the packed alternative E over the sure thing (p=.02).

Example 5

University of Chicago undergraduates were recruited to complete a survey involving several risk and uncertainty questions. The uncertainty question involved the high temperature (in Degrees Fahrenheit) of Chicago on March 1, 1997. Subjects chose between a fixed prospect and either a packed or unpacked prospect. The fixed prospect F is shown below, followed by the packed (G) and unpacked (G') prospects:

F	If Chicago High $\leq$ 25°	*You win $180*
	Otherwise	*You win $0*

G	If Chicago High $\leq$ 30°	*You win $125*
	Otherwise	*You win $0*

	If Chicago High $\leq$ 25°	*You win $125*
G′	If 25° < Chicago High $\leq$ 30°	*You win $120*
	Otherwise	*You win $0*

Once again, even though G' is dominated by G, the subjects choosing the unpacked prospect over the fixed prospect (75%, n=60) was higher than the percentage choosing the packed prospect over the fixed prospect (50%, n=59) (p=.002).

We also asked subjects to provide assessments of the relevant events. Subjects who were asked to choose between F and G' gave probabilities for the events "Chicago High $\leq$ 25°" (E_1) and "25° < Chicago High $\leq$ 30°" (E_2). The other subjects assessed the chance of the event "Chicago High $\leq$ 30°" ($E_1 \cup E_2$). Consistent with support theory, the probability assigned to the packed event, $E_1 \cup E_2$, .54, is significantly lower than the probability assigned to the sum of the constituent events, .75 (p<.0001).

Example 6

The subjects for Example 6 were University of Michigan undergraduates recruited prior to the 1998 American and National League Championship Series of Major League Baseball. Subjects were given the following instructions:

> One of four teams — the Cleveland Indians or New York Yankees from the American League, or the Atlanta Braves or San Diego Padres from the National League — will win the 1998 World Series (the championship of Major League Baseball). The prospect below offers hypothetical amounts of money depending on the outcome of the World Series.

Subjects were then given two binary choice questions, each involving a sure thing and either an unpacked or packed alternative. The first question involved a choice between $100 for sure and either the packed alternative *H* or the unpacked alternative H' described below:

H	If an American League team wins the World Series	*You win $180*
	Otherwise	*You win $0*

H'	If the New York Yankees win the World Series	*You win $180*
	If the Cleveland Indians win the World Series	*You win $160*
	Otherwise	*You win $0*

The alternatives for the second question were $180 for sure and one of the two alternatives described below:

I	If a National League team wins the World Series	*You win $320*
	Otherwise	*You win $0*

I'	If the Atlanta Braves win the World Series	*You win $320*
	If the San Diego Padres win the World Series	*You win $300*
	Otherwise	*You win $0*

Subjects also provided a rating of their knowledge of baseball on a 1 ("know very little") to 9 ("know very much") scale. Finally, we asked subjects for probabilities of the relevant events. If subjects were given a packed prospect, then they provided probabilities that "an American League team will win the World Series" (alternative *H*) or "a National League team will win the World Series" (alternative *I*). If subjects were given an unpacked prospect, subjects estimated the chance that the New York Yankees would win and the chance that the Cleveland Indians would win (Alternative H'); or the chance that the Atlanta Braves would win and the chance that the San Diego Padres would win (Alternative I').

The results were consistent with our previous results. For the National League question, 32% picked the packed prospect I over the sure thing (n=47), compared to 53% for the unpacked prospect I' (n=47). (z=2.10, p<.02). The American League results were in the same direction, but not significant: 34% of 47 subjects chose the packed prospect H, and 43% chose the unpacked prospect H' (p=.20, n.s.).

The probabilities were consistent with support theory. The mean probability that the National League would win the World Series was .49, whereas the probability for the Atlanta Braves and San Diego Padres were .39 and .28 respectively (t(91)=3.06, p=.0029). Similar results were obtained for the American League prospects. The mean probability given that an American League team would win was .58, compared to probabilities for the Yankees (.57) and the Indians (.30) (t(91)=4.69, p<.0001).

4. Theoretical Implications

In our studies, subjects are valuing either a two-outcome prospect, (x, E), $\$x$ if event E obtains and \$0 otherwise; or $\left(x_1, E_1; x_2, E_2\right)$, $\$x_i$ if event E_i obtains and \$0 otherwise, where E_i are mutually exclusive and $x_1 > x_2$. The pricing and choice studies in Sections 2 and 3 indicate that $\left(x, E_1; x-\varepsilon, E_2\right)$ is valued higher than $(x, E_1 \cup E_2)$. Thus, the packed alternative is valued less than the unpacked but dominated alternative.

These results resemble the event-splitting effects first documented by Starmer and Sugden (1993; see also Humphrey, 1995). Starmer and Sugden considered prospects represented in an "act/event matrix." They found that a prospect became more attractive when the event giving rise to a positive outcome was split into two events. For example, the uncertain event in Starmer and Sugden's experiments was the number in a sealed envelope, which could be any integer number from 1 to 100. The number of their subjects who chose a .30 chance at £8 over a .20 chance at £15 went from 51% when the safer gamble was represented as £8 if a number from 1 to 30 was drawn, to 69% when the same gamble was represented as £8 if a number from 1 to 15 was drawn and £8 if a number from 16 to 30 was drawn.

We explain our findings in Starmer and Sugden's by evoking support theory (Tversky and Koehler, 1994; Rottenstreich and Tversky, 1997).[4] Tversky and Koehler reviewed 14 studies and found in each case that unpacking a focal hypothesis into its constituent components increased the probability assigned to that hypothesis. The "unpacking factor", a measure of how much probability was increased by unpacking the focal hypothesis, ranged from 1.22 to 4.25. Of course, additivity requires that the unpacking factor equal one. Tversky and Koehler posit that the probability judgments sum to one for binary partitions (binary complementarity[5]) and are subadditive for finer partitions. Formally, if $\rho(\cdot)$ is an non-additive probability measure defined on events, support theory requires that:

(i) $\rho(E_i)+\rho(E_j)\geq\rho(E_{ij})$ for E_i, E_j disjoint;

(ii) $\rho(E_i)+\rho(\sim E_i)=1$, where $\sim E_i$ is the complement of E_i.

Tversky and Fox (1995) (also Fox and Tversky, 1998) posit a two-stage model for decision under uncertainty in which a prospect, (x,E), is represented by $U(x,E)=\pi\left(\rho(E)\right)v(x)$, in which $\pi:[0,1]\rightarrow[0,1]$ is a probability weighting function that takes objective or subjective probabilities into decision weights (Kahneman and Tversky, 1979; Tversky and Kahneman, 1992; Wu and Gonzalez, 1996). In their study of three-outcome gambles, $\left(x_1,E_1;x_2,E_2\right)$, Wu and Gonzalez (1999) discussed the implications of the following natural generalization of the two-stage model:

$$U\left(x_1,E_1;x_2,E_2\right)=\pi\left(\rho(E_1)\right)v(x_1)+\left[\pi\left(\rho(E_1\cup E_2)\right)-\pi\left(\rho(E_1)\right)\right]v(x_2). \tag{4.1}$$

Although (4.1) is theoretically appealing in the sense that $\pi\left(\rho(\cdot)\right)$ can be thought of as the capacity for Choquet integration (Gilboa, 1987; Schmeidler, 1989), (4.1) cannot explain a preference for $\left(x,E_1;x-\varepsilon,E_2\right)$ over $\left(x,E_1\cup E_2\right)$ as the generalization preserves dominance. This can be seen by applying (4.1) to the two prospects:

$$U(x,E_1\cup E_2)-U(x,E_1;x-\varepsilon,E_2)=$$

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[4] For more recent data, see Fox, Rogers, and Tversky (1996), Fox and Tversky (1998), and Wu and Gonzalez (1999).

[5] For counterexamples, see Brenner and Rottenstreich (1997) and Krantz et al. (1998).

$$\left(\pi\left(\rho(E_1 \cup E_2)\right) - \pi\left(\rho(E_1)\right)\right)\left(v(x) - v(x-\varepsilon)\right),$$

which must be greater than or equal to 0.

A modification of (4.1) that can accommodate the domination violations follows:

$$U\left(x_1, E_1; x_2, E_2\right) = \pi\left(\rho(E_1)\right)v(x_1) + \left[\pi\left(\rho(E_1) + \rho(E_2)\right) - \pi\left(\rho(E_1)\right)\right]v(x_2). \tag{4.2}$$

The central difference between (4.1) and (4.2) is in terms of whether the probability weighting function is applied to the judged probabilities of union of events, $\pi\left(\rho(E_1 \cup E_2)\right)$, or the sum of the judged probabilities of the disjoint events, $\pi\left(\rho(E_1) + \rho(E_2)\right)$.

Note that (4.2) can explain the dominance violations. For ε small,

$$U\left(x_1, E_1; x_1 - \varepsilon, E_2\right) - U\left(x_1, E_1 \cup E_2\right) \approx$$
$$\left[\pi\left(\rho(E_1) + \rho(E_2)\right) - \pi\left(\rho(E_1 \cup E_2)\right)\right]v(x_1),$$

which is positive if $\pi(\cdot)$ is strictly increasing and $\rho(\cdot)$ is strictly subadditive.

Whether (4.1), (4.2), or some other model fits best is an empirical question. The discussion here is reminiscent of the debate about whether old or new prospect theory works better (Camerer and Ho, 1994; Wu, 1994; Wu and Gonzalez, 1996; Fennema and Wakker, 1997; Gonzalez and Wu, 2002). Although original prospect theory (OPT; Kahneman and Tversky, 1979) has undesirable properties (such as permitting violations of stochastic dominance), there are some patterns it can explain but cumulative prospect theory (CPT; Tversky and Kahneman, 1992) cannot (e.g., Wu, 1994). Both models have their appeal, and different decision problem representations might encourage the use of one form over another. This suggests perhaps a unifying theory in which (4.1) (similarly, CPT) is used when problems are represented in one manner, (4.2) (similarly, OPT) is used when problems are represented another way, and other models are used for other representations.

5. Conclusion

In this paper, we presented several examples that showed that splitting an event into constituent components could increase the attractiveness of a prospect, even if the dollar amounts were shaved during the unpacking. In all cases, it was clear that the union of the unpacked events was identical to the packed event, either according to instruction (Examples 1 and 2) or because it was self-evident (Example 3 and 4). The violation demonstrated relies on the robust effect that unpacking an event into constituent components increases the judged probability of that event. Subadditivity has been shown for disparate event spaces, such as event spaces in which the component events cannot be easily recalled (e.g., fault trees), numerical partitions (e.g., Microsoft stock price), as well as categorical partitions (e.g., teams in an NBA basketball conference) (e.g., Fox and Tversky, 1998).

We note that our finding was preceded by Johnson, Hershey, Meszaros, and Kunreuther (1993). Johnson et al. asked subjects how much they would pay for a variety of insurance policies which would pay if the party was terrorized during a one-week trip to Thailand. Whereas the average price that subjects assigned to protection for the roundtrip (U.S. to Thailand and back) was $13.90, the prices they assigned to the individual legs (U.S. to Thailand, and Thailand to U.S.) were $13.63 and $17.19, a total of $30.82! The results are explained as follows: "(t)he imagined dangers that could occur in Thailand, or returning from this trip, may seem more vivid, and therefore more important to insure against."

The results of these studies suggest interesting implications for the framing of choices, as well as the design of products. The representation constructed by a decision maker may dramatically alter how the alternatives are evaluated. To illustrate, suppose that a company must decide whether to submit a proposal for a new contract or invest its resources elsewhere. To simplify, suppose there are two critical uncertainties, a "large" uncertainty (whether the company wins the contract) and a "moderate" uncertainty (the cost of producing the product). One manager might only focus on winning the contract: "If we win the contract, we'll make $800,000." A second manager might consider both uncertainties: "If we win the contract and are able to control our cost, we'll make $850,000, whereas we'll make $750,000 if we can't control costs." Event splitting suggests that the second manager is more likely to endorse the proposal as ρ(Win & control cost) + ρ(Win & don't control cost) > ρ(Win). Ironically, the more detailed a partition the decision maker creates, the more susceptible that decision maker is to event splitting.

To illustrate the implications for design of products, consider state lotteries. The state lottery board might actually increase revenues (and profit margin!) by splitting events. Thus, Lotto could be re-engineered such that matching 5 out of 6 numbers is split into (i) matching 5 out of 6 numbers and matching a bonus number; and (ii) matching 5 out of 6 numbers and not matching a bonus number.

We conclude with some brief remarks on dominance axioms. The reluctance of theorists to embrace models that permit dominance violations is understandable. Models built on dominance axioms are most always more parsimonious, tractable, and elegant. The descriptive validity of dominance is also assumed implicitly; models that permit dominance violations are not needed if we do not observe violations of dominance.

This paper suggests however that individuals do violate dominance at least in indirect choice. An analogy can be drawn between this work and the work on joint and separate evaluation preference reversals (Hsee et al., 1999). Hsee (1998) had subjects price 8 ounces of ice cream in a 10 ounce cup and 5 ounces of ice cream in a 7 ounce cup separately and jointly. He found a reversal of preferences: subjects priced the small overfilled cup higher than the large underfilled cup in separate evaluation, while the opposite pattern held in joint evaluation.

This paper shares much of that spirit. Whereas dominance violations are exceedingly unlikely in direct choice, they are more prevalent in indirect choice. This observation suggests a challenge for modelers. There is no reason to suspect that tractable models are not possible. Indeed, recent work has shown more complex models to be more tractable in the sense of natural parsimonious parameterizations (e.g., Gonzalez and Wu 2002).

Table 1: Violation of Dominance using Pricing (Example 1)

	Mean	SD	N
A (unpacked and dominated)	93.63	39.71	42
A′ (packed)	82.86	36.8	44

Table 2: Violation of Dominance using Pricing (Example 2)

	Mean	SD	N
B (unpacked and dominated)	70.5	27.9	55
B′ (packed)	63.3	24.4	57

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