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# Multivariate discrete first order stochastic dominance

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## Abstract

This paper characterizes the principle of first order stochastic dominance in a multivariate discrete setting. We show that a distribution  $f$  first order stochastically dominates distribution  $g$  if and only if  $f$  can be obtained from  $g$  by iteratively shifting density from one outcome to another that is better. For the bivariate case, we develop the theoretical basis for an algorithmic dominance test that is easy to implement.

JEL classification: D63, I32, O15.

Keywords: multidimensional first degree distributional dominance, robust poverty gap dominance, majorization, generalized equivalence result.

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# 1 Introduction

The stochastic dominance concept is important in economics, finance, statistics, operations research, mathematical physics and mathematical psychology.<sup>1</sup> The concept goes under different names, such as distributional dominance, or stochastic majorization. Levy (1992) surveys the stochastic dominance literature with emphasis on economics and finance applications.

First order dominance is the principal stochastic dominance criterion.<sup>2</sup> In a univariate setting, several equivalent definitions of first order dominance are available. To be concrete, let  $f$  and  $g$  denote two distribution functions over income with finite support. The following three statements are then equivalent: (A)  $g$  can be obtained from  $f$  by a finite sequence of bilateral transfers of density to smaller outcomes; (B) Any expected utility maximizer prefers  $f$  to  $g$  or is indifferent; (C)  $F(t) \leq G(t)$  for every  $t$ , where  $F$  and  $G$  are the cumulative distribution functions corresponding to  $f$  and  $g$ . The equivalence between (B) and (C) was observed by Lehmann (1955) and Quirk and Saposnik (1962). The equivalence between (A) and (C) is straightforward.

Criterion (A) provides a definition of first order dominance explicitly in terms of an elementary operation: that of moving density (probability mass) from one outcome to another, which is less attractive. It captures the intuitive idea that when transferring density to worse outcomes a number of times, the distribution obtained must be inferior to the original one. This

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<sup>1</sup>Bawa (1982) lists more than four hundred references.

<sup>2</sup>For an account of second order stochastic dominance and other dominance criteria, see, e.g., Cowell (2000).

equivalence between a simple and intuitive definition in terms of a set of elementary bilateral transfers (A), a definition founded in expected utility theory (B), and an empirically implementable criterion (C) provides the theoretical underpinnings for the use of first order dominance criteria in a univariate setting.<sup>3</sup>

A variety of first order dominance criteria for comparing multivariate distributions have been proposed in the literature. Levy and Paroush (1974), Harder and Russell (1974), Huang et al. (1978), and Atkinson and Bourguignon (1982) provide results for the bivariate case. They establish conditions implying that any expected utility maximizer would prefer one distribution to another, given that the utility functions belong to some family with specified signs on the first order partial derivatives and the second order cross-derivative. Interpreting assumptions on the signs of the higher order derivatives is not easy in the context of multivariate decision-making under uncertainty, although the sign of the second order cross-derivative is often interpreted in terms of complementary/substitutability of the two attributes. Extensions to cases with more than two attributes are possible, but such extensions rely on conditions on mixed derivatives of an order which can be as high as the number of attributes. Levhari et al. (1975) consider a dominance criterion for the family of non-decreasing (quasi-concave) utility functions. Mosler (1984) derives stochastic dominance criteria with respect to additive, multiplicative, and multilinear utilities, and Russell and Seo (1978) and Scarcini (1988) establish stochastic dominance criteria for

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<sup>3</sup>A corresponding characterization of second order stochastic dominance was provided by Hardy et al. (1934). See also the very illuminating discussion in the Introduction of the paper by Gravel and Moyes (2006).

classes of utility functions satisfying some multivariate generalizations of risk aversion.

The above-mentioned contributions give results of the type where a pair of multivariate distributions satisfy certain (empirically testable) conditions if and only if any expected utility maximizer with a utility function from a specified family of functions prefers one of the distributions to the other. However, it is not shown that the conditions are equivalent to any more elementary notion of multivariate dominance.

The elementary transfer approach to stochastic dominance of the first order (or higher) has, to our knowledge, never been established in a multivariate setting.<sup>4</sup> Only Gravel and Moyes (2006) demonstrate a form of equivalence between notions of dominance when there are two attributes and when one attribute is cardinally measurable.

This paper characterizes first order dominance in a multivariate discrete setting. We define dominance as follows: A distribution  $f$  dominates distribution  $g$  if the latter can be obtained from the former by iteratively transferring density from one outcome to another one that is unambiguously worse. We show that  $f$  dominates  $g$  if and only if a set of inequalities (an empirically testable criterion) is satisfied. This criterion is well-known in the

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<sup>4</sup>Indeed, Trannoy (2006) observes that “the equivalence between the transfer approach and the others seems particularly hard to get”. Gravel and Moyes (2006) observe that “[w]hile there has been in the last thirty years a number of contributions (see e.g. Atkinson and Bourguignon [1982, 1987], Bourguignon [1989], Hadar and Russel [1974], Kolm [1977] and Koshevoy [1995, 1998]) that have proposed dominance criteria for comparing distributions of several attributes, none of them has established an *equivalence* between an *empirically implementable criterion* (such as Lorenz or poverty gap dominance), a *welfarist unanimity over a class of utility functions*, and a *set of elementary redistributive operations* which would capture in an intuitive way the nature of the multidimensional redistribution that is looked for.”

context of stochastic dominance but the equivalence established between an entirely elementary definition and an empirically testable criterion appears to be new. For the bivariate case, we further develop a simple algorithmic test. It is computationally more efficient when the outcome set is large.

## 2 The transfer approach to multivariate dominance

An *outcome* is a vector  $x = (x_1, \dots, x_N)$  described by  $N$  attributes,  $x_j$ ,  $j = 1, \dots, N$ , where each attribute is defined on an attribute set  $X_j = \{1, \dots, \bar{x}_j\}$ . The set of outcomes to be considered is the product set  $X = X_1 \times \dots \times X_N$  of the attribute sets  $X_j$ . Let  $\bar{x} = (\bar{x}_1, \dots, \bar{x}_N)$ . The statement  $x \leq y$  will mean that  $x_j \leq y_j$  for all  $j$ , and  $x < y$  will mean that  $x_j \leq y_j$  for all  $j$  and  $x \neq y$ .

A *distribution* (for example, a probability distribution or a population distribution) is described by a density function  $f(x)$  on  $X$ . Thus,  $f(x) \geq 0$  for all  $x$  and  $\sum_{x \in X} f(x) = 1$ . We say that  $g$  can be derived from  $f$  by a *bilateral transfer* (of density) between  $x$  and  $y$ , if there are outcomes  $x, y$  such that  $g(z) = f(z)$  for  $z \neq x, y$ . The bilateral transfer is *diminishing* if  $g(x) \geq f(x)$  and  $x < y$ . We will say that  $f$  *dominates*  $g$  (or, as an equivalent statement,  $g$  *is dominated by*  $f$ ) if  $g$  can be derived from  $f$  by a finite sequence of diminishing bilateral transfers. Note that the dominance relation is transitive and reflexive but not complete.

For the univariate case  $X = X_1$ , the definition of dominance in terms of diminishing bilateral transfers corresponds to the well-known transfer approach to first order stochastic dominance outlined in the Introduction. For

that case, empirical implementation follows from the equivalence between (A) and (C). For two distributions  $f$  and  $g$ , testing that  $g$  is dominated by  $f$  is just a matter of checking  $\bar{x}_1$  inequalities. The next section treats the general case  $X = X_1 \times \cdots \times X_N$ .

### 3 Empirical implementation

The first result of this paper is a set of necessary and sufficient conditions for  $f$  dominating  $g$ . It specifies a list of inequalities which has to be satisfied for  $g$  to be dominated by  $f$ .

We will make use of the following definitions and notation:  $L(x) = \{y | y \leq x\}$ . Given  $f$  and  $S \subseteq X$ ,  $r(S|f) = \sum_{y \in \cup_{s \in S} L(s)} f(y)$ .

**Theorem 1** *The following two statements are equivalent:*

- (i)  $g$  is dominated by  $f$ .
- (ii)  $r(S|g) \geq r(S|f)$  for each  $S \subseteq X \setminus \{\bar{x}\}$ .

*Moreover, the characterization is sharp, in the sense that none of the constraints in (ii) can be dispensed with.*

Proof: “(i)  $\Rightarrow$  (ii)”. The case  $f = g$  is trivial, hence we can assume  $f \neq g$ . Thus, there is a positive integer  $n$ , and distributions  $g^i$ ,  $i = 0, \dots, n$ , such that  $g^0 = f$ ,  $g^n = g$ , and  $g^{i+1}$  can be derived from  $g^i$  by a diminishing bilateral transfer, for  $i = 0, \dots, n - 1$ .

By the statement “ $g^i$  satisfies the conditions in (ii)” we mean that:  $r(S|g^i) \geq r(S|f)$  for each  $S \subseteq X \setminus \{\bar{x}\}$ . We use an induction argument



to show that  $g^n = g$  satisfies the conditions in (ii). First, note that  $g^0 = f$  satisfies the conditions in (ii). Second, let  $0 \leq i < n$  and suppose that  $g^i$  satisfies the conditions in (ii). Since  $g^{i+1}$  is obtained from  $g^i$  by a diminishing bilateral transfer, for any  $S \subseteq X \setminus \{\bar{x}\}$  we have  $r(S|g^{i+1}) \geq r(S|g^i) \geq r(S|f)$ . The first inequality holds because if  $g^i(y') - g^{i+1}(y') = \delta > 0$  for some  $y'$  in  $L(x)$ ,  $x \in S$ , then  $g^{i+1}(x') - g^i(x') = \delta$  for some other  $x'$  in  $L(x)$  and  $g^{i+1}(z') = g^i(z')$  for any other  $z'$  in  $L(x)$ . The second inequality is the induction hypothesis. Thus,  $g^{i+1}$  satisfies the conditions in (ii), and we are done.

“(ii)  $\Rightarrow$  (i)”. For the proof of the converse implication, we state and prove the following lemma.

**Lemma A** *Consider two distributions  $f$  and  $g$ , for which (ii) is satisfied. Then,  $g$  can be obtained from  $f$  by a finite sequence of bilateral transfers, such that there is not an outcome  $x' \in X \setminus \{\bar{x}\}$  and a bilateral transfer where density is moved from an outcome in  $L(x')$  to an outcome not in  $L(x')$ .*

Proof of Lemma A: Consider a sequence of bilateral transfers leading from  $f$  to  $g$ , arranged as follows: Let  $x^1, x^2, \dots$  be an ordering of the outcomes in  $X$  such that  $z < x^i$  implies  $z \in \{x^1, \dots, x^{i-1}\}$ , whenever  $i \geq 2$  and  $x^i \in X$ . Then, arrange the bilateral transfers such that  $g$  is obtained from  $f$  by an ordered sequence of bilateral transfers where each outcome  $x^i$  is considered in turn (according to the specified order of outcomes), and when outcome  $x^i$  is under consideration all bilateral transfers *from*  $x^i$  to all other outcomes in  $X$  are carried through.

We want to show that  $g$  can be obtained from  $f$  using only bilateral transfers each satisfying the following property: if density is transferred from  $x$  to  $y$ , then  $y \in L(x)$  (i.e., the bilateral transfer is diminishing).

To show this, we proceed by induction on the outcomes in  $X \setminus \{\bar{x}\}$ . First, consider the outcome  $x^1 = (1, \dots, 1)$ . If a total amount  $t$  of density is transferred from  $x^1$  to other outcomes in  $X$ , then later in the sequence a total amount of at least  $t$  is transferred to  $x^1$  from other outcomes. Thus, by redirecting subsequent bilateral transfers if necessary, we can specify the ordered list of bilateral transfers such that no density is transferred from  $x^1$  to other outcomes.

Second, suppose that there are outcomes  $x^1, \dots, x^k$ ,  $k \geq 1$ , and an ordered sequence of bilateral transfers leading from  $f$  to  $g$  in which there are no bilateral transfers from  $x^i$  to outcomes not in  $L(x^i)$ ,  $i = 1, \dots, k$ . Now consider outcome  $x^{k+1}$ . We claim that it is possible to choose the bilateral transfer from  $x^{k+1}$  to other outcomes, such that every bilateral transfer from  $x^i$  goes to an outcome in  $L(x^i)$ ,  $i = 1, \dots, k+1$ , and still be able to obtain the desired distribution  $g$ , by a suitable choice of bilateral transfers from the remaining outcomes  $x^{k+2}, x^{k+3}, \dots$ . For this, suppose that the aforementioned sequence of bilateral transfers involves a bilateral transfer from  $x^{k+1}$  to some  $y' \notin L(x^{k+1})$  where  $y'$  may or may not be in  $\{x^1, \dots, x^k\}$ . Note that  $\{x^1, \dots, x^k\} = L(x^1) \cup \dots \cup L(x^k)$ . We can then redirect bilateral transfers according to the procedure described in i)-iii) below.

Ad. i). Pick  $y \notin \{x^1, \dots, x^k\}$  (if no such outcome exists, go to ii)). By the constraint  $r(\{x^1, \dots, x^{k+1}\}|g) \geq r(\{x^1, \dots, x^{k+1}\}|f)$ , there must be a bilateral transfer from an outcome  $q$  in the set  $\{x^{k+2}, x^{k+3}, \dots\}$  to an outcome  $w$  in

$\{x^1, \dots, x^k\}$ . We can therefore redirect some of these two bilateral transfers, such that (parts of) the bilateral transfer from  $x^{k+1}$  to  $y$  is instead taken from  $q$  and, in a similar amount, (parts of) the transfers from  $q$  to  $w$  is instead taken from  $x^{k+1}$ . By continuing this process of redirecting bilateral transfers from  $x^{k+1}$  to  $y$  and other outcomes in  $\{x^{k+2}, x^{k+3}, \dots\}$ , we can in a finite number of steps eliminate all bilateral transfers from  $x^{k+1}$  to outcomes  $\{x^{k+2}, x^{k+3}, \dots\}$ . When there are no more bilateral transfers from  $x^{k+1}$  to outcomes  $y$  in  $\{x^{k+2}, x^{k+3}, \dots\}$ , go to ii):

Ad. ii). Pick  $y \in \{x^1, \dots, x^k\}$  and there is  $z \in \{x^1, \dots, x^k\}$  such that  $y < z$  (if no such outcome exists, go to iii)). We can decompose the bilateral transfer from  $x^{k+1}$  to  $y$  into a bilateral transfer from  $x^{k+1}$  to  $z$  and a bilateral transfer from  $z$  to  $y$ . Note that the bilateral transfer from  $z$  to  $y$  is diminishing, i.e. this respecification of the sequence of bilateral transfers does not introduce bilateral transfers from outcomes in  $\{x^1, \dots, x^k\}$  that are not diminishing. We can continue this process of decomposing bilateral transfers until all bilateral transfers from  $x^{k+1}$  are either diminishing or as in the residual case iii) below. When this situation is reached, go to iii):

Ad. iii). Pick  $y \in \{x^1, \dots, x^k\}$  for which  $y < v$  implies  $v \notin \{x^1, \dots, x^{k+1}\}$  (if no such outcome exists, we are done). Due to the constraint  $r(\{x^{k+1}\}|g) \geq r(\{x^{k+1}\}|f)$ , there is a bilateral transfer from some  $z \notin L(x^{k+1})$  to an element  $w$  in  $\{x^1, \dots, x^{k+1}\}$ .

If  $z \notin \{x^1, \dots, x^{k+1}\}$ , then by redirecting bilateral transfers we can eliminate or decrease the bilateral transfer from  $x^{k+1}$  to  $y$ , by letting  $z$  transfer to  $y$  and letting  $x^{k+1}$  transfer to  $w$ .

Thus, assume that  $z \in \{x^1, \dots, x^{k+1}\}$ . Due to the constraint  $r(\{x^{k+1}, z\}|g) \geq r(\{x^{k+1}, z\}|f)$  there is a bilateral transfer from some  $z' \notin L(x^{k+1}) \cup L(z)$  to an element  $w'$  in  $L(x^{k+1}) \cup L(z)$ . If  $w' \notin L(x^{k+1})$ , we can respecify the bilateral transfers such that there is a bilateral transfer directly from  $z'$  to  $z$  and, if  $w' \neq z$ , a diminishing bilateral transfer within the set  $L(z) \setminus L(x^{k+1})$  from  $z$  to  $w'$ . With this respecification, there is both a bilateral transfer from  $z'$  to  $z$  and again a bilateral transfer from  $z$  to  $w$ .

Now, due to the constraint  $r(\{x^{k+1}, z, z'\}|g) \geq r(\{x^{k+1}, z, z'\}|f)$ , there is a bilateral transfer from an outcome  $z'' \notin L(x^{k+1}) \cup L(z) \cup L(z')$  to an element  $w''$  in  $L(x^{k+1}) \cup L(z) \cup L(z')$ . In particular, either  $w''$  is in  $L(x^{k+1})$  or this bilateral transfer can be decomposed into a bilateral transfer from  $z''$  either to  $z$  and a diminishing bilateral transfer within  $L(z)$  or a bilateral transfer from  $z''$  to  $z'$  and a diminishing bilateral transfer within  $L(z')$ .

In a similar way, we can in a sequential manner find new outcomes  $z''', z'''' , \dots, z^j, \dots, z^J$ , where  $z''' \notin L(x^{k+1}) \cup L(z) \cup L(z') \cup L(z'')$ ,  $z^j \notin L(x^{k+1}) \cup L(z) \cup \dots \cup L(z^{j-1})$ , etc., such that for any new  $z^j$  there is a bilateral transfer from  $z^j$  to the set  $L(x^{k+1}) \cup L(z) \cup \dots \cup L(z^{j-1})$  and  $z^J \notin X \setminus \{x^1, \dots, x^{k+1}\}$ . By redirecting bilateral transfers for each new outcome in a way analogous to that specified above for the bilateral transfers from  $z$ ,  $z'$  and  $z''$ , we get a sequence of nested bilateral transfer from  $z^J$  — through elements  $z, z', \dots, z^j, \dots$  to an element in  $L(x^{k+1})$ .

There is a nested sequence of bilateral transfers from  $z^J \notin \{x^1, \dots, x^{k+1}\}$  to  $w$  in  $L(x^{k+1})$  and a bilateral transfer from  $x^{k+1}$  to  $y' \notin L(x^{k+1})$ . Thus, by redirecting bilateral transfers, such that density is transferred from  $x^{k+1}$  to  $w$  and from  $z^J$  to  $y'$ , we can reduce the transferring of density from  $x^{k+1}$  to

outcomes not in  $L(x^{k+1})$ . Since this process of redirecting bilateral transfers can be repeated until no more density is being transferred from  $x^{k+1}$  to an outcome not in  $L(x^{k+1})$ , we get that there are outcomes  $x^1, \dots, x^{k+1}$ , and an ordered sequence of bilateral transfers leading from  $f$  to  $g$  in which there are no bilateral transfers from  $x^i$  to outcomes not in  $L(x^i)$ ,  $i = 1, \dots, k + 1$ . Verification of the statement of the lemma is then immediate.  $\square$

Lemma A tells that if the inequalities in (ii) are satisfied, then we can always obtain  $g$  from  $f$  by a sequence of diminishing bilateral transfers in  $X$ . This proves that (ii) implies (i).

It remains to be verified that the characterization provided in Theorem 1 is sharp, in the sense that none of the inequalities in (ii) can be dispensed with. For this, let  $S' \subseteq X \setminus \{\bar{x}\}$ , and suppose that  $r(S|g) \geq r(S|f)$  for each  $S \subseteq X \setminus \{\bar{x}\}$ ,  $S \neq S'$ .

We need to show that there exist  $f$  and  $g$  such that  $g$  cannot be obtained from  $f$  by a finite sequence of diminishing bilateral transfers. For this, imagine that  $g$  is obtained from  $f$  in the following way: Let  $\{s^1, \dots, s^j, \dots, s^J\}$  denote the set of outcomes in  $S'$  satisfying the condition that if  $s^j < z$  then  $z \notin S'$ . Next, an amount  $t$  is transferred from outcome  $s^j$  to  $m$ ,  $j = 1, \dots, J$ , and an amount  $t$  is transferred from  $m$  to each element  $z = (z_1, \dots, z_N)$  for which there is some  $y \in \cup_{j=1, \dots, J} L(s^j)$  where  $y_i = z_i - 1$  for some  $i$  and  $y_h = z_h$  for  $h \neq i$ . Further, an amount  $t(|S'| - 1)$  is transferred from  $m$  to the minimal outcome in  $X$ , i.e. the outcome  $x$  for which  $x \leq z$  for all  $z$  in  $X$ . It is clear that there exist  $f$ ,  $g$  and  $t$ , for which such bilateral transfers are possible, without violating the requirement that the density associated

with each outcome should be non-negative. With such bilateral transfers,  $r(S'|g) < r(S'|f)$ , and  $r(S|g) \geq r(S|f)$  for any  $S \neq S', S \subseteq X \setminus \{\bar{x}\}$  (as can be verified). In particular, we cannot obtain  $g$  from  $f$  by a finite sequence of diminishing bilateral transfers. This completes the proof of Theorem 1.  $\square$

Theorem 1 allows us to generalize the fundamental equivalence (A)-(C) reviewed in the Introduction. For completeness, we add to this a fourth equivalence. We can define a *multidimensional poverty line* as a set  $L$  in  $X$  with the property that  $x \in L$  and  $y < x$  implies  $y \notin L$ .<sup>5</sup> The poor outcomes are delimited by the poverty line and given by the set  $P(L) = \{y \in X | y \leq x \text{ for some } x \in L\}$ . Given  $L$ , the ratio of poor to non-poor in distribution  $f$  is then  $\sum_{x \in P(L)} f(x)$ . Headcount poverty comparisons are *poverty line robust* if they are insensitive to the choice of poverty line. See Duclos, Sahn and Younger (2006) for a detailed discussion of this issue.

**Corollary 1 (Generalized equivalence of first order dominance concepts).** *The following four statements are equivalent:*

- (i)  $g$  is dominated by  $f$ .
- (ii)  $r(S|g) \geq r(S|f)$  for every  $S \subseteq X \setminus \{\bar{x}\}$ .
- (iii)  $\sum u(x)f(x) \geq \sum u(x)g(x)$  for every non-decreasing function  $u$ .<sup>6</sup>
- (iv) The fraction of the population that is poor is at least as large in  $g$  as in  $f$  for every poverty line.

Equivalence between (ii) and (iii) was proved or noted by Lehmann

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<sup>5</sup>See, e.g., Tsui (2002), Bourguignon and Chakravarty (2003), Duclos, Sahn and Younger (2006).

<sup>6</sup>A real-valued function  $u$  on  $X$  is *non-decreasing* if  $x, y \in X$  and  $x \leq y$  implies  $u(x) \leq u(y)$ .

(1955), Levhari et al. (1975) and Kamae et al. (1977). See also Scarcini (1988). Equivalence between (ii) and (iv) follows by noticing that both conditions are equivalent to the requirement that  $\sum_{x \in Y} g(x) \geq \sum_{x \in Y} f(x)$  for any comprehensive set  $Y$ .<sup>7</sup>

Theorem 1 / Corollary 1 tells that, for two distributions  $f$  and  $g$ , the analyst can test whether a distribution  $g$  is dominated by  $f$  by checking certain inequalities. In applications, one could perform such tests using a spreadsheet. For testing condition (ii) it is not necessary to inspect every subset of  $X \setminus \{\bar{x}\}$  since if  $\cup_{s \in S} L(s) = \cup_{s \in S'} L(s)$  for  $S, S' \subseteq X \setminus \{\bar{x}\}$  then  $r(S|f) = r(S'|f)$ . Thus, we only need to go through the sets  $S \subseteq X \setminus \{\bar{x}\}$  for which there is no pair  $s, s'$  in  $S$ ,  $s \neq s'$ , where  $s \in L(s')$ . Nevertheless, the number of inequalities to be tested grows rapidly as the number of attributes and number of levels in each attribute increases. For example, in the two-dimensional case, the 2x2 case (two binary variables) yields 3 inequalities, the 2x3 case (one binary variable and one ternary variable) yields 7 inequalities. The 2x4 case and the 3x3 case yield 12 and 18 inequalities, respectively.

## 4 The bivariate case: algorithmic implementation

This section develops an algorithm for testing whether one distribution dominates another. The advantage of this algorithm is that it is computationally more tractable for large attribute sets. Moreover, whenever  $g$  is dominated by  $f$  in a sense it gives us a way to quantify *how much*  $g$  is dominated by

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<sup>7</sup>A set  $Y \subseteq X$  is called *comprehensive* if  $x \in Y$ ,  $y \in X$  and  $y \leq x$  implies  $y \in Y$ .

$f$ . The disadvantage of this alternative method is that it only applies to the bivariate case, and developing the method for practical use requires some algorithmic programming.

In this section, we therefore assume that an outcome is a vector  $x = (x_1, x_2)$ , where each attribute  $x_j$  is defined on an attribute set  $X_j = \{1, 2, \dots, \bar{x}_j\}$ ,  $j = 1, 2$ . Thus, the outcome set is the product set  $X = X_1 \times X_2$ .

We say that an outcome  $x = (x_1, x_2)$  is *left-adjacent* to  $y = (y_1, y_2)$  if  $x_i = y_i - 1$  for some  $i$  and  $x_j = y_j$ ,  $j \neq i$ , and  $y$  is *right-adjacent* to  $x$  if  $x$  is left-adjacent to  $y$ . Two outcomes are *adjacent* if one of them is left-adjacent to the other.

A bilateral transfer from  $x$  to  $y$  is an *adjacent bilateral transfer* if  $x$  and  $y$  are adjacent outcomes. A bilateral transfer from  $x$  to  $y$  is a *diminishing adjacent bilateral transfer* if  $y$  is left-adjacent to  $x$ .

We will make use of the following notation for bilateral transfers: The variable  $\tau_{xy} \geq 0$  denotes the amount transferred from  $x$  to  $y$ . Thus, a sequence  $T = (\tau_{xy}, \tau_{x'y'}, \dots)$  can be used to describe a sequence of diminishing adjacent bilateral transfers. Specifically, let  $T_{fg}$  denote a sequence of diminishing adjacent bilateral transfers leading from  $f$  to  $g$ . Define  $\bar{T}_{fg} = \tau_{xy} + \tau_{x'y'} + \dots$ . Thus,  $\bar{T}_{fg}$  indicates how much density is moved if equal weight is assigned to any two diminishing adjacent bilateral transfers moving a given amount of density. We will refer to  $\bar{T}_{fg}$  as the amount of density moved (by diminishing adjacent bilateral transfers) in  $T_{fg}$ .

The following Theorem 2 lays the foundation for the algorithm. It tells that if a distribution  $g$  is dominated by  $f$ , any two sequences of diminishing bilateral transfers leading from  $f$  to  $g$  displace an equal amount of density.



**Theorem 2** *Suppose that  $g$  is dominated by  $f$ , and let  $T_{fg}$  and  $T'_{fg}$  denote two sequences of diminishing bilateral transfers leading from  $f$  to  $g$ . Then  $\bar{T}_{fg} = \bar{T}'_{fg}$ .*

Proof: For the proof of Theorem 2, we will make use of the following lemma.

**Lemma B** *Suppose that  $y \in L(x'), y' \in L(x)$ ,  $\tau_{xy}, \tau_{x'y'}$  are diminishing bilateral transfers and  $\tau_{xy} = \tau_{x'y'}$ . Let  $T$  be a pair of diminishing adjacent bilateral transfers moving density of an amount  $\tau_{xy}$  from  $x$  to  $y$  and moving an equal amount of density from  $x'$  to  $y'$ . Further, let  $T'$  be a pair of diminishing adjacent bilateral transfers moving density of an amount  $\tau_{xy}$  from  $x'$  to  $y$  and moving an equal amount of density from  $x$  to  $y'$ . Then  $\bar{T} = \bar{T}'$ .*

Proof of Lemma B: Consider the outcomes  $y, y'$ . First, we claim that there is one and only outcome  $z$ , such that  $y, y' \in L(z)$  and if  $w \in L(z)$ ,  $w \neq z$ , then either  $y \notin L(w)$  or  $y' \notin L(w)$ . It is obvious that such outcome  $z$  exists. To verify that it is uniquely determined, it is sufficient to note that if  $z = (z_1, z_2)$  and  $z' = (z'_1, z'_2)$  are two outcomes,  $z \notin L(z'), z' \notin L(z)$  for which  $y, y' \in L(z), L(z')$  then for the outcome  $z'' = (z''_1, z''_2)$  defined by  $z''_i = \min\{z_i, z'_i\}$  we have  $z'' \in L(z), L(z')$ ,  $z'' \neq z, z'$ , and  $y, y' \in L(z'')$  (since  $y = (y_1, y_2) \leq (z_1, z_2)$  and  $(y_1, y_2) \leq (z'_1, z'_2)$  implies  $(y_1, y_2) \leq (\min\{z_1, z'_1\}, \min\{z_2, z'_2\})$ , and similarly with  $y'$ ). In particular, we have  $z = (z_1, z_2) = (\max\{y_1, y'_1\}, \max\{y_2, y'_2\})$ .

Next, we claim that  $z \in L(x), L(x')$ . For this, suppose not. Then for one of the outcomes  $x, x'$  — say for  $x = (x_1, x_2)$  — we have  $x_i < z_i$  for either

$i = 1$  or  $i = 2$ . Then,  $x_i < z_i = \max\{y_i, y'_i\}$  implying that either  $y \notin L(x)$  or  $y' \notin L(x)$  — a contradiction.

For two outcomes  $x, y \in L(x)$ , we note that if an amount can be transferred from  $x$  to  $y$  by a sequence of  $k$  diminishing adjacent bilateral transfers, then any other sequence of diminishing adjacent bilateral transfers transferring this amount from  $x$  to  $y$  will do so by means of  $k$  diminishing adjacent bilateral transfers (though maybe via other outcomes). In particular, without changing the number of diminishing adjacent bilateral transfers involved we can specify the sequence  $T$  such that it leads all transfers via  $z$ , and similarly with  $T'$ . Since we can then obtain  $T'$  by respecifying the bilateral transfers in  $T$ , such that a sequence of bilateral transfers now leads density from  $x$  via  $z$  to  $y'$  and the other sequence of bilateral transfers leads density from  $x'$  via  $z$  to  $y$ , it follows that  $T$  and  $T'$  contains the same total number of diminishing adjacent bilateral transfers, i.e.  $\bar{T} = \bar{T}'$ .  $\square$

It follows from Lemma B that if  $T$  and  $T'$  are two sequences of diminishing bilateral transfers, where  $T'$  is identical with  $T$  except that in  $T$  two bilateral transfers  $\tau_{xy}$  and  $\tau_{x'y'}$  for which  $\tau_{xy} = \tau_{x'y'}$  have been replaced by the two bilateral transfers  $\tau_{xy'}$  and  $\tau_{x'y}$  (where  $\tau_{xy'} = \tau_{x'y} = \tau_{xy} = \tau_{x'y'}$ ), then  $\bar{T} = \bar{T}'$ . In this case, we will say  $T'$  is obtained from  $T$  by a *pairwise swap of bilateral transfers* (or a *2-swap*).

**Lemma C** *If  $T_{fg}$  and  $T'_{fg}$  are two sequences of diminishing bilateral transfers leading from  $f$  to  $g$ , then  $T'_{fg}$  can be obtained from  $T_{fg}$  by a finite number of pairwise swaps of bilateral transfers.*

Proof of Lemma C: Suppose not. Then, going from  $T_{fg}$  to  $T'_{fg}$  must in-

volve at least one swap that is not pairwise. In particular, there is  $k \geq 3$ , and outcomes  $x^1, \dots, x^k, y^1, \dots, y^k$  such that  $T_{fg}$  contains bilateral transfers  $\tau_{x^1 y^1}, \tau_{x^2 y^2}, \dots, \tau_{x^k y^k}$ , and  $T'_{fg}$  contains bilateral transfers  $\tau_{x^1 y^2}, \tau_{x^2 y^3}, \dots, \tau_{x^k y^1}$ . A rearrangement of bilateral transfers of this type will be called a  $k$ -swap. Without loss of generality we can assume that the bilateral transfers involved are equally large, i.e.  $\tau_{x^1 y^1} = \tau_{x^2 y^2} = \dots = \tau_{x^1 y^2} = \tau_{x^2 y^3} = \dots = \tau_{x^k y^1}$ , since we can make several bilateral transfers from one outcome to another (and hence  $T_{fg}$  to  $T'_{fg}$  can be respecified accordingly if needed).

Going from  $T_{fg}$  to  $T'_{fg}$  must involve swaps that are not pairwise. Thus, we can choose  $k \geq 3$  and a  $k$ -swap as above such that the  $k$ -swap cannot be replaced by one or more other  $h$ -swaps where  $h \leq k - 1$ , in the sense that the total amount transferred from or to any outcome is the same after replacement.

We consider two cases: i) there is  $2 \leq h \leq k$  and  $y^h$  such that  $x^1 \in L(x^h)$ , and ii) which covers the opposite case.

Ad i). Suppose that  $2 \leq h < k$  and  $x^1 \in L(x^h)$ . Then the bilateral transfer  $\tau_{x^h y^1}$  is diminishing. Thus, the bilateral transfers  $\tau_{x^1 y^2}, \tau_{x^2 y^3}, \dots, \tau_{x^{h-1} y^h}, \tau_{x^h y^1}$  constitute a  $h$ -swap relative to  $\tau_{x^1 y^1}, \tau_{x^2 y^2}, \dots, \tau_{x^h y^h}$ . Further, the bilateral transfers  $\tau_{x^h y^{h+1}}, \tau_{x^{h+1} y^{h+2}}, \dots, \tau_{x^{k-1} y^k}, \tau_{x^k y^1}$  constitute a  $(k - h + 1)$ -swap relative to  $\tau_{x^h y^1}, \tau_{x^{h+1} y^{h+1}}, \dots, \tau_{x^k y^k}$ . Thus, the  $k$ -swap can be decomposed (in the sense that the density transferred from one outcome to another is eventually the same) into two shorter swaps — a contradiction.

Suppose that  $x^1 \in L(x^k)$ . Then the bilateral transfer  $\tau_{x^k y^2}$  is diminishing. Thus, the bilateral transfers  $\tau_{x^2 y^3}, \dots, \tau_{x^{k-1} y^k}, \tau_{x^k y^2}$  constitute a  $(k - 1)$ -swap relative to  $\tau_{x^2 y^2}, \dots, \tau_{x^h y^h}$ . Further, the bilateral transfers  $\tau_{x^1 y^2}$  and  $\tau_{x^k y^1}$

constitute a 2-swap relative to  $\tau_{x^1 y^1}$  and  $\tau_{x^k y^2}$ . Thus, the  $k$ -swap can again be decomposed into two shorter swaps — a contradiction.

Ad ii). Suppose that there are no  $2 \leq h < k$  for which  $x^1 \in L(x^h)$ .

First we note that the following simplifying assumption can be made. In accordance with the usual notation for the attribute variables of  $y^1, y^2$  and  $x^1$ , let  $y^1 = (y_1^1, y_2^1)$ ,  $y^2 = (y_1^2, y_2^2)$  and  $x^1 = (x_1^1, x_2^1)$ . We claim that without loss of generality it can be assumed that a)  $y^i \notin L(y^j)$ ,  $i \neq j$ ,  $i, j = 1, 2$ , and b)  $y_i^1 = x_i^1$ ,  $y_j^2 = x_j^1$  for some  $i = 1, 2$ , and  $j \neq i$ . For b), it suffices to note that if a  $k$ -swap is required in a situation involving  $y^1, y^2$  and  $x^1$  for which condition b) is not satisfied, then if replacing  $x^1$  by the outcome  $\bar{x}^1 = (\bar{x}_1^1, \bar{x}_2^1)$  defined by  $\bar{x}_i^1 = \max\{y_i^1, y_i^2\}$ , a  $k$ -swap would still be needed. Now, a) follows from b).

We impose these two assumptions, and note that it gives rise to a partitioning of  $X$  into the following four (non-empty) compartments:  $A = \{z \in X | x^1 \in L(z)\}$ ,  $B = L(x^1)$ ,  $C = \{z \in X | y^2 \in L(z), x^1 \notin L(z)\}$ , and  $D = \{z \in X | y^1 \in L(z), x^1 \notin L(z)\}$ .

Since  $y^k \notin A$ , we have  $y^k \in D$ , and  $x^2 \notin A$ , so  $x^2 \in C$ . Thus, there must be some  $3 \leq h \leq k$  such that  $y^h \in B$  (since for the lowest number  $i$  for which  $x^i \in D$ , we must have  $y^i \in B$ ).

We observe that the bilateral transfer  $\tau_{x^1 y^h}$  is diminishing. The bilateral transfers  $\tau_{x^1 y^h}, \tau_{x^h y^{h+1}}, \dots, \tau_{x^{k-1} y^k}, \tau_{x^k y^1}$  therefore constitute a  $(k - h + 2)$ -swap relative to  $\tau_{x^1 y^1}, \tau_{x^h y^h}, \tau_{x^{h+1} y^{h+1}}, \dots, \tau_{x^k y^k}$ . Further,  $\tau_{x^1 y^2}, \tau_{x^2 y^3}, \dots, \tau_{x^{h-1} y^h}$  constitute a  $(h - 1)$ -swap relative to  $\tau_{x^1 y^h}, \tau_{x^2 y^2}, \tau_{x^3 y^3}, \dots, \tau_{x^{h-1} y^{h-1}}$ , so the  $k$ -swap can again be decomposed into two shorter swaps — a contradiction.

□

To conclude, by Lemma C  $T'_{fg}$  can be obtained from  $T_{fg}$  by a finite sequence of pairwise swaps. By Lemma B it follows that each of these pairwise swaps change the amount of density transferred. This verifies Theorem 2.  $\square$

Theorem 2 tells that if  $g$  is obtained from  $f$  by a finite sequence of diminishing adjacent bilateral transfers, the amount of density moved is the same as for any other way of obtaining  $g$  from  $f$  by diminishing adjacent bilateral transfers. It therefore constitutes the theoretical justification for using the following algorithm which for the bivariate case tests whether one distribution  $g$  is dominated by  $f$ . As a by-product, it gives a way of quantifying how much  $g$  differs from  $f$ . In the spirit of Allison and Foster (2004) we measure it by the amount of density that needs to be moved when going from  $f$  to  $g$ , assigning equal weight to any two similarly sized adjacent bilateral transfers.

Suppose that  $f$  and  $g$  are two distributions. The following algorithm makes use of the following  $|X| + 1$  variables:  $Q \in \mathbb{R}_+$  and  $s(x) \in \mathbb{R}, x \in X$ . Step 0 specifies the initial values of these variables.<sup>8</sup>

**Bilateral Transfers Constructing Algorithm:**

STEP 0: Let  $Q := 0$ . For  $z \in X$ , let  $s(z) := f(z) - g(z)$ .

STEP 1: If  $s(z) = 0$  for all  $z \in X$ , conclude that  $g$  is dominated by  $f$ , let  $Q$  specify how much  $g$  is dominated by  $f$ , and terminate the algorithm.

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<sup>8</sup>The statement  $Q := 0$  means that the value of  $Q$  is set to zero. The statement  $Q := Q + 1$  means that the value of the variable  $Q$  is increased with 1, etc..

Otherwise, let  $P := \{z \in X | s(z) > 0\}$ . If  $P$  is an empty set, conclude that  $g$  is not dominated by  $f$ , and terminate the algorithm. If  $P$  is non-empty go to Step 2.

STEP 2: Let  $p^*$  be the element  $(p_1, p_2)$  in  $P$  such that for all  $p' = (p'_1, p'_2)$  in  $P$  it holds that  $p_1 \leq p'_1$  and if  $p_1 = p'_1$  then  $p_2 \geq p'_2$ . Let  $R := \{z \in X | s(z) < 0\}$ . If  $L(p^*) \cap R$  is empty, conclude that  $g$  is not dominated by  $f$ , and terminate the algorithm. Otherwise, let  $r^*$  be the outcome  $(r_1, r_2)$  in  $L(p^*)$  with the lowest  $r_1$  for which:  $(r_1, r_2) \in L(p^*)$  and there is no other  $z$  in  $L(p^*) \cap R$  for which  $(r_1, r_2) \in L(z)$ . Define  $\lambda^* = \min\{s(p^*), |s(r^*)|\}$ . Let  $s(p^*) := s(p^*) - \lambda^*$  and  $s(r^*) := s(r^*) + \lambda^*$ . Let  $Q := Q + \lambda^*(p_1^* + p_2^* - r_1^* - r_2^*)$ . Go to Step 1.

**Theorem 3** *Suppose that  $X$  has two attributes. Then the BTC algorithm works: It concludes that  $g$  is dominated by  $f$  if and only if this is, in fact, the case. Moreover, whenever  $g$  is dominated by  $f$ , the terminating  $Q$  value does, in fact, determine how much  $g$  is dominated by  $f$ .*

Proof: Every bilateral transfer specified in the BTC algorithm is a diminishing bilateral transfer. Thus, if at some point we have  $s(z) = 0$  for all  $X$ , it is clear that  $g$  is dominated by  $f$  and the terminal value of  $Q$  is in fact the correct measure of how much  $g$  is dominated by  $f$ .

To verify the contrary statement, suppose that  $g$  is dominated by  $f$ . What we need to verify is that whenever  $g$  can be obtained from  $f$  by a finite sequence of diminishing bilateral transfers then the BTC algorithm will

conclude so. It is sufficient to show that whenever a distribution  $g'$  can be obtained from  $f'$  by a finite sequence of diminishing bilateral transfers, then  $g'$  can also be obtained from the distribution  $f''$ , where  $f''$  is the distribution obtained from  $f'$  after going through one round in the BTC algorithm (i.e., after one bilateral transfer has been conducted).

We assume that  $P$  is non-empty, i.e., we consider a bilateral transfer of the kind specified in Step 2. Given  $f'$  and  $g'$ , let the values  $s(z)$ ,  $z \in X$ ,  $r^*$  and  $p^*$  be as specified in the algorithm. Note that if  $(r_1, r_1) \in R$  and  $r_1 \leq r_1^*$  then  $(r_1, r_2) \in L(r^*)$ .

We claim that if  $r^* \in L(p')$ ,  $p' \neq p^*$ , then  $r \in L(p^*)$  implies  $r \in L(p')$ . For this, note that by the choice of  $p^*$  in Step 2 we have either i)  $p^* \in L(p')$ , or ii)  $p_1^* = p_1'$  and  $p_2^* < p_2'$ , or iii)  $p_1^* < p_1'$  and  $p_2^* > p_2'$ . Verification of the claim is immediate in case i). For ii), note first that by the definition of  $r^*$ , the set  $\{z \in R | r^* \in L(z)\} \cap L(p^*)$  is empty. Hence, if  $r \in L(p^*)$  we have either  $r \in L(r^*)$ , or  $r_2 < r_2^*$  and  $r_1 \leq r_1^* = r_1'$ . In either situation, we have  $r \leq p'$ . For the remaining case iii), it is sufficient to note that if  $r = (r_1, r_2)$  is such that  $r_2 > r_2^*$  then  $r \notin L(p^*)$ .

The (by now verified) claim is useful since it implies that if  $g'$  can be obtained from  $f'$  (by a finite sequence of diminishing bilateral transfers) then if  $\lambda^* = \min\{s(p^*), |s(r^*)|\}$  is transferred from  $p^*$  to  $r^*$ ,  $g'$  can also be obtained from (by a finite sequence of diminishing bilateral transfers) from the resulting distribution. The reason is that a total amount of at least  $\lambda^*$  of density have been transferred to  $r^*$  after some point in the sequence, and if the density is not taken from  $p^*$ , it must be taken from other outcomes in  $P$ . For every other outcome  $p'$  in  $P$  it holds that if  $r^* \in L(p')$  and  $r \in L(p^*)$

then  $r \in L(p')$ . So nothing is achieved (in terms of which final distributions can be obtained from further diminishing bilateral transfers from outcomes with positive  $s$  to outcomes with negative  $s$ ) from redirecting the transfer of density from  $p^*$  to  $r^*$  of an amount  $\lambda^*$  to other outcomes.  $\square$

## 5 Concluding remarks

First order stochastic dominance is an ordinal concept. Thus, the validity of measuring the distance between two distributions (one of them being dominant) by assigning equal weight to each similarly sized adjacent bilateral transfer needs to be considered carefully. In some empirical contexts assigning equal weight is not meaningful. However, in situations where the analyst holds no information about the relative importance of attributes and their levels, there is some merit in such an approach. Arguments in favor are parallel to those defending Laplace’s principle of insufficient reasoning in decision-making under uncertainty.

We have primarily interpreted distributions as representing probabilities, although many important uses of dominance concepts concern comparisons of population distributions. In this context, comparisons of inequalities are usually of interest as well. While considerable progress has been made in terms of developing methods of inequality measurement in recent years,<sup>9</sup> to date, no purely ordinal theories are available for multivariate settings. Based on the results presented in this paper, we believe that “elementary” transfer approaches to higher order dominance and inequality comparisons

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<sup>9</sup>See, e.g., Weymark (2006).



merit further investigation.

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