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TRANSFORMATIONS WHICH PRESERVE CONVEXITY

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ABSTRACT. Let C be the class of convex nondecreasing functions $f: [0,\infty) \to [0,\infty)$ which satisfy $f(0) = 0$. Marshall and Proschan [1] determine the one-to-one and onto functions $\psi: [0,\infty) \to [0,\infty)$ such that $g = \psi \circ f \circ \psi^{-1}$ belongs to C whenever f belongs to C. We study several natural models for multivariate extension of the Marshall-Proschan result. We show that these result in essentially a restatement of the original Marshall-Proschan characterization.

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1. INTRODUCTION.

Let C denote the class of convex, nondecreasing functions $f: [0,\infty) \to [0,\infty)$ which satisfy $f(0) = 0$. A known and useful result is that if $p \geq 1$, then

$$g(x) = f^p(x^{\frac{1}{p}})$$

belongs to C whenever f belongs to C. There is an interesting geometrical interpretation of the relationship between f and g. Beginning with the equation of the graph of g,

$$y = f^p(x^{\frac{1}{p}}),$$

one obtains that

$$y^{\frac{1}{p}} = f(x^{\frac{1}{p}})$$

and, thus, that the graph of f is obtained from the graph of g (and vice versa) by applying the <u>same</u> transformation to both of the coordinate axes.

In [1], A. W. Marshall and F. Proschan, motivated by the special case $\psi(x) = x^p$, pose and solve the following problem: Determine those one-to-one and onto functions

ψ: $[0, \infty) \to [0, \infty)$ such that $g = \psi \circ f \circ \psi^{-1}$ belongs to C whenever f belongs to C. The answer to this question is of interest in several applications. Karlin ([2], pp. 368, 369) uses the answer to the question in obtaining bounds on the survival function $\bar{F}(x)$ in terms of an exponential survival function. Barlow and Proschan ([3] pp. 110, 111) also use the result in obtaining bounds on the survival function $\bar{F}$ in terms of $\bar{G}$, where $\bar{G}^{-1}\bar{F}$ is convex. Marshall and Proschan show that if ψ is continuous at some point, then g belongs to C whenever f belongs to C if and only if $\psi(x) = cx^p$ for some $c > 0$ and $p \geq 1$.

In this note we study several natural models for multivariate extension of the Marshall-Proschan result. We show that these result in essentially a restatement of the original Marshall-Proschan characterization.

2. EXTENSIONS OF MARSHALL-PROSCHAN RESULT

We begin by establishing some notation. Let R_n^+ denote the nonnegative orthant of n-dimensional Euclidean space equipped with coordinatewise ordering, multiplication, and addition. If $\underline{x}$ and $\underline{y} \in R_n^+$, let $\underline{x} + \underline{y}$ and $\underline{xy}$ denote the sum and the product, computed coordinatewise, of $\underline{x}$ and $\underline{y}$. Let $\underline{0}$ and $\underline{e}$ denote the vectors all of whose entries are 0 and 1, respectively. If $x > \underline{0}$, let $\underline{x}^{-1}$ denote the multiplicative inverse of $\underline{x}$. Finally, let $\underline{x}^n$ denote the nth power of $\underline{x}$.

We now examine several possible extensions of the Marshall-Proschan result. Let C denote the set of those convex functions $f\colon R_n^+ \to [0, \infty)$ such that $f(\underline{0}) = 0$ and f is nondecreasing in each argument. The following question is natural: If $p \geq 1$, f belongs to C, and

$$g(\underline{x}) = f^p(x_1^{\frac{1}{p}}, \ldots, x_n^{\frac{1}{p}})$$

for $\underline{x} = (x_1, \ldots, x_n)$ in R_n^+, does g belong to C? The following example shows that the answer is "No".

EXAMPLE 1. Let $n \geq 2$ and $p > 1$. For $\underline{x}$ in R_n^+, let $f(\underline{x}) = x_1 + x_2$. Then

$$g(\underline{x}) = (x_1^{\frac{1}{p}} + x_2^{\frac{1}{p}})^p$$

is not convex since the partial derivative of g with respect to x_2 is decreasing as a function of x_2, for fixed x_1. Thus, for fixed x_1, g is not a convex function of x_2([4],Thm.12B). Hence g does not belong to C.

Example 1, the theorem of Marshall and Proschan, and the fact that the present class C contains a copy of the class C of interest to Marshall and Proschan show that, given the present choice of C, there is no point in considering real-valued functions $\psi(x)$ which operate on each coordinate separately. If we wish to look at such functions $\psi(x)$, we must choose C differently. For example, we might let C be the class of functions $f\colon R_n^+ \to [0, \infty)$ which are convex and nondecreasing in each variable separately and which satisfy $f(\underline{0}) = 0$; however, Example 1 shows that this choice is not suitable. Alternatively, we might let C consist of those functions $f\colon R_n^+ \to [0, \infty)$ which satisfy $f(\underline{0}) = 0$, are nondecreasing in each argument, and whose restrictions to rays through the origin are convex functions of one variable. In this case, the C-preserving functions are the same as those in the one-dimensional case; the proof is a trivial and, hence, uninteresting application of the theorem of Marshall and Proschan.

In one way, the result of Example 1 is not surprising: there is an obvious difference between the dimension of the transforming function x^p and the argument $\underline{x}$ of the functions to be transformed. Thus we now consider the case where both the convex functions and the transformation function ψ map R_n^+ into R_n^+. We say that $\underline{f}$: $R_n^+ \to R_n^+$ is convex if the inequality

$$\underline{f}(\lambda x + (1 - \lambda)\underline{y}) \le \lambda\underline{f}(\underline{x}) + (1 - \lambda)\underline{f}(\underline{y})$$

holds for all $\underline{x}, \underline{y} \in R_n^+$ and all $\lambda \in [0, 1]$. It is immediate that $\underline{f}$ is convex if and only if each of the n coordinate functions of $\underline{f}$ is convex in the usual sense. Let C denote the set of convex functions $\underline{f}$: $R_n^+ \to R_n^+$ which are nondecreasing in each coordinate and satisfy $\underline{f}(\underline{0}) = \underline{0}$. We now pose the following problem: Determine those one-to-one and onto functions $\underline{\psi}$: $R_n^+ \to R_n^+$ which are continuous at some point (or bounded in a neighborhood of some point; the answer is the same) and have the property that

$$\underline{f} \in C \text{ implies that } \underline{\psi} \circ \underline{f} \circ \underline{\psi}^{-1} \in C. \tag{2.1}$$

In Example 2 (below) we shall find a necessary condition that (2.1) is satisfied by a function $\underline{\psi}$ of a certain type. To aid us, we will use the following remark:

REMARK 1. Let $a_1, a_2, \ldots, a_n$ be real numbers. Let

$$h(\underline{x}) = \prod_{j=1}^{n} x_j^{a_j}, \quad \underline{x} > \underline{0}.$$

Suppose that $a_j > 0$ and $a_k > 0$ for some integers j and k such that $j \neq k$. We claim that h is not convex. To see this, suppose, without loss of generality, that $j = 1$, $k = 2$. The first two principal minors of the Hessian matrix, the matrix of second order partial derivatives of h, must be nonnegative if h is convex ([4],Thm. 42F). Thus the inequalities

$$a_1(1 - a_1) \le 0$$

and

$$a_1 a_2(1 - a_1 - a_2) \ge 0$$

must simultaneously hold if h is convex. These inequalities cannot both hold; thus h is not convex.

EXAMPLE 2. Let A be a real $n \times n$ matrix. Let $\underline{f}$ be the R_n^+-valued function with domain $\underline{x} > \underline{0}$, each of whose component functions is of the type given in Remark 1 such that the exponents in the kth component function are, in order, the elements of the kth row of A, $k = 1,\ldots,n$. Represent $\underline{f}$ as follows:

$$\underline{f}(\underline{x}) = \underline{x}^A \quad \text{for} \quad \underline{x} > 0.$$

It is easy and interesting to see that if

$$\underline{g}(\underline{x}) = \underline{x}^B$$

for $\underline{x} > \underline{0}$ and for some real $n \times n$ matrix B, then

$$\underline{g} \circ \underline{f}(\underline{x}) = \underline{x}^{BA},$$

where BA is the usual matrix product of B and A. Also $\underline{f}$ is invertible if and only if A is invertible and, in this case,

$$\underline{f}^{-1}(\underline{x}) = \underline{x}^{A^{-1}}.$$

Let us call a matrix simple if it is invertible and each row contains exactly one nonzero entry. A permutation matrix is a simple matrix such that the nonzero entry in each row is 1.

We will now present a result about non-preservation of convexity. Let A be an $n \times n$ non-simple invertible matrix and let $\underline{\psi}: R_n^+ \to R_n^+$ be one-to-one and onto and also satisfy

$$\underline{\psi}(\underline{x}) = \underline{x}^A, \ \underline{x} > \underline{0}. \tag{2.2}$$

An easy argument, which we omit, shows that there exists an $n \times n$ diagonal matrix P, all of whose diagonal entries are greater than or equal to one, such that the matrix $Q = APA^{-1}$ has a row with two (strictly) positive entries. Choose such a P and let

$$\underline{f}(\underline{x}) = \underline{x}^P, \ \underline{x} \in R_n^+.$$

It is clear that $\underline{f}$ belongs to C. On the other hand, by Remark 1, the function $\underline{\psi} \circ \underline{f} \circ \underline{\psi}^{-1}$ does not belong to C. Thus $\underline{\psi}$ does not satisfy (2.1).

Suppose that we now consider an arbitrary simple matrix A. Using "test" functions in C of the form

$$\underline{f}(\underline{x}) = (g(x_1), g(x_2), \ldots, g(x_n)),$$

where $g: [0, \infty] \to [0, \infty]$ is convex, nondecreasing, and satisfies $g(0) = 0$ and using the Marshall-Proschan result, it is easy to see that if $\underline{\psi}$ satisfies (2.1) and (2.2), then A must be a permutation matrix.

3. MAIN RESULTS.

THEOREM. **Suppose that $n \geq 2$ and $\underline{\psi}: R_n^+ \to R_n^+$ is one-to-one, onto, and continuous at** some point. Then $\underline{\psi}$ satisfies (2.1), if and only if

$$\underline{\psi}(x) = \underline{c}\underline{x}^B \tag{3.1}$$

for $\underline{x}$ in R_n^+, some vector $\underline{c} > \underline{0}$, and some permutation matrix B.

PROOF. If $\underline{\psi}$ satisfies (3.1) for some vector $\underline{c} > \underline{0}$ and some permutation matrix A, then $\underline{\psi}$ clearly satisfies (2.1).

Suppose that $\underline{\psi}$ satisfies (2.1). We shall derive a functional equation which is satisfied by $\underline{\psi}$. Motivated by the proof in [1] and consideration of invertible linear functions in C, we ask the following question: If $\underline{g}$ is one-to-one, onto, and $\underline{g}$ and $\underline{g}^{-1}$ both belong to C, what must be true of $\underline{g}$? It is easy to see that the equations

$$\underline{g}(\lambda\underline{x} + \underline{y}) = \lambda\underline{g}(\underline{x}) + \underline{g}(\underline{y})$$

$$\underline{g}^{-1}(\lambda\underline{x} + \underline{y}) = \lambda\underline{g}^{-1}(\underline{x}) + \underline{g}(\underline{y})$$

must hold for all $\lambda > 0$ and all $\underline{x}, \underline{y} \in R_n^+$. It then follows that $\underline{g}(\underline{x}) = \underline{x}A$, $\underline{x}$ in R_n^+, for some nonnegative simple matrix A.

For any $\underline{a} > \underline{0}$, let $\underline{f}(\underline{x}) = \underline{ax}$ and let $\underline{g} = \underline{\psi} \circ \underline{f} \circ \underline{\psi}^{-1}$. Since $\underline{\psi}$ satisfies (2.1) and both $\underline{f}$ and $\underline{f}^{-1}$ belong to C, both $\underline{g}$ and $\underline{g}^{-1}$ also belong to C. Thus there is a nonnegative simple matrix A such that

$$\underline{\psi} \circ \underline{f} \circ \underline{\psi}^{-1}(\underline{z}) = \underline{z}A, \ \underline{z} \in R_n^+.$$

Substituting $\underline{z} = \underline{\psi}(\underline{x})$ and $\underline{f}(\underline{x}) = \underline{ax}$, we obtain

$$\underline{\psi}(\underline{ax}) = \underline{\psi}(\underline{x})A, \ \underline{x} \in R_n^+,$$

where A depends on a.

We will now show that A is a diagonal matrix. First, note that since A is simple, there is some vector $\underline{b} > \underline{0}$ and a linear transformation Π, depending on $\underline{a}$, which permutes coordinates, such that

$$\underline{\psi}(\underline{ax}) = \underline{b}\Pi(\underline{\psi}(\underline{x})), \ \underline{x} \in R_n^+. \tag{3.2}$$

Note that Π is multiplicative, that is,

$$\Pi(\underline{xy}) = \Pi(\underline{x})\Pi(\underline{y}), \ \underline{x}, \underline{y} \in R_n^+. \tag{3.3}$$

Using (3.2) and (3.3), for any positive integer m, we obtain that

$$\underline{\psi}(\underline{a}^m\underline{x}) = \underline{c}\Pi^m(\underline{\psi}(\underline{x})), \ \underline{x} \in R_n^+,$$

for some $\underline{c} > \underline{0}$ which depends on $\underline{a}$. Take $m = n!$. Using elementary group theory and the fact that the linear transformations on R_n of permutation type form a group of order m, we have that Π^m is the identity transformation. Thus

$$\underline{\psi}(\underline{a}^m\underline{x}) = \underline{c}\underline{\psi}(\underline{x}), \ \underline{x} \in R_n^+.$$

Replacing $\underline{a}^m$ by $\underline{a}$, we may write

$$\underline{\psi}(\underline{ax}) = \underline{c}\underline{\psi}(\underline{x}), \ \underline{x} \in R_n^+, \tag{3.4}$$

for all $\underline{a} > \underline{0}$ and some $\underline{c} > \underline{0}$ which depends on $\underline{a}$.

Our next step is to express $\underline{c}$ in (3.4) in terms of $\underline{\psi}$. We claim that if $\underline{z} \nmid \underline{0}$, then $\underline{\psi}(\underline{z}) \nmid \underline{0}$. Suppose that $z_i = 0$ for some i, $1 \le i \le n$. Let $\underline{a} > \underline{0}$ and $b > 0$ be such that $a_i \neq b_i$ and $a_j = b_j$, $j \neq i$. By (3.4) there exist $\underline{c} > \underline{0}$ and $\underline{d} > \underline{0}$ such that

$$\underline{\psi}(\underline{ax}) = \underline{c}\underline{\psi}(\underline{x})$$

and

$$\underline{\psi}(\underline{bx}) = \underline{d}\underline{\psi}(\underline{x}) \tag{3.5}$$

for all $\underline{x}$ in R_n^+. Suppose that $\underline{\psi}(\underline{z}) > \underline{0}$. Since $\underline{az} = \underline{bz}$ and $\underline{\psi}(\underline{z})$ has a multiplicative inverse, it follows from (3.5) that $\underline{c} = \underline{d}$. Using (3.5) again with $\underline{x} = \underline{e}$, we obtain $\underline{\psi}(\underline{a}) = \underline{\psi}(\underline{b})$, which contradicts the fact that $\underline{\psi}$ is one-to-one. Thus our claim is established. Furthermore, since $\underline{\psi}^{-1}$ also satisfies (3.4) with

$\underline{a}$ and $\underline{c}$ interchanged, it follows that if $\underline{z} > \underline{0}$, then $\underline{\psi}(\underline{z}) > \underline{0}$. In particular, $\underline{\psi}(\underline{e}) > 0$ and $(\underline{\psi}(\underline{e}))^{-1}$ exists.

Let $\underline{\phi}(\underline{x}) = \underline{\psi}(\underline{x})(\underline{\psi}(\underline{e}))^{-1}$. It is clear that (3.4) is equivalent to the functional equation

$$\underline{\phi}(\underline{ax}) = \underline{\phi}(\underline{a})\underline{\phi}(\underline{x}), \ \underline{a} > \underline{0}, \ \underline{x} \in R_n^+. \tag{3.6}$$

Using (3.6) and the result in the previous paragraph, we obtain $\underline{\phi}(\underline{0}) = \underline{0}$. Considering (3.6) for $\underline{a} > \underline{0}$ and $\underline{x} > \underline{0}$ and using exponential and logarithmic functions coordinatewise as appropriate, we transform (3.6) into a functional equation of the type

$$\underline{\beta}(\underline{y} + \underline{z}) = \underline{\beta}(\underline{y}) + \underline{\beta}(\underline{z}), \ \underline{y}, \ \underline{z} \in R_n.$$

Note that $\underline{\beta}$ is bounded on some open set in R_n. The solution of this equation [5] is

$$\underline{\beta}(\underline{z}) = \underline{z}C, \ \underline{z} \in R_n,$$

for some real matrix C. Transforming and letting A denote the transpose of C, we get

$$\underline{\phi}(\underline{x}) = \underline{x}^A, \ \underline{x} > 0. \tag{3.7}$$

Using Example 2 and the fact that $\underline{\phi}$ satisfies (2.1), we have that A is a permutation matrix.

To finish the proof, we must show that (3.7) holds for all $\underline{x}$ in R_n^+. Let

$$\Pi(\underline{x}) = \underline{x}^{A^{-1}}, \ \underline{x} \in R_n$$

Note that Π is a linear transformation, that $\underline{\alpha} = \Pi \circ \underline{\phi}$ satisfies (2.1), that $\alpha(\underline{0}) = \underline{0}$, and that

$$\underline{\alpha}(\underline{x}) = \underline{x}, \ \underline{x} > \underline{0}. \tag{3.8}$$

To complete the argument, we require the following result, whose proof is left to the reader: If $\underline{g}$: $R_n^+ \to R_n^+$ is convex and nondecreasing then $\underline{g}$ is <u>continuous from above</u> at every point $\underline{x}$, that is, for every sequence $(\underline{x}_n)$ of points such that $\underline{x}_n \geq \underline{x}$, for all n, and $\underline{x}_n \to \underline{x}$, $g(\underline{x}_n) \to \underline{g}(\underline{x})$. Choose $\underline{f}$ in C such that $\underline{f}$ is one-to-one and $\underline{x} \neq \underline{0}$ implies $f(x) > \underline{0}$; for example, take $f(\underline{x}) = \underline{x}B$ where B is an invertible $n \times n$ matrix all of whose entries are positive.

Using (3.8) and the result about continuity from above, we obtain that

$$\underline{\alpha} \circ \underline{f} \circ \underline{\alpha}^{-1}(\underline{x}) = \underline{x} \ \text{ for all } \ \underline{x} \in R_n^+ .$$

By the choice of $\underline{f}$, $\underline{f}(\underline{\alpha}^{-1}(\underline{x})) = \underline{f}(\underline{x})$ holds for $\underline{x} \neq \underline{0}$. Thus $\underline{\alpha}^{-1}(\underline{x}) = \underline{x}$ and hence $\underline{\alpha}(\underline{x}) = \underline{x}$ holds for all $\underline{x}$ in R_n^+. This completes the proof of the theorem.

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