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A COUNTEREXAMPLE TO PEREZ'S GENERALIZATION OF THE SHANNON-MCMILLAN THEOREM

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A counterexample is given to a result of Perez which makes a statement about the convergence of a sequence of logarithms of Radon-Nikodym derivatives. The result, if true, would have been a generalization of the Shannon-McMillan theorem of information theory.

Perez ([1], Theorem 2.3 and Corollary 3.3) gives a result which is a generalization of the Shannon-McMillan theorem of information theory. It is the purpose of this note to show that Perez's result is false by providing a simple counterexample. We first state Perez's result and then proceed with the formulation of the counterexample.

Statement of Perez's result. Let P, Q be probability measures on a measurable space $(\Omega, \mathscr{F})$. Let $X_1, X_2, X_3, \cdots$ be a sequence of measurable maps from this space to another. We further suppose that P and Q are stationary measures with respect to this sequence. For $n = 1, 2, 3, \cdots$, let $\mathscr{F}_n$ be the sub sigma-field of $\mathscr{F}$ generated by $X_1, X_2, \cdots, X_n$, and let $P_n(Q_n)$ be the restriction of $P(Q)$ to $\mathscr{F}_n$. We suppose for each n that P_n is absolutely continuous with respect to Q_n; we let f_n denote the Radon-Nikodym derivative of P_n with respect to Q_n. Perez's result states that if $\lim_{n\to\infty} n^{-1} \int \log f_n \, dP$ exists and is finite, then $\lim_{n\to\infty} n^{-1} \log f_n$ exists in the sense of $L^1(P)$ convergence and also in the sense of a.e. $[P]$ convergence. (All logarithms we take to the base 2.)

Convex sequences. To formulate the counterexample we need certain results about convex sequences. A sequence of real numbers $c_1, c_2, \cdots$, is *convex* if $c_{n+2} - 2c_{n+1} + c_n \geqq 0$, $n = 1, 2, 3, \cdots$. It is well known (see [2]) that a nonnegative convex sequence $c_1, c_2, \cdots$ converging to zero satisfies

$$\sum_{i=n}^{\infty} (i - n + 1)(c_{i+2} - 2c_{i+1} + c_i) = c_n , \qquad n = 1, 2, \cdots . \tag{1}$$

The following lemma is useful in constructing convex sequences.

LEMMA. *Let $a_1, a_2, \cdots$ be a sequence of real numbers such that*

(a) $a_n \geqq 2$, $n = 1, 2, \cdots$

(b) $a_{n+1} \geqq a_n - n^{-1}$, $n = 1, 2, \cdots$.

Then the sequence $(2^{-(n-1)a_n})_1^\infty$, *is convex.*

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PROOF. From (b) we have $1 - na_{n+1} \leqq -na_n + 2$. From (a) we have $-na_n + 2 \leqq -na_n + a_n = -(n-1)a_n$. It follows that $2^{1-na_{n+1}} \leqq 2^{-(n-1)a_n}$. The convexity condition $2^{-(n+1)a_{n+2}} - 2(2^{-na_{n+1}}) + 2^{-(n-1)a_n} \geqq 0$ is now satisfied.

We construct some sequences we will need later.

Let $a_1, a_2, \cdots$ be a sequence such that

(a) $|a_{n+1} - a_n| \leqq n^{-1}$, $n = 1, 2, \cdots$

(b) $2 \leqq a_n \leqq 3$, $n = 1, 2, \cdots$

(c) $a_n = 2$ and $a_n = 3$ for infinitely many n. (It is not hard to see that such a sequence exists.) Define the sequences $(p_n)_1^\infty$ and $(q_n)_1^\infty$ as follows:

$$p_n = 2^{-(n-1)a_n}, \qquad q_n = 2^{-(n-1)(5-a_n)}, \qquad n = 1, 2, \cdots .$$

Using the lemma we see that these two sequences are convex; furthermore, they are positive, converge to zero, and $p_1 = q_1 = 1$.

The counterexample. We take Ω to consist of all doubly infinite sequences $(\cdots, x_1, x_2, \cdots)$ that can be formed from 0, 1, 2. $\mathscr{F}$ is the usual product sigma-field. Take X_n to be the nth coordinate mapping, $n = 1, 2, \cdots$. We take P to be the discrete probability measure which assigns probability $\frac{1}{2}$ to the sequence identically equal to 0 and to the sequence identically equal to 2. P is clearly stationary.

Q is the discrete probability measure defined as follows:

(a) For $n = 1, 2, \cdots, Q$ assigns probability $\frac{1}{2}(p_{n+2} - 2p_{n+1} + p_n)$ to each of the n periodic sequences in Ω that can be formed by repeating the block of digits consisting of a one followed by $n - 1$ zeroes.

(b) For $n = 1, 2, \cdots, Q$ assigns probability $\frac{1}{2}(q_{n+2} - 2q_{n+1} + q_n)$ to each of the n periodic sequences formed from repeating the block consisting of a one followed by $n - 1$ twos.

Referring back to property (1) of convex sequences, we see that the probabilities sum to one. Therefore Q is a probability measure; it is easily seen to be stationary.

P_n is absolutely continuous with respect to Q_n because

(a) $Q_n(X_1 = 0, \cdots, X_n = 0) = \frac{1}{2} \sum_{i=n+1}^\infty (i - n)(p_{i+2} - 2p_{i+1} + p_i) = \frac{1}{2}p_{n+1} > 0$; and

(b) $Q_n(X_1 = 2, \cdots, X_n = 2) = \frac{1}{2}q_{n+1} > 0$. (Property 1 of convex sequences was again used.)

Also,

$$\lim_{n\to\infty} \frac{1}{n} \int \log f_n \, dP = \lim_{n\to\infty} \frac{1}{2n}\left(\log \frac{1}{p_{n+1}} + \log \frac{1}{q_{n+1}}\right) = \frac{5}{2}\,.$$

Therefore every hypothesis of Perez's result is satisfied. However, $n^{-1}\log f_n(\cdots, 0, 0, \cdots) = n^{-1} \log p_{n+1}^{-1}$, and therefore has no limit as $n \to \infty$. Therefore the sequence of functions $(n^{-1} \log f_n)_1^\infty$ cannot converge a.e. $[P]$ or in the $L^1(P)$ sense.

Final remark. Suppose in Perez's result the hypothesis that Q be stationary is replaced with the requirement that $X_1, X_2, \cdots$ be a Markov process with respect to Q, with stationary transition probabilities. Then a true theorem is obtained, which is again a generalization of the Shannon–McMillan Theorem. This theorem was proved by Moy [3] by making essential use of martingale theory and by this author [4] with no use of martingale theory. A version of the theorem for continuous time processes $(X_t : t > 0)$ can also be obtained (see [1]).

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