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ON A CHARACTERIZATION OF THE SHANNON ENTROPY

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We give a characterization of the Shannon entropy using less restrictive assumptions on symmetry than extreme symmetry and block symmetry of Prem Nath and Mohan Kaur [2].

1. INTRODUCTION

Let

$$\mathscr{D}_n = \{(p_1, p_2, \ldots, p_n): p_i \geqq 0, \quad i = 1, 2, \ldots, n, \quad \sum_{i=1}^{n} p_i = 1\}, \quad n \geqq 1,$$

be the set of all finite discrete n-component probability distribution with nonnegative elements. There are different axioms for the Shannon entropy $H_n: \mathscr{D}_n \to \mathbb{R}$, $n \geqq 1$, defined by

$$H_n(p_1, p_2, \ldots, p_n) = -\sum_{k=1}^{n} p_k \log_2 p_k \tag{1}$$

with $0 \log_2 0 = 0$. For instance, D. K. Fadeev [1] proposed the following postulates:

I. $p \to h(p) := H_2(p, 1 - p)$ is a continuous function of p, $0 \leqq p \leqq 1$.

II$_n$. H_n is a real symmetric function of $(p_1, p_2, \ldots, p_n)$ on $\mathscr{D}_n$ for $n \geqq 2$.

III$_n$. H_n is recursive, that is

$$H_n(p_1, p_2, \ldots, p_n) = H_{n-1}(p_1, p_2, \ldots, p_n) + \\ + (p_1 + p_2) H_2(p_1/(p_1 + p_2), p_2/(p_1 + p_2)), \quad p_1 + p_2 > 0$$

IV. $H_2(\frac{1}{2}, \frac{1}{2}) = 1$

H. Tverberg [4] has shown that (1) holds true when in I h is an integrable function while P. M. Lee [3] ordered only h to be measurable. Moreover, Prem Nath and Man Mohan Kaur [2] have shown that one can use in II$_n$ an extreme symmetric function or a block symmetric function instead of symmetric function.

In this note we weaken the symmetry postulate II$_n$ and we generalize results of Prem Nath and Man Mohan Kaur. Moreover, we use so called grouping axiom instead of III$_n$.

2. THE MAIN RESULTS

The following theorem characterizes the Shannon entropy.

Theorem 1. Let $H_1(1)$, $H_2(p_1, p_2), \ldots, H_n(p_1, p_2 \ldots, p_n)$ be a sequence of real functions defined on $\mathscr{D}_n$, $n \geqq 1$.

We assume the following three conditions as axioms:

I′ $h(p) := H_2(p, 1 - p)$ is a Lebesgue integrable function on $[0, 1]$.

II′$_n$ (the axiom of reduced symmetry).

$$H_n(p_1, \ldots, p_{n-2}, p_{n-1}, p_n) = H_n(p_1, \ldots, p_{n-2}, p_n, p_{n-1}) \quad \text{for all}$$
$$(p_1, p_2, \ldots, p_n) \in \mathscr{D}_n, \quad n \geqq 2.$$

III′$_n$ (the grouping axiom).

Letting $P_n = \sum_{k=1}^{n} p_k$, $P_1 = 1$, we have

$$H_n(p_1, p_2, \ldots, p_n) = H_2(P_{n-1}, p_n) + P_{n-1} H_{n-1}(p_1/P_{n-1}, \ldots, p_{n-1}/P_{n-1}).$$

Then

$$H_n(p_1, p_2, \ldots, p_n) = -C \sum_{k=1}^{n} p_k \log p_k \tag{2}$$

where C is a positive constant.

Proof. By III′$_n$ we have

$$H_3(p_1, p_2, p) = H_2(p_1 + p_2, p) + (p_1 + p_2) H_2(p_1/(p_1 + p_2), p_2/(p_1 + p_2))$$

and

$$H_3(p_1, p, p_2) = H_2(p_1 + p, p_2) + (p_1 + p) H_2(p_1/(p_1 + p), p/(p_1 + p)).$$

Now, by II'_n we get

$$H_2(p_1 + p_2, p) + (p_1 + p_2) H_2(p_1/(p_1 + p_2), p_2/(p_1 + p_2)) =$$
$$= H_2(p_1 + p, p_2) + (p_1 + p) H_2(p_1/(p_1 + p), p/(p_1 + p)).$$

Again using II′$_n$ we have

$$H_2(p_1 + p_2, p) + (1 - p) H_2(p_1/(1 - p), p_2/(1 - p)) =$$
$$= H_2(p_2, p_1 + p) + (1 - p_2) H_2(p/(1 - p_2), p_1/(1 - p_2)).$$

Hence we conclude that the function h satisfies the following functional equations

(a) $h(p) = h(1 - p)$

(b) $h(p) + (1 - p) h(p_2/(1 - p)) = h(p_2) + (1 - p_2) h(p/(1 - p_2))$

Now following Tveberg's arguments [4] we can get

$$h(p) = C[-p \log p - (1 - p) \log (1 - p)]$$

where C is a positive constant, which proves (2) for $n = 2$.

Using now III_n' and the induction principle we get

$$H_n(p_1, p_2, \ldots, p_n) = H_2(P_{n-1}, p_n) + P_{n-1}H_{n-1}(p_1/P_{n-1}, \ldots, p_{n-1}/P_{n-1}) =$$

$$= -C[P_{n-1} \log P_{n-1} + p_n \log p_n + P_{n-1} \sum_{k=1}^{n-1} (p_k/P_{n-1}) \log (p_k/P_{n-1})] =$$

$$= -C \sum_{k=1}^{n} p_k \log p_k ,$$

which completes the proof of (2). □

It is not difficult to verify that the function

$$f_n: \mathscr{D}_n \to \mathbb{R} \quad \text{defined by}$$

$$f_n(x_1, x_2, \ldots, x_{n-2}, x_{n-1}, x_n) = x_{n-1} + x_n$$

satisfies the axiom of reduced symmetry but it is not symmetric and even it is no extreme symmetric neither block symmetric. Indeed, we see that

$$f_4(\tfrac{1}{2}, \tfrac{1}{6}, \tfrac{1}{4}, \tfrac{1}{12}) = \tfrac{1}{4} + \tfrac{1}{12} = \tfrac{1}{3} = f_4(\tfrac{1}{2}, \tfrac{1}{6}, \tfrac{1}{12}, \tfrac{1}{4}),$$

but

$$f_4(\tfrac{1}{6}, \tfrac{1}{12}, \tfrac{1}{2}, \tfrac{1}{4}) = \tfrac{1}{2} + \tfrac{1}{4} = \tfrac{3}{4} \neq f_4(\tfrac{1}{2}, \tfrac{1}{6}, \tfrac{1}{4}, \tfrac{1}{12}) .$$

Moreover,

$$f_4(\tfrac{1}{12}, \tfrac{1}{6}, \tfrac{1}{4}, \tfrac{1}{2}) = \tfrac{1}{4} + \tfrac{1}{2} = \tfrac{3}{4} \neq f_4(\tfrac{1}{2}, \tfrac{1}{6}, \tfrac{1}{4}, \tfrac{1}{12}) ,$$

and

$$f_4(\tfrac{1}{4}, \tfrac{1}{12}, \tfrac{1}{2}, \tfrac{1}{6}) = \tfrac{1}{2} + \tfrac{1}{6} = \tfrac{2}{3} \neq f_4(\tfrac{1}{2}, \tfrac{1}{6}, \tfrac{1}{4}, \tfrac{1}{12}) .$$

One can also state that the axiom of reduced symmetry is independent of the postulates of extreme symmetry and block symmetry. It is enough to take into account the functions

$$f_n(x_1, x_2, \ldots, x_n) = x_1 + x_n$$

and

$$f_{2n}(x_1, x_2, \ldots, x_{2n}) = x_1 + x_2 + x_{n+1} + x_{n+2} ,$$

respectively.

3. GENERALIZATIONS

Note that in the proof of Theorem 1 we have used II_n' only for $n = 2$ and 3. Thus in fact we have proved the following result.

Theorem 2. Suppose that real functions $H_1(1)$, $H_2(p_1, p_2), \ldots, H_n(p_1, p_2, \ldots, p_n)$ defined on $\mathscr{D}_n$, $n \geqq 1$, satisfy I′, III_n' and

II″. $H_2(p_1, p_2) = H_2(p_2, p_1)$

$$H_3(p_1, p_2, p_3) = H_3(p_1, p_3, p_2) .$$

Then (2) holds.

Note that the conditions II″ and III$'_n$ for $n = 3$ imply the symmetry of $H_3(p_1, p_2, p_3)$ Indeed, using III$'_n$ and II″, we have

$$\begin{aligned}
&H_3(p_1, p_2, p_3) = H_2(p_1 + p_2, p_3) + \\
&+ (p_1 + p_2)\, H_2(p_1/(p_1 + p_2), p_2/(p_1 + p_2)) = \\
&= H_2(p_2 + p_1, p_3) + (p_2 + p_1)\, H_2(p_2/(p_2 + p_1), p_1/(p_2 + p_1)) = \\
&= H_3(p_2, p_1, p_3) = H_3(p_2, p_3, p_1)\,.
\end{aligned}$$

On the other hand from II″ and III$'_n$ we deduce that

$$\begin{aligned}
&H_3(p_1, p_2, p_3) = H_3(p_1, p_3, p_2) = \\
&= H_2(p_1 + p_3, p_2) + (p_1 + p_3)\, H_2(p_1/(p_1 + p_3), p_3/(p_1 + p_3)) = \\
&= H_2(p_3 + p_1, p_2) + (p_3 + p_1)\, H_2(p_3/(p_3 + p_1), p_1/(p_3 + p_1)) = \\
&= H_3(p_3, p_1, p_2) = H_3(p_3, p_2, p_1)
\end{aligned}$$

Hence we get the following equalities

$$\begin{aligned}
&H_3(p_3, p_2, p_1) = H_3(p_3, p_1, p_2) = H_3(p_1, p_3, p_2) = \\
&= H_3(p_1, p_2, p_3) = H_3(p_2, p_1, p_3) = H_3(p_2, p_3, p_1)
\end{aligned}$$

which prove the symmetry of $H_3(p_1, p_2, p_3)$.

The above observation leads us to a stronger version of P. M. Lee [3] characterization of the Shannon entropy, in which the symmetry of $H_2(p_1, p_2)$ and $H_3(p_1, p_2, p_3)$ is replaced by the symmetry of $H_2(p_1, p_2)$ and the reduced symmetry of $H_3(p_1, p_2, p_3)$.

Namely, we have the following result.

Theorem 3. Suppose that real functions $H_1(1), H_2(p_1, p_2), \ldots, H_n(p_1, p_2, \ldots, p_n)$, $n \geqq 1$, satisfy the axioms II″ and III$'_n$ of Theorem 2, and $h(p) := H_2(p, 1 - p)$ is a Lebesgue measurable function on $(0, 1)$.

Then (2) holds true.

Note that H_n for $n \geqq 3$ can be expressed in terms of the single function h. The property III$'_n$ gives the following formula

$$H_n(p_1, p_2, \ldots, p_n) = \sum_{k=2}^{n} P_k h(p_k/P_k)\,.$$

In the case $p_1 = p_2 = \ldots = p_n = 1/n$ we have

$$f(n) := H_n(1/n, 1/n, \ldots, 1/n) = (1/n) \sum_{k=2}^{n} kh(1/k)\,.$$

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