

Pacific Journal of Mathematics

**SOME THEOREMS ON THE RATIO OF EMPIRICAL
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S. C. TANG

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1. Introduction. Let X_1, X_2, \dots, X_n be mutually independent random variables with the common cumulative distribution function $F(x)$. Let $X_1^*, X_2^*, \dots, X_n^*$ be the same set of variables rearranged in increasing order of magnitude. In statistical language X_1, X_2, \dots, X_n form a sample of n drawn from the distribution with distribution function $F(x)$. The empirical distribution of the sample X_1, \dots, X_n is the step function $F'_n(x)$ defined by

$$(1) \quad F'_n(x) = \begin{cases} 0 & \text{for } x \leq X_1^* \\ \frac{k}{n} & \text{for } X_k^* < x \leq X_{k+1}^* \\ 1 & \text{for } x > X_n^* . \end{cases}$$

A. Kolmogorov developed a well-known limit distribution law for the difference between the empirical distribution and the corresponding theoretical distribution, assuming $F(x)$ continuous:

$$\lim_{n \rightarrow \infty} P \left\{ \sqrt{n} \sup_{-\infty < x < \infty} |F'_n(x) - F(x)| < z \right\} = \begin{cases} 0, & \text{for } z \leq 0, \\ \sum_{k=-\infty}^{\infty} (-1)^k e^{-2k^2 z^2}, & \text{for } z > 0. \end{cases}$$

Equally interesting is Smirnov's theorem:

$$\lim_{n \rightarrow \infty} P \left\{ \sqrt{n} \sup_{-\infty < x < \infty} [F'_n(x) - F(x)] < z \right\} = \begin{cases} 0, & \text{for } z \leq 0, \\ 1 - e^{-2z^2}, & \text{for } z > 0. \end{cases}$$

In this paper we shall study the ratio of the empirical distribution to the theoretical distribution, and evaluate the distribution functions of the upper and lower bounds of the ratio. We shall prove the following four theorems.

THEOREM 1. *If F is everywhere continuous then*

$$P \left\{ \sup_{0 \leq F(x) \leq 1} \frac{F'_n(x)}{F(x)} < z \right\} = s(z) = \begin{cases} 0 & \text{for } z \leq 1 \\ 1 - \frac{1}{z} & \text{for } z > 1. \end{cases}$$

Received July 28, 1961. I am deeply indebted to the referee for his corrections of my English writing. Without his aid, the present paper would not be read clearly, although the responsibility of errors rests with me.

THEOREM 2. *Let c be a positive number no larger than n and suppose that $F(x)$ is continuous in the range $0 \leq F(x) \leq c/n$. Then*

$$P \left\{ \sup_{0 < F_n(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} < z \right\} = \begin{cases} \sum_{r=0}^{\lfloor cz \rfloor} \binom{n}{r} \left(1 - \frac{c}{n}\right)^{n-r} \left(\frac{c}{n}\right)^r \\ - \sum_{k=1}^{\lfloor cz \rfloor} \binom{n}{k} \frac{k^{k-1} (nz - k)^{n-k}}{(nz)^n} \\ \cdot \sum_{r=k}^{\lfloor cz \rfloor} \binom{n-k}{r-k} \left(\frac{cz-k}{nz-k}\right)^{r-k} \left(1 - \frac{cz-k}{nz-k}\right)^{n-r} & \text{for } 0 < z \leq \frac{n}{c} \\ 0 & \text{for } z \leq 0 \\ 1 - \frac{1}{z} & \text{for } z > \frac{n}{c}. \end{cases}$$

THEOREM 3. *Under the assumption of Theorem 1,*

$$P \left\{ \inf_{0 < F_n(x) \leq 1} \frac{F_n(x)}{F(x)} \leq z \right\} = I_n(z) = \begin{cases} 0 & \text{for } z < \frac{1}{n} \\ \left(1 - \frac{1}{nz}\right)^n \\ + \sum_{k=1}^{\lfloor nz \rfloor} \binom{n}{k} \frac{(k-1)^{k-1} (nz - k)^{n-k}}{(nz)^n} & \text{for } \frac{1}{n} \leq z \leq 1 \\ 1 & \text{for } z > 1. \end{cases}$$

THEOREM 4. *Under the assumptions of Theorem 2, if $1 \leq c \leq n$ then*

$$P \left\{ \inf_{0 < F_n(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} \leq z \right\} = \begin{cases} 0 & \text{for } z < \frac{1}{n} \\ \left(1 - \frac{1}{nz}\right)^n + \sum_{k=1}^{\lfloor nz \rfloor} \binom{n}{k} \frac{(k-1)^{k-1} (nz - k)^{n-k}}{(nz)^n} & \text{for } \frac{1}{n} \leq z \leq \frac{c}{n} \\ \left(1 - \frac{1}{nz}\right)^n + \sum_{k=1}^{\lfloor c \rfloor} \binom{n}{k} \frac{(k-1)^{k-1} (nz - k)^{n-k}}{(nz)^n} & \text{for } z > \frac{c}{n}. \end{cases}$$

2. An elementary lemma. We shall use the following lemma.

LEMMA. Let k be a positive integer and α an arbitrary real number. Then

$$(2) \quad \sum_{r=1}^k \frac{r^{r-1}}{r!} \frac{(\alpha - r)^{k-r}}{(k-r)!} = \frac{\alpha^{k-1}}{(k-1)!},$$

$$(3) \quad \frac{(\alpha - 1)^k}{k!} + \sum_{r=1}^k \frac{(r-1)^{r-1}}{r!} \frac{(\alpha - r)^{k-r}}{(k-r)!} = \frac{\alpha^k}{k!}.$$

If $\alpha = k$ (a special case) then

$$(4) \quad \sum_{r=1}^k \frac{r^{r-1}}{r!} \frac{(k-r)^{k-r}}{(k-r)!} = \frac{k^{k-1}}{(k-1)!} = \frac{k^k}{k!},$$

$$(5) \quad \frac{(k-1)^k}{k!} + \sum_{r=1}^k \frac{(r-1)^{r-1}}{r!} \frac{(k-r)^{k-r}}{(k-r)!} = \frac{k^k}{k!}.$$

Proof. Let $f(x)$ be a polynomial whose degree is less than k . Then

$$\sum_{r=0}^k \binom{k}{r} (-1)^r f(r) = (-1)^n [\mathcal{A}_n f(x)]_{x=0} = 0$$

i.e.
$$\sum_{r=1}^k \binom{k}{r} (-1)^r f(r) = -f(0).$$

Now we can directly obtain (2) and (3):

$$\begin{aligned} \sum_{r=1}^k \frac{r^{r-1}}{r!} \frac{(\alpha - r)^{k-r}}{(k-r)!} &= \sum_{r=1}^k \frac{r^{r-1}}{r!} \sum_{s=0}^{k-r} \frac{\alpha^s (-r)^{k-r-s}}{s! (k-r-s)!} \\ &= \sum_{s=0}^{k-1} \frac{(-1)^{k-s} \alpha^s}{s!} \sum_{r=1}^{k-s} \frac{(-1)^r r^{k-s-1}}{r! (k-r-s)!} \\ &= \frac{(-1)^{k-(k-1)} \alpha^{k-1}}{(k-1)!} (-1) = \frac{\alpha^{k-1}}{(k-1)!}. \end{aligned}$$

$$\begin{aligned} \frac{(\alpha - 1)^k}{k!} + \sum_{r=1}^k \frac{(r-1)^{r-1}}{r!} \frac{(\alpha - r)^{k-r}}{(k-r)!} &= \frac{(\alpha - 1)^k}{k!} + \sum_{r=1}^k \frac{(r-1)^{r-1}}{r!} \sum_{s=0}^{k-r} \frac{(\alpha - 1)^s (-r+1)^{k-r-s}}{s! (k-r-s)!} \\ &= \frac{(\alpha - 1)^k}{k!} + \sum_{s=0}^{k-1} \frac{(-1)^{k-s} (\alpha - 1)^s}{s!} \sum_{r=1}^{k-s} \frac{(-1)^r r (r-1)^{k-s-1}}{r! (k-r-s)!} \\ &= \frac{(\alpha - 1)^k}{k!} + \sum_{s=0}^{k-1} \frac{(-1)^{k-s} (\alpha - 1)^s (-1)^{k-s}}{s! (k-s)!} \\ &= \sum_{s=0}^k \frac{(\alpha - 1)^s}{s! (k-s)!} = \frac{\alpha^k}{k!}. \end{aligned}$$

3. Proof of Theorem 1. First we consider the case $z \geq 1$. Let y_k be the largest root of the equation

$$F(x) = \frac{k}{nz} \quad (1 \leq k \leq n).$$

Since F is continuous, y_k is well defined. Now we evaluate probability of the inequality

$$(6) \quad \sup_{0 \leq F(x) \leq 1} \frac{F_n(x)}{F(x)} \geq z$$

that is, the probability that there exists an x such that

$$(7) \quad \frac{F_n(x)}{F(x)} \geq z.$$

If (7) is true, then, since $F(x)$ is nondecreasing and $\lim_{x \rightarrow \infty} (F_n(x)/F(x)) = 1$, there exists an x_0 such that

$$\frac{F_n(x_0)}{F(x_0)} = z.$$

By the definition of F_n , $F_n(x_0) = k/n$ for some k , so that $F(x_0) = k/nz$. Therefore we can take x_0 as one of y_k . In other words, for one value of y_k we have

$$F_n(y_k) = \frac{k}{n}$$

and the inequality

$$(8) \quad X_k^* < y_k \leq X_{k+1}^*$$

is true. Now let A_k be the event that this inequality holds.

Clearly (6) occurs if, and only if, at least one among the events

$$A_1, A_2, A_3, \dots, A_n$$

occurs. Generally the A_k are not mutually exclusive events so that the additive law is of no use. We may, with the help of an associated set of mutually exclusive events, deal with this situation. Put

$$u_k = \bar{A}_1 \bar{A}_2 \dots \bar{A}_{k-1} A_k \quad (k = 1, 2, \dots, n).$$

where \bar{A} denotes the complementary event of A . We have

$$(9) \quad P \left\{ \sup_{0 < F(x) \leq 1} \frac{F_n(x)}{F(x)} \geq z \right\} = P \left\{ \sum_{k=1}^n A_k \right\} = P \left\{ \sum_{k=1}^n u_k \right\} = \sum_{k=1}^n P(u_k).$$

If we employ the following conditional probability formula, we can evaluate $P(u_k)$.

$$(10) \quad P(A_k) = \sum_{r=1}^k P(u_r) P\{A_k | u_r\} = \sum_{r=1}^k P(u_r) P\{A_k | A_r\}.$$

Now A_k occurs if k of the n observations fall to the left of y_k , and $n - k$ to the right; hence

$$P(A_k) = \binom{n}{k} \left(\frac{k}{nz}\right)^k \left(1 - \frac{k}{nz}\right)^{n-k}.$$

And $P(A_k | A_r)$ is the probability that of $(n - r)$ observations, known to lie to the right of y_r , $(k - r)$ lie to the left of y_k and $n - k$ to the right. The probability of occurrence of an event, whose value is greater than or equal to y_r and is on the interval $y_r \leq x \leq y_k$ is

$$\frac{k/nz - r/nz}{1 - r/nz} = \frac{k - r}{nz - r}.$$

Therefore

$$P(A_k | A_r) = \binom{n - r}{k - r} \left(\frac{k - r}{nz - r}\right)^{k-r} \left(1 - \frac{k - r}{nz - r}\right)^{n-k}.$$

If we employ the notation

$$p_k(z) = \frac{(nz - n + k)^k}{k!},$$

we get

$$P(A_k) = \frac{p_k(1)p_{n-k}(z)}{p_n(z)}, \quad P(A_k | A_r) = \frac{p_{k-r}(1)p_{n-k}(z)}{p_{n-r}(z)}.$$

Equation (10) can be reduced to

$$\begin{aligned} \frac{p_k(1)p_{n-k}(z)}{p_n(z)} &= \sum_{r=1}^k P(u_r) \frac{p_{k-r}(1)p_{n-k}(z)}{p_{n-r}(z)}, \\ p_k(1) &= \sum_{r=1}^k P(u_r) \frac{p_n(z)}{p_{n-r}(z)} p_{k-r}(1). \end{aligned}$$

Hence $P_k(1) = k^k/k!$ and $P_{k-r}(1) = (k - r)^{k-r}/(k - r)!$. By (3) of our lemma we know that

$$P(u_r) \frac{p_n(z)}{p_{n-r}(z)} = \frac{r^{r-1}}{r!}, \quad P(u_r) = \frac{r^{r-1}}{r!} \frac{p_{n-r}(z)}{p_n(z)} = \frac{n!}{(nz)^n} \frac{r^{r-1}}{r!} \frac{(nz - r)^{n-r}}{(n - r)!}.$$

And (9) and the (2) of our lemma tell us that

$$\begin{aligned} P\left\{ \sup_{0 < F(x) \leq 1} \frac{F_n(x)}{F(x)} < z \right\} &= 1 - P\left\{ \sup_{0 \leq F(x) \leq 1} \frac{F_n(x)}{F(x)} \geq z \right\} = 1 - \sum_{k=1}^n P(u_k) \\ &= 1 - \frac{n!}{(nz)^n} \sum_{k=1}^n \frac{k^{k-1}}{k!} \frac{(nz - k)^{n-k}}{(n - k)!} \\ &= 1 - \frac{n!}{(nz)^n} \frac{(nz)^{n-1}}{(n - 1)!} = 1 - \frac{1}{z}, \quad (z \geq 1). \end{aligned}$$

This completes the proof of Theorem 1.

Proof of Theorem 2. Since the ratio is nonnegative, the probability of the inequality is zero if $z \leq 0$. Under the condition $z > n/c$, we know that the event $\{\sup_{0 < F(x) \leq c/n} F_n(x)/F(x) \geq z\}$ is still equal to $\sum_{k=1}^n A_k$ by the result of Theorem 1. Suppose $0 < z \leq n/c$. Then

$$P\left\{\sup_{0 < F(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} \geq z\right\} = P\left\{\sum_{k=1}^{[cz]} A_k + A_{cz}^*\right\} = \sum_{k=1}^{[cz]} P(u_k) + P(u_{cz}^*),$$

where

$$A_{cz}^* = \{X_{[cz]+1}^* < y_{cz}\}, \quad y_{cz} = \sup\left\{x: F(x) = \frac{c}{n}\right\},$$

$$u_{cz}^* = \bar{A}_1 \bar{A}_2 \cdots \bar{A}_{[cz]} A_{cz}^*.$$

Since $P(U_k)$ has been computed, we need only evaluate $P(U_{cz}^*)$. We have

$$P(A_{cz}^*) = \sum_{k=1}^{[cz]} P(u_k)P\{A_{cz}^* | A_k\} + P(u_{cz}^*)P\{A_{cz}^* | A_{cz}^*\},$$

$$P(u_{cz}^*) = P(A_{cz}^*) - \sum_{k=1}^{[cz]} P\{A_{cz}^* | A_k\}.$$

From this we obtain

$$\begin{aligned} P\left\{\sup_{0 \leq F(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} < z\right\} &= 1 - \sum_{k=1}^{[cz]} P(u_k) - P(u_{cz}^*) \\ &= 1 - P(A_{cz}^*) - \sum_{k=1}^{[cz]} P(u_k)[1 - P\{A_{cz}^* | A_k\}] \\ &= P(\bar{A}_{cz}^*) - \sum_{k=1}^{[cz]} P(u_k)P\{\bar{A}_{cz}^* | A_k\} \\ &= \sum_{r=0}^{[cz]} \binom{n}{r} \left(\frac{c}{n}\right)^r \left(1 - \frac{c}{n}\right)^{n-r} - \sum_{k=1}^{[cz]} \binom{n}{k} \frac{k^{k-1}(nz - k)^{n-k}}{(nz)^n} \\ &\quad \cdot \sum_{r=k}^{[cz]} \binom{n-k}{r-k} \left(\frac{cz - k}{nz - k}\right)^{r-k} \left(1 - \frac{cz - k}{nz - k}\right)^{n-r}. \end{aligned}$$

Since

$$P(\bar{A}_{cz}^*) = P\{y_{cz} \leq X_{[cz]+1}^*\} = \sum_{r=0}^{[cz]} P\{X_r^* < y_{cz} \leq X_{r+1}^*\}$$

$$= \sum_{r=0}^{[cz]} \binom{n}{r} \left(\frac{c}{n}\right)^r \left(1 - \frac{c}{n}\right)^{n-r}$$

we have

$$P(\bar{A}_{cz}^* | A_k) = \sum_{r=k}^{[cz]} \binom{n-k}{r-k} \left(\frac{cz - k}{nz - k}\right)^{r-k} \left(1 - \frac{cz - k}{nz - k}\right)^{n-r}$$

which completes the proof. The distribution of Theorem 1 is continuous; the distribution of Theorem 2 is not continuous on the interval $0 \leq z \leq n/c$.

Theorem 3 is a special case of Theorem 4 under the condition $c = n$. In fact, by (4) of our lemma, setting $z = 1$, we deduce Theorem 3 as follows:

$$\begin{aligned} P\left\{ \inf_{0 < F_n(x) \leq 1} \frac{F'_n(x)}{F(x)} \leq 1 \right\} &= \left(1 - \frac{1}{n}\right)^n + \sum_{k=1}^n \binom{n}{k} \frac{(k-1)^{k-1} (n-k)^{n-k}}{n^n} \\ &= \frac{n!}{n^n} \left[\frac{(n-1)^n}{n!} + \sum_{k=1}^n \frac{(k-1)^{k-1}}{k!} \frac{(n-k)^{n-k}}{(n-k)!} \right] \\ &= \frac{n!}{n^n} \frac{n^n}{n!} = 1. \end{aligned}$$

Thus we need only prove Theorem 4. The distribution function of Theorem 3 has a discontinuity corresponding to $z = 1$; the distribution function of Theorem 4 is continuous on the interval $1 \leq c \leq n$.

5. Proof of Theorem 4. On the interval $F_n(x) > 0$ the maximum of $F(x)$ is 1; the minimum of $F_n(x)$ is $1/n$. From these results it follows that the lower bound of the ratio is no smaller than $1/n$. Therefore

$$P\left\{ \inf_{0 < F_n(x) \leq \frac{c}{n}} \frac{F'_n(x)}{F(x)} \leq z \right\} = 0$$

if $z < 1/n$. Let z_k be the least root of the equation

$$F(x) = \frac{k}{nz} \quad \left(z \geq \frac{1}{n}, \quad 1 \leq k \leq [nz] \right).$$

Define events

$$\begin{aligned} B_0: X_1 &\geq z_1, \\ B_k: X_k^* &< z_k \leq X_{k+1}^*. \end{aligned}$$

If $1/n \leq z \leq c/n$, the event

$$\inf_{0 < F_n(x) \leq \frac{c}{n}} \frac{F'_n(x)}{F(x)} \leq z$$

is the union of the events

$$B_0, B_1, B_2, \dots, B_{[nz]}.$$

For the purpose of evaluating the probability of $\sum_k B_k$ we put

$$V_0 = B_0, \quad V_k = \bar{B}_0 \bar{B}_1 \dots \bar{B}_{k-1} B_k \quad (k = 1, 2, \dots, [nz]).$$

We have

$$(11) \quad P(B_k) = \sum_{r=0}^k P(V_r)P(B_k | B_r), \quad (k = 0, 1, \dots, [nz])$$

Here

$$P(V_0) = P(B_0) = \left(1 - \frac{1}{nz}\right)^n,$$

$$P\{B_k | B_0\} = \binom{n}{k} \left(\frac{k-1}{nz-1}\right)^k \left(\frac{nz-k}{nz-1}\right)^{n-k}.$$

Now we transform (11) into the following form:

$$\frac{p_k(1)p_{n-k}(z)}{p_n(z)} = \frac{(k-1)^k p_{n-k}(z)}{k! p_n(z)} + \sum_{r=1}^k P(V_r) \frac{p_{k-r}(1)p_{n-k}(z)}{p_{n-r}(z)},$$

$$p_k(1) = \frac{(k-1)^k}{k!} + \sum_{r=1}^k P(V_r) \frac{p_n(z)}{p_{n-r}(z)} p_{k-r}(1).$$

By (4) of our lemma we obtain

$$P(V_r) = \frac{(r-1)^{r-1}}{r!} \frac{p_{n-r}(z)}{p_n(z)} = \binom{n}{r} \frac{(r-1)^{r-1}(nz-r)^{n-r}}{(nz)^n}, \quad (1 \leq r \leq [nz])$$

It follows that if $1/n \leq z \leq c/n$,

$$P\left\{\inf_{0 < F_n(x) \leq \frac{c}{n}} \frac{F'_n(x)}{F(x)} \leq z\right\} = P\left\{\sum_{k=0}^{[nz]} B_k\right\} = \sum_{k=0}^{[nz]} P(V_k)$$

$$= \left(1 - \frac{1}{nz}\right)^n + \sum_{k=1}^{[nz]} \binom{n}{k} \frac{(k-1)^{k-1}(nz-k)^{n-k}}{(nz)^n}.$$

If $z > c/n$,

$$P\left\{\inf_{0 < F_n(x) \leq \frac{c}{n}} \frac{F'_n(x)}{F(x)} \leq z\right\} = P\left\{\sum_{k=0}^{[c]} B_k\right\} = \sum_{k=0}^{[c]} P(V_k)$$

$$= \left(1 - \frac{1}{nz}\right)^n + \sum_{k=1}^{[c]} \binom{n}{k} \frac{(k-1)^{k-1}(nz-k)^{n-k}}{(nz)^n}.$$

Theorem 4 is thus proved.

6. Conclusions. Theorems 1 and 3 can be applied to test whether statistical data correspond with the theoretical distribution or not. In the process of testing, z_s and z_i are separately representative of the ratio's upper and lower bounds. If $S(z_s)$ is small and $I_n(z_i)$ large, we conclude that the empirical data in two extreme tails correspond with the theoretical distribution; conversely, if $S(z_s)$ is very large and $I_n(z_i)$ very small, the statistical data do not correspond with the theoretical distribution. Our test is more sensitive in the two tails, but less sensitive in the central part, than Smirnov's test.

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50 reprints per author of each article are furnished free of charge; additional copies may be obtained at cost in multiples of 50.

The *Pacific Journal of Mathematics* is published quarterly, in March, June, September, and December. Effective with Volume 13 the price per volume (4 numbers) is \$18.00; single issues, \$5.00. Special price for current issues to individual faculty members of supporting institutions and to individual members of the American Mathematical Society: \$8.00 per volume; single issues \$2.50. Back numbers are available.

Subscriptions, orders for back numbers, and changes of address should be sent to Pacific Journal of Mathematics, 103 Highland Boulevard, Berkeley 8, California.

Printed at Kokusai Bunken Insatsusha (International Academic Printing Co., Ltd.), No. 6, 2-chome, Fujimi-cho, Chiyoda-ku, Tokyo, Japan.

PUBLISHED BY PACIFIC JOURNAL OF MATHEMATICS, A NON-PROFIT CORPORATION

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