SOME THEOREMS ON THE RATIO OF EMPIRICAL DISTRIBUTION TO THE THEORETICAL DISTRIBUTION

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

\[
F_n(x) = \begin{cases} 
0 & \text{for } x \leq X_1^* \\
\frac{k}{n} & \text{for } X_k^* < x \leq X_{k+1}^* \\
1 & \text{for } x > X_n^* .
\end{cases}
\]

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:

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

Equally interesting is Smirnov’s theorem:

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

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

\[
P\left\{ \sup_{0 \leq F(x) \leq 1} \frac{F_n(x)}{F(x)} < z \right\} = s(z) = \begin{cases} 
0 & \text{for } z \leq 1 \\
\frac{1}{z} & \text{for } z > 1 .
\end{cases}
\]

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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

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

THEOREM 3. Under the assumption of Theorem 1,

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

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

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

2. An elementary lemma. We shall use the following lemma.
Lemma. Let \( k \) be a positive integer and \( \alpha \) 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

\[
(4) \quad \frac{(k-1)^k}{k!} + \sum_{r=1}^{k} \frac{(r-1)^{r-1}}{r!} \frac{(k - r)^{k-r}}{(k-r)!} = \frac{\alpha^k}{k!}.
\]

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

\[
\sum_{r=1}^{k} \binom{k}{r} (-1)^r f(r) = (-1)^r [A_n f(x)]_{x=0} = 0
\]

i.e.

\[
\sum_{r=1}^{k} \binom{k}{r} (-1)^r f(r) = -f(0).
\]

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

\[
\sum_{r=1}^{k} \frac{r^{r-1}}{r!} \frac{(\alpha - r)^{k-r}}{(k-r)!} = \sum_{r=1}^{k} \frac{r^{r-1}}{r!} \frac{\alpha^{k-r} (-r)^{r-s}}{s! (k-r-s)!} = \sum_{s=0}^{k-1} \frac{(-1)^s \alpha^{k-s}}{s! k!} \frac{(-1)^r (r-1)^{r-s-1}}{r! (k-r-s)!}
\]

\[
= \frac{(-1)^{k-1} \alpha^{k-1}}{(k-1)!} (-1) = \frac{\alpha^{k-1}}{(k-1)!}.
\]

\[
(\alpha - 1) \frac{\alpha^{k-1}}{(k-1)!} + \sum_{r=1}^{k} \frac{(r-1)^{r-1}}{r!} \frac{(\alpha - r)^{k-r}}{(k-r)!} = \frac{(\alpha - 1)^k}{k!} + \sum_{s=0}^{k-1} \frac{(-1)^{k-s} (\alpha - 1)^s}{s! (k-r-s)!} \frac{(-1)^r (r-1)^{r-s-1}}{r! (k-r-s)!}
\]

\[
= \frac{(\alpha - 1)^k}{k!} + \sum_{s=0}^{k-1} \frac{(-1)^{k-s} (\alpha - 1)^s}{s! (k-s)!} \frac{(-1)^r (r-1)^{r-s-1}}{r! (k-s)!}
\]

\[
= \sum_{s=0}^{k-1} \frac{(-1)^s (\alpha - 1)^s}{s! (k-s)!} = \frac{\alpha^k}{k!}.
\]

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

\[
\sup_{0 \leq F(x) \leq 1} \frac{F'(x)}{F(x)} \geq z
\]

that is, the probability that there exists an \( x \) such that

\[
\frac{F'(x)}{F(x)} \geq z.
\]

If (7) is true, then, since \( F(x) \) is nondecreasing and \( \lim_{x \to \infty} (F_n(x)/F(x)) = 1 \), 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

\[
X_k^* < y_k \leq X_{k+1}^*
\]

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

\[ A_1, A_2, A_3, \ldots, A_n \]

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

\[
\bar{A} = \bar{A}_1\bar{A}_2\cdots\bar{A}_{k-1}\bar{A}_k
\]

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

\[
P\left\{ \sup_{0 \leq F(x) \leq 1} \frac{F'(x)}{F(x)} \geq z \right\} = P\left\{ \sum_{k=1}^{n} A_k \right\} = P\left\{ \sum_{k=1}^{n} u_k \right\} = \sum_{k=1}^{n} P(u_k).
\]

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

\[
P(A_k) = \sum_{r=1}^{k} P(u_r)P\{A_k \mid u_r\} = \sum_{r=1}^{k} P(u_r)P\{A_k \mid A_r\}.
\]
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 $P(A_k \mid A_r)$ 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

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

If we employ the notation

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

we get

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

Equation (10) can be reduced to

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

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

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

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

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

$$P \left\{ \sup_{0 \leq x \leq 1} \frac{F_n(x)}{F(x)} < z \right\} = 1 - P \left\{ \sup_{0 \leq x \leq 1} \frac{F_n(x)}{F(x)} \geq z \right\} = 1 - \sum_{h=1}^{n} P(u_h)$$

$$= 1 - \frac{n!}{(nz)^n} \sum_{k=1}^{n} \frac{k^{k-1}}{k!} \frac{(nz - k)^{n-k}}{(n - k)!}$$

$$= 1 - \frac{n!}{(nz)^n} \frac{(nz)^{n-1}}{(n - 1)!} = 1 - \frac{1}{z}, \quad (z \geq 1).$$
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 \( \{ \sup_{0 < F(x) \leq n} F_n(x)/F(x) \geq z \} \) is still equal to \( \sum_{k=1}^{n_c} A_k \) by the result of Theorem 1. Suppose \( 0 < z \leq n/c \). Then

\[
\Pr \left\{ \sup_{0 < F(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} \geq z \right\} = \Pr \left\{ \sum_{k=1}^{n_c} A_k + A^*_{c} \right\} = \sum_{k=1}^{n_c} \Pr(A_k) + \Pr(A^*_{c}),
\]

where

\[
A^*_{c} = \{ X_{[c]_{c+1}} < y_c \}, \quad y_c = \sup \left\{ x : F(x) = \frac{c}{n} \right\},
\]

\[
u^*_{c} = \bar{A}_1 \bar{A}_2 \cdots \bar{A}_{[c]} A^*_{c}.
\]

Since \( \Pr(U_k) \) has been computed, we need only evaluate \( \Pr(U^*_c) \). We have

\[
\Pr(A^*_{c}) = \sum_{k=1}^{n_c} \Pr(A_k) \Pr(A^*_{c} | A_k) + \Pr(u^*_{c}) \Pr(A^*_{c} | A^*_{c}) \]

\[
\Pr(u^*_{c}) = \Pr(A^*_{c}) - \sum_{k=1}^{n_c} \Pr(A^*_{c} | A_k) \]

From this we obtain

\[
\Pr \left\{ \sup_{0 < F(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} < z \right\} = 1 - \sum_{k=1}^{n_c} \Pr(A_k) - \Pr(u^*_{c})
\]

\[
= 1 - \Pr(A^*_{c}) - \sum_{k=1}^{n_c} \Pr(A_k) \Pr(A^*_{c} | A_k)\]

\[
= \Pr(\bar{A}^*_{c}) - \sum_{k=1}^{n_c} \Pr(u^*_{c}) \Pr(A^*_{c} | A_k)
\]

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

\[
\cdot \sum_{r=k}^{n_c} \binom{n-k}{r-k} \left( \frac{c z - k}{nz - k} \right)^{r-k} \left( 1 - \frac{c z - k}{nz - k} \right)^{n-r}.
\]

Since

\[
\Pr(\bar{A}^*_{c}) = \Pr(y_{c} \leq X_{[c]_{c+1}}) = \sum_{r=0}^{n_c} \Pr(X_r < y_c \leq X_{r+1})
\]

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

we have

\[
\Pr(\bar{A}^*_{c} | A_k) = \sum_{r=k}^{n_c} \binom{n-k}{r-k} \left( \frac{c z - k}{nz - k} \right)^{r-k} \left( 1 - \frac{c z - k}{nz - k} \right)^{n-r}
\]
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:

$$P\left\{ \inf_{0 < F_n(x) \leq 1} \frac{F_n(x)}{F(x)} \leq 1 \right\} = \left(1 - \frac{1}{n}\right)^n + \sum_{k=1}^{n} \frac{(n - 1)^{k-1}(n - k)^{n-k}}{n^n} \cdot \frac{n!}{n!} \frac{n^n}{n!} = 1.$$

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 internal $F_n(x) > 0$ 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

$$P\left\{ \inf_{0 < F_n(x) \leq z_n} \frac{F_n(x)}{F(x)} \leq z \right\} = 0$$

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

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

Define events

$$B_0: X_1 \geq z_1,$$

$$B_k: X_k^* < z_k \leq X_{k+1}^*.$$

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

$$\inf_{0 < F_n(x) \leq z_n} \frac{F_n(x)}{F(x)} \leq z$$

is the union of the events

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

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

$$V_0 = B_0, \quad V_k = B_0 B_1 B_2 \cdots B_{k-1} B_k \quad (k = 1, 2, \cdots, [nz]).$$
We have

\[ P(B_k) = \sum_{r=0}^{k} P(V_r)P(B_k \mid B_r), \quad (k = 0, 1, \cdots, [nz]) \]

Here

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

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

Now we transform (11) into the following form:

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

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

By (4) of our lemma we obtain

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

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

\[ P\left\{ \inf_{0 \leq F_n(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} \leq z \right\} = P\left\{ \sum_{k=0}^{[nz]} B_k \right\} = \sum_{k=0}^{[nz]} P(V_k) = \left(1 - \frac{1}{nz}\right)^n + \sum_{k=1}^{[nz]} \binom{n}{k} \frac{(k - 1)^{k-1}(nz - k)^{s-k}}{(nz)^s}. \]

If \(z > c/n\),

\[ P\left\{ \inf_{0 \leq F_n(x) \leq \frac{c}{n}} \frac{F_n(x)}{F(x)} \leq z \right\} = P\left\{ \sum_{k=0}^{[c]} B_k \right\} = \sum_{k=0}^{[c]} P(V_k) = \left(1 - \frac{1}{nz}\right)^n + \sum_{k=1}^{[c]} \binom{n}{k} \frac{(k - 1)^{k-1}(nz - k)^{s-k}}{(nz)^s}. \]

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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