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VARIANCE OF SAMPLE VARIANCE WITH REPLACEMENT

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Abstract: The variance of variance of finite samples taken from a finite population with replacement is expressed in terms of the sample size and the second and fourth order moments of population.

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1. Introduction

We give a formula of the variance of with-replacement sample variance in terms of the sample size and the second and fourth moments of the population about the mean. The derivation of the formula does not require working with the more elaborate "polykay" approach of Tukey [4], [5], [6], [7]. Formula for the variance of the variance of *without-replacement* samples from a finite population given in Cho et al [1] is quoted for comparison at the end of this paper.

2. Main Theorem

Let A be a finite set $\{a_1, \ldots, a_N\}$ and s a sample of n elements $\{x_1, \ldots, x_n\}$

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taken from A *with replacement*. n is not bounded by the population size N, though often in practice $n \ll N$. The sample s is viewed as a realization of independent identically distributed random variables $X_1, \ldots, X_n$ on A. Following notation will be used.

$$\begin{aligned} \overline{X} &= \frac{\sum_{i=1}^{n} X_i}{n}, \quad S^2 = \frac{\sum_{i=1}^{n} \left(X_i - \overline{X}\right)^2}{n-1}, \quad \mu = \frac{\sum_{i=1}^{N} a_i}{N}, \\ \mu_k &= \frac{\sum_{i=1}^{N} (a_i - \mu)^k}{N}, \quad \mu'_k = \frac{\sum_{i=1}^{N} {a_i}^k}{N}. \end{aligned}$$

Theorem 1. Let S^2 be the variance of *with-replacement* samples of size n from a set A of real numbers $a_1, a_2, \ldots, a_N$. The variance of S^2

$$Var\left(S^2\right) = \frac{1}{n}\left(\mu_4 - \frac{n-3}{n-1}\,{\mu_2}^2\right) \tag{1}$$

$$= \frac{1}{n}\left(\mu_4 - {\mu_2}^2\right) + \mathbf{O}\left(n^{-2}\right). \tag{2}$$

Proof. Let $Z_i = X_i - \mu$ for $i = 1, 2, \ldots n$ so that $E\left(Z_i\right) = 0$. Since $Var\left(S^2\right) = E\left(S^4\right) - {\mu_2}^2$, we derive an expression of $E(S^4)$ in terms of n and the moments. We can write

$$S^2 = \frac{n \sum_{i=1}^{n} {Z_i}^2 - \left(\sum_{i=1}^{n} Z_i\right)^2}{n\,(n-1)}$$

and by squaring

$$S^4 = \frac{n^2 \left(\sum_{i=1}^{n} {Z_i}^2\right)^2 - 2\,n \left(\sum_{i=1}^{n} {Z_i}^2\right) \left(\sum_{i=1}^{n} Z_i\right)^2 + \left(\sum_{i=1}^{n} Z_i\right)^4}{n^2\,(n-1)^2},$$

$$E(S^4) = \frac{n^2\, E\left(\sum_{i=1}^{n} {Z_i}^2\right)^2 - 2nE\left(\left(\sum_{i=1}^{n} {Z_i}^2\right)\left(\sum_{i=1}^{n} Z_i\right)^2\right) + E\left(\sum_{i=1}^{n} Z_i\right)^4}{n^2\,(n-1)^2}.$$

Since $Z_1, \ldots, Z_n$ are independent, we have

$$\begin{aligned} E\left(Z_i\, Z_j\right) &= 0, \qquad E\left({Z_i}^3\, Z_j\right) = 0, \qquad E\left({Z_i}^2\, Z_j\, Z_k\right) = 0, \\ E\left({Z_i}^2\, {Z_j}^2\right) &= {\mu_2}^2, \qquad E\left({Z_i}^4\right) = \mu_4, \quad \text{for distinct} \quad i, j, k. \end{aligned}$$

Routine algebraic simplification with the expected values given above yields

$$E\left(\sum_{i=1}^{n} {Z_i}^2\right)^2 = n\,\mu_4 + n\,(n-1)\,{\mu_2}^2, \tag{3}$$

$$E\left(\left(\sum_{i=1}^{n} {Z_i}^2\right)\left(\sum_{i=1}^{n} Z_i\right)^2\right) = n\,\mu_4 + n\,(n-1)\,{\mu_2}^2, \tag{4}$$

$$E\left(\sum_{i=1}^{n} Z_i\right)^4 \quad = \quad n\,\mu_4 + 3\,n\,\left(n-1\right)\mu_2{}^2\,. \tag{5}$$

Substitution of (3), (4) and (5) into the expansion of $E\left(S^4\right)$ and simplification give

$$E\left(S^4\right) \quad = \quad \frac{\left(n-1\right)\,\mu_4 + \left(n^2 - 2n + 3\right)\mu_2{}^2}{n\,\left(n-1\right)} \tag{6}$$

and

$$\begin{aligned} Var\left(S^2\right) &= E\left(S^4\right) - \mu_2{}^2 \\ &= \frac{\left(n-1\right)\,\mu_4 + \left(n^2 - 2n + 3\right)\mu_2{}^2}{n\,\left(n-1\right)} - \mu_2{}^2 \\ &= \frac{1}{n}\left(\mu_4 - \frac{n-3}{n-1}\mu_2{}^2\right) \\ &= \frac{1}{n}\left(\mu_4 - \mu_2{}^2\right) + \frac{2}{n(n-1)}\mu_2{}^2\,. \qquad \square \end{aligned}$$

To obtain an expression of the formula of $Var(S^2)$ in terms of μ and the moments μ_2', μ_3' and μ_4' about zero, we substitute

$$\begin{aligned} \mu_2 &= \mu_2' - \mu^2\,, \\ \mu_4 &= \mu_4' - 4\mu\mu_3' + 6\mu^2\mu_2' - 3\mu^4 \end{aligned}$$

into (1) and get

$$\begin{aligned} Var\left(S^2\right) \quad = \quad & \frac{1}{n}\,\mu_4' - \frac{4}{n}\,\mu\mu_3' - \frac{n-3}{n\,\left(n-1\right)}\,\mu_2'{}^2 \\ & + \frac{4\,\left(2\,n-3\right)}{n\,\left(n-1\right)}\,\mu^2\mu_2' - \frac{2\,\left(2\,n-3\right)}{n\,\left(n-1\right)}\,\mu^4\,. \end{aligned} \tag{7}$$

3. Comparison with Without-Replacement Samples

Here we compare (1) with the variance of variance of *without-replacement* samples given in [1]. Let $Var_{wo}\left(S^2\right)$ denote the variance of variance of *without-replacement* samples of size n from A. The following is a simplified (improved) version from [1]:

$$Var_{wo}\left(S^2\right) = c_1\,\mu_4 + c_3\,\mu_2{}^2\,, \tag{8}$$

where

$$c_1 \quad = \quad \frac{N\left(N-n\right)\left(Nn - N - n - 1\right)}{n\left(n-1\right)\left(N-3\right)\left(N-2\right)\left(N-1\right)}\,,$$

$$c_3 = -\frac{N\,(N-n)\left(N^2 n - 3\,n - 3\,N^2 + 6\,N - 3\right)}{n\,(n-1)\,(N-1)^2\,(N-2)\,(N-3)}\,. \tag{9}$$

We note

$$\lim_{N\to\infty} Var_{wo}\left(S^2\right) = \frac{1}{n}\,\mu_4 - \frac{n-3}{n\,(n-1)}\,{\mu_2}^2 = Var\left(S^2\right)\,,$$

as expected. The difference of $Var_{wo}\left(S^2\right)$ and $Var\left(S^2\right)$ is of order $1/N$, that is, $|Var_{wo}\left(S^2\right) - Var\left(S^2\right)|$ is $\mathbf{O}(N^{-1})$. In most practical situations where $n = cN^{\alpha}$ for some $c > 0$ and $0 < \alpha < 1$, $|Var_{wo}\left(S^2\right) - Var\left(S^2\right)|$ is $\mathbf{O}(n^{-\frac{1}{\alpha}})$. For example, if $n = \sqrt{N}$, then the difference of $Var_{wo}\left(S^2\right)$ and $Var\left(S^2\right)$ is $\mathbf{O}(n^{-2})$. As we did for $Var(S^2)$, we represent $Var_{wo}\left(S^2\right)$ in terms of the moments μ_2' and μ_4' about zero by substitution of (7) into (8):

$$Var_{wo}\left(S^2\right) = c_1\,\mu_4' + c_2\,\mu\mu_3' + c_3\,{\mu_2'}^2 + c_4, \mu^2\mu_2' + c_5\,\mu^4\,, \tag{10}$$

where c_1 and c_3 are as before (9) and

$$\begin{aligned} c_2 &= -4\,\frac{N\,(N-n)\,(Nn - N - n - 1)}{n\,(n-1)\,(N-3)\,(N-2)\,(N-1)}\,,\\ c_4 &= 4\,\frac{N^2\,(N-n)\,(2\,Nn - 3\,N - 3\,n + 3)}{n\,(n-1)\,(N-1)^2\,(N-2)\,(N-3)}\,,\\ c_5 &= -2\,\frac{N^2\,(N-n)\,(2\,Nn - 3\,N - 3\,n + 3)}{n\,(n-1)\,(N-1)^2\,(N-2)\,(N-3)}\,. \end{aligned}$$

Here again, each c_i converges to the corresponding coefficient in (7)

$$\begin{aligned} \lim_{N\to\infty} c_2 &= -\frac{4}{n}\,, \qquad \lim_{N\to\infty} c_4 = \frac{4(2n-3)}{n(n-1)}\,,\\ \lim_{N\to\infty} c_5 &= -\frac{2n-3}{n(n-1)}\,. \end{aligned}$$

Following are examples where the population itself is like a finite sample from a specific distribution.

Example 1. If a finite population follows the Gaussian distribution and $\mu_4 = 3{\mu_2}^2$, then the variance of variance of *with-replacement* samples of size n,

$$Var\left(S^2\right) = \frac{1}{n}\left(3{\mu_2}^2 - \frac{n-3}{n-1}\,{\mu_2}^2\right) = \frac{2}{n-1}{\mu_2}^2\,.$$

Example 2. If a finite population follows Poisson distribution with $\mu = \lambda$, $\mu_2 = \lambda$ and $\mu_4 = 3\,\lambda^2 + \lambda$, then

$$Var(S^2) = \frac{1}{n}\left(3\,\lambda^2 + \lambda - \frac{n-3}{n-1}\,\lambda^2\right) = \left(\frac{2\lambda}{n-1} + \frac{1}{n}\right)\lambda\,.$$

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