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Sums of Squares Using Induction
(and no Matrices)

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Establishing χ^2 Properties of Sums of Squares Using Induction (and no Matrices)

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ABSTRACT

The between-classes sum of squares in a between-and-within classes analysis of variance has, under normality, a χ^2 distribution. Although "substantial mathematical machinery" (Stigler, 1984) is often used in classroom derivation of this distribution, it can be avoided by using induction and independence properties of standard normal variables. This is the derivation given here — for unequal-subclass-numbers data. Independence of the between-and within-classes sums of squares is also shown.

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1. Introduction

Stigler (1984) points out, quite rightly, that "In introductory courses in mathematical statistics, the proof that the sample mean \bar{X} and sample variance S^2 are independent when one is sampling from normal populations is commonly deferred until substantial mathematical machinery has been developed". Contrasting this, Stigler then gives a very nice proof for the one-sample case that requires understanding nothing more than normality and independence, together with the definition of a χ^2 variable as the sum of squares of independent and identically distributed standard normal variables. The sum of independent χ^2 variables being distributed as χ^2 is also used. His method of proof, which relies on induction on sample size, is extended here to sums of squares in a one-way classification with unbalanced data (unequal subclass numbers data). It is in this situation, of the analysis of variance of unbalanced data, that Stigler's "substantial mathematical machinery" is, generally speaking, nowhere more evident, so that for teaching purposes there are great advantages in being able to avoid such complexities as is done here.

For observations y_{ij} for $i = 1, \dots, a$ and $j = 1, \dots, n_i$ assume that observations having the same value of i (those in the i 'th class) are identically distributed with a normal density having mean μ_i and variance σ^2 . Write this as

$$y_{ij} \sim \text{i.i.d. } N(\mu_i, \sigma^2) \quad \text{for } j = 1, \dots, n_i; \quad (1)$$

and let this be true for each $i = 1, \dots, a$. Also assume that observations in each class are independent of those in every other class. Thus, using $v(y_{ij})$ for the variance of y_{ij} and $\text{cov}(y_{ij}, y_{hk})$ for the covariance between y_{ij} and y_{hk} ,

$$v(y_{ij}) = \sigma^2 \quad \text{and } \text{cov}(y_{ij}, y_{hk}) = 0 \quad (2)$$

for all i, j and for all h, k except $i = h$ with $j = k$.

The sample mean of the observations in class i will be denoted by

$$\bar{y}_i = \sum_{j=1}^{n_i} y_{ij} / n_i. \quad (3)$$

We define (for subsequent convenience) partial sums of the n_i -values:

$$s_i = \sum_{t=1}^i n_t, \quad \text{and particularly } s_a = \sum_{t=1}^a n_t = n_{..} \quad (4)$$

And the mean of all observations in all a classes will be denoted by

$$m_a = \bar{y}_{..} = \sum_{i=1}^a n_i \bar{y}_i / \sum_{i=1}^a n_i = \sum_{i=1}^a n_i \bar{y}_i / s_a = \sum_{i=1}^a \sum_{j=1}^{n_i} y_{ij} / s_a. \quad (5)$$

Then from (2), (3) and (5)

$$v(\bar{y}_i) = \sigma^2 / n_i \quad \text{and } v(m_a) = \sigma^2 / s_a. \quad (6)$$

$$\text{cov}(y_{ij}, \bar{y}_i) = \sigma^2 \quad \text{and, for } i \neq i', \quad \text{cov}(\bar{y}_i, \bar{y}_{i'}) = 0; \quad (7)$$

and, for $i = 1, \dots, a$

$$\text{cov}(\bar{y}_i, m_a) = n_i \sigma^2 / (n_i s_a) = \sigma^2 / s_a. \quad (8)$$

Four distributional results are taken as known: (i) that normal variables having zero covariance are independent; (ii) that linear combinations of normal variables are normally distributed; (iii) that a χ_k^2 variable (having k degrees of freedom) is definable as the sum of squares of k i.i.d. normal standard variables; and (iv) that sums of independent χ^2 variables are χ^2 variables. These results are referred to frequently in what follows.

We deal with between-class and within-class sums of squares defined for a classes as

$$B_a = \sum_{i=1}^a n_i (\bar{y}_i - m_a)^2 = \sum_{i=1}^a n_i \bar{y}_i^2 - s_a m_a^2 \quad (9)$$

and

$$W_a = \sum_{i=1}^a \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2 \quad (10)$$

with

$$W_a = \sum_{i=1}^a W_i \quad \text{for} \quad W_i = \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2. \quad (11)$$

2. Independence

The independence of B_a and W_a stems directly from (i). Consider one of the terms in B_a of (9) that is squared, say $\bar{y}_i - m_a$; and a similar term from W_a of (10), say $y_{hj} - \bar{y}_h$. The covariance of these terms for $i = h$ is, from (7) and (8)

$$\begin{aligned} & \text{cov}(\bar{y}_i - m_a, y_{ij} - \bar{y}_i) \\ &= \text{cov}(\bar{y}_i, y_{ij}) - v(\bar{y}_i) - \text{cov}(m_a, y_{ij}) + \text{cov}(m_a, \bar{y}_i) \\ &= \sigma^2(1/n_i - 1/n_i - 1/s_a + 1/s_a) \\ &= 0; \end{aligned}$$

and, similarly for $i \neq h$,

$$\text{cov}(\bar{y}_i - m_a, y_{hj} - \bar{y}_h) = \sigma^2(0 - 0 - 1/s_a + 1/s_a) = 0.$$

Thus $\bar{y}_i - m_a$ and $y_{hj} - \bar{y}_h$ have zero covariance and so, since by (ii) each of them is normally distributed, they are by (i) independent. Since this is so for all i, h and j it is true for every pair of terms that are squared, one in B_a and one in W_a . Therefore B_a and W_a are independent.

3. Induction

By induction on a we show that $B_a/\sigma^2 \sim \chi_{a-1}^2$. The starting point is the case of $a = 2$. From (9)

$$\begin{aligned} B_2 &= n_1 \bar{y}_1^2 + n_2 \bar{y}_2^2 - (n_1 \bar{y}_1 + n_2 \bar{y}_2)^2 / (n_1 + n_2) \\ &= n_1 n_2 (\bar{y}_1 - \bar{y}_2)^2 / (n_1 + n_2). \end{aligned}$$

From (6) and (7)

$$v(\bar{y}_1 - \bar{y}_2) = \sigma^2(1/n_1 + 1/n_2) = (n_1 + n_2)\sigma^2/n_1n_2, \quad (12)$$

and so, under the hypothesis $H : \mu_1 = \mu_2$, (12) and (ii) yield

$$\bar{y}_1 - \bar{y}_2 \sim N[0, (n_1 + n_2)\sigma^2/n_1n_2].$$

Therefore on defining $g = \sqrt{n_1n_2/(n_1 + n_2)}(\bar{y}_1 - \bar{y}_2)$, we have $g \sim N(0, 1)$, and so, since $B_2/\sigma^2 = g^2$, (iii) gives $B_2/\sigma^2 \sim \chi_1^2 = \chi_{2-1}^2$. Thus $B_a/\sigma^2 \sim \chi_{a-1}^2$ is certainly true for $a = 2$. With this as a base we now show that assuming $B_a/\sigma^2 \sim \chi_{a-1}^2$ yields $B_{a+1}/\sigma^2 \sim \chi_a^2$; i.e., induction on a establishes that $B_a/\sigma^2 \sim \chi_a^2$ is true generally.

Relationships between m_a and m_{a+1} , and B_a and B_{a+1} , are needed that are extensions of well-known recurrence formulae for sample means and variances given in Searle (1983) and Stigler (1984). First, from (4) and (5)

$$\begin{aligned} m_{a+1} &= \sum_{i=1}^{a+1} n_i \bar{y}_i / s_{a+1} \\ &= (s_a m_a + n_{a+1} \bar{y}_{a+1}) / (s_a + n_{a+1}) \\ &= m_a + n_{a+1} (\bar{y}_{a+1} - m_a) / s_{a+1}; \end{aligned} \quad (13)$$

and second, from (9)

$$B_{a+1} = \sum_{i=1}^{a+1} n_i \bar{y}_i^2 - s_{a+1} m_{a+1}^2$$

and on using (13) this is

$$\begin{aligned} B_{a+1} &= \sum_{i=1}^a n_i \bar{y}_i^2 + n_{a+1} \bar{y}_{a+1}^2 - s_{a+1} [m_a + n_{a+1} (\bar{y}_{a+1} - m_a) / s_{a+1}]^2 \\ &= \sum_{i=1}^a n_i \bar{y}_i^2 + n_{a+1} \bar{y}_{a+1}^2 - (s_a + n_{a+1}) m_a^2 \\ &\quad - 2m_a n_{a+1} (\bar{y}_{a+1} - m_a) - n_{a+1}^2 (\bar{y}_{a+1} - m_a)^2 / s_{a+1} \\ &= \sum_{i=1}^a n_i \bar{y}_i^2 - s_a m_a^2 + n_{a+1} (\bar{y}_{a+1} - m_a)^2 - n_{a+1}^2 (\bar{y}_{a+1} - m_a)^2 / s_{a+1} \\ &= B_a + n_{a+1} (1 - n_{a+1} / s_{a+1}) (\bar{y}_{a+1} - m_a)^2, \end{aligned}$$

i. e.,

$$B_{a+1} = B_a + \delta \text{ for } \delta = (n_{a+1} s_a / s_{a+1}) (\bar{y}_{a+1} - m_a)^2. \quad (14)$$

Now \bar{y}_{a+1} and m_a are independent, and so

$$v(\bar{y}_{a+1} - m_a) = \sigma^2(1/n_{a+1} + 1/s_a) = s_{a+1} \sigma^2 / n_{a+1} s_a.$$

Hence, under the hypothesis

$$H : \mu_1 = \mu_2 = \dots = \mu_{a+1} \quad (15)$$

$$\bar{y}_{a+1} - m_a \sim N\left(0, \frac{s_{a+1}}{n_{a+1}s_a} \sigma^2\right).$$

Thus, just as in deriving $B_2/\sigma^2 \sim \chi_1^2$, we have $\delta/\sigma^2 \sim \chi_1^2$. Furthermore, $B_a = \sum_{i=1}^a n_i (\bar{y}_i - m_a)^2$ and for $i = 1, \dots, a$, $\text{cov}(\bar{y}_i - m_a, \bar{y}_{a+1} - m_a) = \sigma^2(0 - 1/s_a - 0 + 1/s_a) = 0$. Therefore, since $\bar{y}_i - m_a$ and $\bar{y}_{a+1} - m_a$ are by (ii) normally distributed, they are by (i) independent. Therefore in (14) B_a and δ are independent; and so with $B_a/\sigma^2 \sim \chi_{a-1}^2$ and $\delta/\sigma^2 \sim \chi_1^2$, this independence means from (iv) that $B_{a+1}/\sigma^2 = B_a/\sigma^2 + \delta/\sigma^2 \sim \chi_{a-1+1}^2 = \chi_a^2$. Thus is the χ^2 property of B_a proven, without recourse to any "substantial mathematical machinery".

4. The within-class sum of squares

The χ^2 property of W_a can now be derived from that of B_a . Suppose that $n_i = 1$ for $i = 1, \dots, a$. Then B_a becomes $\sum_{i=1}^a (y_i - \bar{y})^2$ for $\bar{y} = \sum_{i=1}^a y_i/a$, and so by the immediately preceding result, $\sum_{i=1}^a (y_i - \bar{y})^2/\sigma^2 \sim \chi_{a-1}^2$. A special case of this is W_i of (11): $W_i/\sigma^2 = \sum_{j=1}^{n_i} (y_{ij} - \bar{y}_i)^2/\sigma^2 \sim \chi_{n_i-1}^2$. Hence, since the W_i 's are distributed independently, $W/\sigma^2 = \sum_{i=1}^a W_i/\sigma^2$ has, by (iv), a χ^2 distribution on $\sum_{i=1}^a (n_i - 1) = n. - a$ degrees of freedom, i.e., $W/\sigma^2 \sim \chi_{n.-a}^2$.

5. Application

The ultimate application of these results is, of course, that under the hypothesis (15), which gives $B_a/\sigma^2 \sim \chi_{a-1}^2$ independently of $W_a/\sigma^2 \sim \chi_{n.-a}^2$, the ratio

$$F = \frac{(B_a/\sigma^2)/(a-1)}{(W_a/\sigma^2)/(n.-a)} = \frac{B_a/(a-1)}{W_a/(n.-a)}$$

has the F -distribution on $(a-1)$ and $(n.-a)$ degrees of freedom, and can be used as a test-statistic for the hypothesis (15).

6. Extending Helmert's transformation

In the simple case of x_i for $i = 1, \dots, n$ with $x_i \sim \text{i.i.d. } N(0, \sigma^2)$, the χ_{n-1}^2 distribution of $S^2/\sigma^2 = \sum_{i=1}^n (x_i - \bar{x})^2/\sigma^2$ can be derived using what is known (e.g., Lancaster, 1972) as Helmert's transformation:

$$u_i = \sum_{j=1}^i \lambda_{ij} x_j \quad \text{for } i = 2, \dots, n \quad (16)$$

with

$$\lambda_{ij} = 1/\sqrt{i(i-1)} \quad \text{for } j = 1, 2, \dots, i-1,$$

and

$$\lambda_{ii} = -\sqrt{(i-1)/i}.$$

It is then easily shown that the u_i of (16) are $\text{i.i.d. } N(0, \sigma^2)$ and that $S^2 = \sum_{i=2}^n u_i^2$; then (iv) gives $S^2/\sigma^2 \sim \chi_{n-1}^2$.

An extension of (16) provides a second proof that $B_a/\sigma^2 \sim \chi_{a-1}^2$. It uses

$$z_i = \sum_{j=1}^i t_{ij} \bar{y}_j \quad \text{for } i = 2, \dots, a \quad (17)$$

with

$$t_{ij} = n_j \sqrt{n_i/s_{i-1}s_i} \quad \text{for } j = 1, \dots, i-1$$

and

$$t_{ii} = -\sqrt{n_i s_{i-1}/s_i}.$$

It can then be shown that $v(z_i) = \sigma^2$ and $\text{cov}(z_i, z_h) = 0$ for all $i \neq h = 2, \dots, a$; and that $\sum_{i=2}^a z_i^2 = B_a$. Hence the z_i are i.i.d. $N(0, \sigma^2)$ and so $B_a/\sigma^2 \sim \chi_{a-1}^2$.

In passing, observe that $n_i = 1$ for all i reduces t_{ij} and t_{ii} of (17) to λ_{ij} and λ_{ii} respectively, of (16) — as one would expect.

A final, matrix comment is not out of order: on defining $t_{ij} = 0$ for $j = i+1, \dots, a$ and $i = 2, \dots, a$, the resulting $(a-1) \times a$ matrix $\mathbf{T} = \{t_{ij}\}$ for $i = 2, \dots, a$ and $j = 1, \dots, a$ is related to a more general Helmert-style matrix of Irwin (1942), quoted as \mathbf{H} in (4) of Lancaster (1972). The relationship is

$$\mathbf{H} = \begin{bmatrix} \mathbf{n}'/\sqrt{s_a} \\ \mathbf{T} \end{bmatrix} \mathbf{D}$$

where \mathbf{n}' is the row vector $[n_1, \dots, n_a]$ and \mathbf{D} is the diagonal matrix of diagonal elements $1/\sqrt{n_1}, \dots, 1/\sqrt{n_a}$.

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