Mathematical Statistics 1

Chapter 2. Multivariate Distributions
2.5. The Correlation Coefficient—Proofs of Theorems

Theorem 2.5.1

Theorem 2.5.1. For all jointly distributed random variables \((X, Y)\) whose correlation coefficient \(\rho\) exists (so that \(\sigma_1 > 0\) and \(\sigma_2 > 0\) by the definition of \(\rho\)), we have \(-1 \leq \rho \leq 1\).

Proof. With \(E[X] = \mu_1\) and \(E[Y] = \mu_2\), consider the polynomial in \(\nu\) given by

\[ h(\nu) = E[((X - \mu_1) + \nu(Y - \mu_2))^2]. \]

Then \(h(\nu) \geq 0\) for all \(\nu\). Hence the discriminant of \(h(\nu)\) is less than or equal to 0 (for if the discriminant is positive then \(h\) has two roots and \(h\) is negative between those two roots).

Theorem 2.5.1 (continued)

Proof (continued). Since \(E\) is linear (by Theorem 1.8.2) we have

\[
\begin{align*}
  h(\nu) &= E[((X - \mu_1) + \nu(Y - \mu_2))^2] \\
         &= E[(X - \mu_1)^2 + 2\nu(X - \mu_1)(Y - \mu_2) + \nu^2(Y - \mu_2)^2] \\
         &= E[(X - \mu_1)^2] + 2\nu E[(X - \mu_1)(Y - \mu_2)] + \nu^2 E[(Y - \mu_2)^2] \\
         &= \sigma_1^2 + 2\nu \text{cov}(X, Y) + \nu^2 \sigma_2^2 \text{ by Definition 2.5.1} \\
         &= \sigma_1^2 + 2\nu \rho \sigma_1 \sigma_2 + \nu^2 \sigma_2^2 \text{ by Definition 2.5.2.}
\end{align*}
\]

So the discriminant is nonpositive then \(4(\rho^2 - 1)\sigma_1^2 \sigma_2^2 \leq 0\) or \(\rho^2 - 1 \leq 0\) or \(|\rho| \leq 1\), as claimed.

Theorem 2.5.2

Theorem 2.5.2. If \(X\) and \(Y\) are independent random variables then \(\text{cov}(X, Y) = 0\) and hence \(\rho = 0\).

Proof. If \(X\) and \(Y\) are independent then by Theorem 2.4.2 we have \(E[XY] = E[X]E[Y]\). So by Note 2.5.A,

\[ \text{cov}(X, Y) = E[XY] - \mu_1 \mu_2 = \mu_1 \mu_2 - \mu_1 \mu_2 = 0, \]

as claimed.
Theorem 2.5.3

Theorem 2.5.3. Suppose \((X, Y)\) have a joint distribution with the variances of \(X\) and \(Y\) finite and positive. Denote the means and variances of \(X\) and \(Y\) by \(\mu_1, \mu_2\) and \(\sigma_1^2, \sigma_2^2\), respectively, and let \(\rho\) be the correlation coefficient between \(X\) and \(Y\). If \(E[Y \mid X]\) is linear in \(X\) then

\[
E[Y \mid X] = \mu_2 + \rho \frac{\sigma_2}{\sigma_1} (X - \mu_1) \quad \text{and} \quad E[\text{Var}(Y \mid X)] = \sigma_2^2 (1 - \rho^2).
\]

Proof. We give a proof for the continuous case and leave the discrete case as an exercise. Suppose \(E[Y \mid X]\) is linear in \(X\), say \(E[Y \mid x] = a + bx\). By the definition of conditional probability function (see Section 2.3) we have

\[
f_{Y \mid X}(y \mid x) = \frac{f_{X,Y}(y \mid x)}{f_X(x)} = \frac{f(x, y)}{f_1(x)}
\]

and so by the definition of expected value (Definition 1.8.1) we have \(\ldots\)

Theorem 2.5.3 (continued 1)

Proof (continued). \(\ldots\) we have the conditional expectation

\[
a + bx = E[Y \mid x] = \int_{-\infty}^{\infty} y f_{Y \mid X}(y \mid x) \, dy = \int_{-\infty}^{\infty} y f(x, y) \frac{f_1(x)}{f_1(x)} \, dy
\]

\[
= \frac{1}{f_1(x)} \int_{-\infty}^{\infty} y f(x, y) \, dy.
\]

Hence

\[
\int_{-\infty}^{\infty} y f(x, y) \, dy = (a + bx) f_1(x) \tag{2.56}
\]

By the definition of \(E[Y]\) (see Section 2.1),

\[
E[Y] = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y f(x, y) \, dx \, dy \quad \text{so from (2.56) we have}
\]

\[
E[Y] = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} y f(x, y) \, dy = \int_{-\infty}^{\infty} (a + bx) f_1(x) \, dx
\]

\[
= a \int_{-\infty}^{\infty} f_1(x) \, dx + b \int_{-\infty}^{\infty} x f_1(x) \, dx = a + bE[X] \ldots
\]

Theorem 2.5.3 (continued 2)

Proof (continued). \(\ldots\) or \(\mu_2 = a + b \mu_1\) where \(\mu_1 = E[X]\) and \(\mu_2 = E[Y]\). Also from (2.56) (multiplying both sides by \(x\) and then integrating with respect to \(x\)):

\[
\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} xy f(x, y) \, dy \, dx = \int_{-\infty}^{\infty} (ax + bx^2) f_1(x) \, dx
\]

\[
= a \int_{-\infty}^{\infty} x f_1(x) \, dx + b \int_{-\infty}^{\infty} x^2 f_1(x) \, dx
\]

or \(E[XY] = aE[X] + bE[X^2]\). Now \(E[XY] = \mu_1 \mu_2 + \rho \sigma_1 \sigma_2\) by Note 2.5.B and \(E[X^2] = \sigma_1^2 + \mu_1^2\) by Note 1.9.A so that now we have \(\mu_1 \mu_2 + \rho \sigma_1 \sigma_2 = a \mu_1 + b (\sigma_1^2 + \mu_1^2)\). We can now solve for \(a\) and \(b\) using the two linear equations \(a + \mu_1 b = \mu_2\) and \(\mu_1 a + (\sigma_1^2 + \mu_1^2) b = \mu_1 \mu_2 + \rho \sigma_1 \sigma_2\) to get \(a = \mu_2 - \rho \mu_1 \sigma_2 / \sigma_1\) and \(b = \rho \sigma_2 / \sigma_1\). Therefore,

\[
E[Y \mid x] = a + bx = \mu_2 = \rho \mu_1 \sigma_2 / \sigma_1 + \rho \sigma_2 x / \sigma_1 = \mu_2 + \rho \frac{\sigma_2}{\sigma_1} (x - \mu_1),
\]

or \(E[Y \mid X] = \mu_2 + \rho \frac{\sigma_2}{\sigma_1} (X - \mu_1)\), as claimed.

Theorem 2.5.3 (continued 3)

Proof (continued). Next, we consider \(\text{var}(Y \mid x)\). To do so, we need the conditional mean of \(Y\) given \(x\) which we see from above is \(E[Y \mid x] = \mu_2 + \rho \frac{\sigma_2}{\sigma_1} (x - \mu_1)\). We have

\[
\text{var}(Y \mid x) = \int_{-\infty}^{\infty} \left( y - \left( \mu_2 + \rho \frac{\sigma_2}{\sigma_1} (x - \mu_1) \right) \right)^2 f_{Y \mid X}(y \mid x) \, dy
\]

\[
= \frac{1}{f_1(x)} \int_{-\infty}^{\infty} \left( y - \mu_2 - \rho \frac{\sigma_2}{\sigma_1} (x - \mu_1) \right)^2 f(x, y) \, dy.
\]

So

\[
E[\text{var}(Y \mid X)] = \int_{-\infty}^{\infty} \text{var}(Y \mid x) f_1(x) \, dx
\]

\[
= \int_{-\infty}^{\infty} \left( \frac{1}{f_1(x)} \int_{-\infty}^{\infty} \left( y - \mu_2 - \rho \frac{\sigma_2}{\sigma_1} (x - \mu_1) \right)^2 f(x, y) \, dy \right) f_1(x) \, dx
\]
Proof (continued). . .

\[
= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left( y - \mu_2 - \rho \frac{\sigma_2}{\sigma_1} (x - \mu_1) \right)^2 f(x, y) \, dy \, dx
\]

\[
= \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \left( y = \mu_2 \right)^2 - 2\rho \frac{\sigma_2}{\sigma_1} (x - \mu_1)(y - \mu_2) + \rho^2 \frac{\sigma_2^2}{\sigma_1^2} (x - \mu_1)^2 \, dy \, dx
\]

\[
= E[(Y - \mu_2)^2] - 2\rho \frac{\sigma_2}{\sigma_1} E[(X - \mu_1)(Y - \mu_2)] + \rho^2 \frac{\sigma_2^2}{\sigma_1^2} E[(X - \mu_1)^2]
\]

\[
= \sigma_2^2 - 2\rho \frac{\sigma_2}{\sigma_1} \text{cov}(X, Y) + \rho^2 \frac{\sigma_2^2}{\sigma_1^2} \sigma_1^2
\]

\[
= \sigma_2^2 - 2\rho \frac{\sigma_2}{\sigma_1} \left( \rho \sigma_1 \sigma_2 \right) + \rho^2 \sigma_2^2 \text{ since, by Definition 2.5.2, } \rho = \frac{\text{cov}(X, Y)}{\sigma_1 \sigma_2}
\]

\[
= \sigma_2^2 - 2\rho^2 \sigma_2^2 + \rho^2 \sigma_2^2 = \sigma_2^2 (1 - 2\rho^2 + \rho^2) = \sigma_2^2 (1 - \rho^2),
\]
as claimed.