556: MATHEMATICAL STATISTICS I

MULTIVARIATE 1-1 TRANSFORMATIONS

We consider the case of 1-1 transformations g, as in this case the probability transform result coincides with changing variables in a k-dimensional integral. We can consider $\underset{\sim}{g} = (g_1, \ldots, g_k)$ as a vector of functions forming the components of the new random vector $\underset{\sim}{Y}$.

Given a collection of variables $(X_1, \ldots X_k)$ with range $\mathbb{X}^{(k)}$ and joint pdf $f_{X_1,\ldots,X_k}$ we can construct the pdf of a transformed set of variables $(Y_1, \ldots Y_k)$ using the following steps:

1 Write down the set of transformation functions $g_1, \ldots, g_k$
$$Y_1 = g_1(X_1, \ldots, X_k)$$
$$\vdots$$
$$Y_k = g_k(X_1, \ldots, X_k)$$

2 Write down the set of inverse transformation functions $g_1^{-1}, \ldots, g_k^{-1}$
$$X_1 = g_1^{-1}(Y_1, \ldots, Y_k)$$
$$\vdots$$
$$X_k = g_k^{-1}(Y_1, \ldots, Y_k)$$

3 Consider the joint range of the new variables, $\mathbb{Y}^{(k)}$.

4 Compute the Jacobian of the transformation: first form the matrix of partial derivatives
$$D_y = \begin{bmatrix} \dfrac{\partial x_1}{\partial y_1} & \dfrac{\partial x_1}{\partial y_2} & \cdots & \dfrac{\partial x_1}{\partial y_k} \\ \dfrac{\partial x_2}{\partial y_1} & \dfrac{\partial x_2}{\partial y_2} & \cdots & \dfrac{\partial x_2}{\partial y_k} \\ \vdots & \vdots & \ddots & \vdots \\ \dfrac{\partial x_k}{\partial y_1} & \dfrac{\partial x_k}{\partial y_2} & \cdots & \dfrac{\partial x_k}{\partial y_k} \end{bmatrix}$$

where, for each (i, j)
$$\frac{\partial x_i}{\partial y_j} = \frac{\partial}{\partial y_j}\{g_i^{-1}(y_1, \ldots, y_k)\}$$
and then set $|J(y_1, \ldots, y_k)| = |\det D_y|$

Note that
$$\det D_y = \det D_y^{\mathsf{T}}$$
so that an alternative but equivalent Jacobian calculation can be carried out by forming D_y^{T}. Note also that
$$|J(y_1, \ldots, y_k)| = \frac{1}{|J(x_1, \ldots, x_k)|}$$
where $J(x_1, \ldots, x_k)$ is the Jacobian of the transformation regarded in the reverse direction (that is, if we start with $(Y_1, \ldots, Y_k)$ and transfrom to $(X_1, \ldots, X_k)$)

5 Write down the joint pdf of $(Y_1, \ldots Y_k)$ as
$$f_{Y_1,\ldots,Y_k}(y_1, \ldots, y_k) = f_{X_1,\ldots,X_k}(g_1^{-1}(y_1, \ldots, y_k), \ldots, g_k^{-1}(y_1, \ldots, y_k)) \times |J(y_1, \ldots, y_k)|$$
for $(y_1, \ldots, y_k) \in \mathbb{Y}^{(k)}$

EXAMPLE Suppose that X_1 and X_2 have joint pdf

$$f_{X_1, X_2}(x_1, x_2) = 2 \qquad 0 < x_1 < x_2 < 1$$

and zero otherwise. Compute the joint pdf of random variables

$$Y_1 = \frac{X_1}{X_2} \qquad Y_2 = X_2$$

SOLUTION

1 Given that $\mathbb{X}^{(2)} \equiv \{(x_1, x_2) : 0 < x_1 < x_2 < 1\}$ and

$$g_1(t_1, t_2) = \frac{t_1}{t_2} \qquad g_2(t_1, t_2) = t_2$$

2 Inverse transformations:

$$\left. \begin{array}{l} Y_1 = X_1/X_2 \\ Y_2 = X_2 \end{array} \right\} \Longleftrightarrow \left\{ \begin{array}{l} X_1 = Y_1 Y_2 \\ X_2 = Y_2 \end{array} \right.$$

and thus

$$g_1^{-1}(t_1, t_2) = t_1 t_2 \qquad g_2^{-1}(t_1, t_2) = t_2$$

3 Range: to find $\mathbb{Y}^{(2)}$ consider point by point transformation from $\mathbb{X}^{(2)}$ to $\mathbb{Y}^{(2)}$ For a pair of points $(x_1, x_2) \in \mathbb{X}^{(2)}$ and $(y_1, y_2) \in \mathbb{Y}^{(2)}$ linked via the transformation, we have

$$0 < x_1 < x_2 < 1 \Longleftrightarrow 0 < y_1 y_2 < y_2 < 1$$

and hence we can extract the inequalities

$$0 < y_2 < 1 \text{ and } 0 < y_1 < 1 \qquad \mathbb{Y}^{(2)} \equiv (0, 1) \times (0, 1)$$

4 The Jacobian for points $(y_1, y_2) \in \mathbb{Y}^{(2)}$ is

$$D_y = \begin{bmatrix} \dfrac{\partial x_1}{\partial y_1} & \dfrac{\partial x_1}{\partial y_2} \\ \dfrac{\partial x_2}{\partial y_1} & \dfrac{\partial x_2}{\partial y_2} \end{bmatrix} = \begin{bmatrix} y_2 & y_1 \\ 0 & 1 \end{bmatrix} \Rightarrow |J(y_1, y_2)| = |\det D_y| = |y_2| = y_2$$

Note that for points $(x_1, x_2) \in \mathbb{X}^{(2)}$ is

$$D_x = \begin{bmatrix} \dfrac{\partial y_1}{\partial x_1} & \dfrac{\partial y_1}{\partial x_2} \\ \dfrac{\partial y_2}{\partial x_1} & \dfrac{\partial y_2}{\partial x_2} \end{bmatrix} = \begin{bmatrix} \dfrac{1}{x_2} & \dfrac{x_1}{x_2^2} \\ 0 & 1 \end{bmatrix} \Rightarrow |J(x_1, x_2)| = |\det D_x| = \left| \dfrac{1}{x_2} \right| = \dfrac{1}{x_2}$$

so that

$$|J(y_1, y_2)| = \frac{1}{|J(x_1, x_2)|}$$

5 Finally, we have

$$f_{Y_1, Y_2}(y_1, y_2) = f_{X_1, X_2}(y_1 y_2, y_2) \times y_2 = 2y_2 \qquad 0 < y_1 < 1, 0 < y_2 < 1$$

and zero otherwise

EXAMPLE Suppose that X_1 and X_2 are **independent** and **identically distributed** random variables defined on $\mathbb{R}^+$ each with pdf of the form

$$f_X(x) = \sqrt{\frac{1}{2\pi x}} \exp\left\{-\frac{x}{2}\right\} \qquad x > 0$$

and zero otherwise. Compute the joint pdf of random variables $Y_1 = X_1$ and $Y_2 = X_1 + X_2$

SOLUTION

1 Given that $\mathbb{X}^{(2)} \equiv \{(x_1, x_2) : 0 < x_1, 0 < x_2\}$ and

$$g_1(t_1, t_2) = t_1 \qquad\qquad g_2(t_1, t_2) = t_1 + t_2$$

2 Inverse transformations:

$$\left.\begin{array}{l} Y_1 = X_1 \\ Y_2 = X_1 + X_2 \end{array}\right\} \iff \left\{\begin{array}{l} X_1 = Y_1 \\ X_2 = Y_2 - Y_1 \end{array}\right.$$

and thus

$$g_1^{-1}(t_1, t_2) = t_1 \qquad\qquad g_2^{-1}(t_1, t_2) = t_2 - t_1$$

3 Range: to find $\mathbb{Y}^{(2)}$ consider point by point transformation from $\mathbb{X}^{(2)}$ to $\mathbb{Y}^{(2)}$ For a pair of points $(x_1, x_2) \in \mathbb{X}^{(2)}$ and $(y_1, y_2) \in \mathbb{Y}^{(2)}$ linked via the transformation; as both original variables are strictly positive, we can extract the inequalities

$$0 < y_1 < y_2 < \infty$$

4 The Jacobian for points $(y_1, y_2) \in \mathbb{Y}^{(2)}$ is

$$D_y = \left[\begin{array}{cc} \dfrac{\partial x_1}{\partial y_1} & \dfrac{\partial x_1}{\partial y_2} \\[2ex] \dfrac{\partial x_2}{\partial y_1} & \dfrac{\partial x_2}{\partial y_2} \end{array}\right] = \left[\begin{array}{cc} 1 & 0 \\ -1 & 1 \end{array}\right] \Rightarrow |J(y_1, y_2)| = |\det D_y| = |1| = 1$$

Note, here, $J(x_1, x_2) = |\det D_x| = 1$ also so that again

$$|J(y_1, y_2)| = \frac{1}{|J(x_1, x_2)|}$$

5 Finally, we have for $0 < y_1 < y_2 < \infty$

$$\begin{aligned} f_{Y_1, Y_2}(y_1, y_2) &= f_{X_1, X_2}(y_1, y_2 - y_1) \times 1 = f_{X_1}(y_1) \times f_{X_2}(y_2 - y_1) \qquad \text{by independence} \\[2ex] &= \sqrt{\frac{1}{2\pi y_1}} \exp\left\{-\frac{y_1}{2}\right\} \sqrt{\frac{1}{2\pi(y_2 - y_1)}} \exp\left\{-\frac{(y_2 - y_1)}{2}\right\} \\[2ex] &= \frac{1}{2\pi} \frac{1}{\sqrt{y_1(y_2 - y_1)}} \exp\left\{-\frac{y_2}{2}\right\} \end{aligned}$$

and zero otherwise

Here, for $y_2 > 0$

$$
\begin{aligned}
f_{Y_2}(y_2) &= \int f_{Y_1,Y_2}(y_1, y_2)\, dy_1 = \int_0^{y_2} \frac{1}{2\pi} \frac{1}{\sqrt{y_1 (y_2 - y_1)}} \exp\left\{-\frac{y_2}{2}\right\} dy_1 \\
&= \frac{1}{2\pi} \exp\left\{-\frac{y_2}{2}\right\} \int_0^{y_2} \frac{1}{\sqrt{y_1 (y_2 - y_1)}}\, dy_1 \\
&= \frac{1}{2\pi} \exp\left\{-\frac{y_2}{2}\right\} \int_0^1 \frac{1}{\sqrt{ty_2 (y_2 - ty_2)}} y_2\, dt \qquad \text{setting } y_1 = ty_2 \\
&= \frac{1}{2\pi} \exp\left\{-\frac{y_2}{2}\right\} \int_0^1 \frac{1}{\sqrt{t(1-t)}}\, dt \\
&= \frac{1}{2} \exp\left\{-\frac{y_2}{2}\right\}
\end{aligned}
$$

as

$$
\int_0^1 \frac{1}{\sqrt{t(1-t)}}\, dt = \pi
$$