HW6

2024-10-26

Homework 6

Outline:

Q1: DONE Q2: DONE Q3: DONE
Q4: DONE Q5: Started Q6: WIP Q7: Started

Q1: 4.17, Casella & Berger

Let X be an exponential(1) random variable, and define Y to be the integer part of X+1, that is:

$$Y = i + 1 \text{ iff } i \leq X < i + 1, i = 0, 1, 2, ...$$

(a)

Find the distribution of Y. What well-known distribution does Y have?

$$P(Y = i + 1) = \int_{i}^{i+1} e^{-x} dx = -e^{-x}\Big|_{x=i}^{i+1} = -e^{-(i+1)} + e^{-i} = e^{-i}(1 - e^{-1})$$

This is a geometric distribution with $p = 1 - e^{-1}$, such that
$Y \sim Geom(1 - e^{-1})$

(b)

Find the conditional distribution of X - 4 given $Y \geq 5$

As defined, $Y = i + 1$, such that

$$Y \geq 5 \iff i + 1 \geq 5 \iff X \geq 4$$

Utilizing the distributions as defined and found, we then have

$$P(X - 4 \leq x \mid Y \geq 5) = P(X - 4 \leq x \mid X \geq 4) = P(X \leq x + 4 \mid X \geq 4)$$

$$P(X - 4 \leq x \mid Y \geq 5) = P(X \leq x + 4 \mid X \geq 4) = 1 - P(X > x + 4 \mid X \geq 4) = 1 - P(X > x) = 1 - e^{-x}$$

This sure looks like the memoryless property we observed previously!

$$P(X - 4 \leq x \mid Y \geq 5) = P(X \leq x) = 1 - e^{-x}$$

Q2: 4.32(a), Casella & Berger

(a)

For a hierarchical model:

$$Y|\Lambda \sim Poisson(\Lambda) \text{ and } \Lambda \sim Gamma(\alpha, \beta)$$

find the marginal distribution, mean, and variance of Y. Show that the marginal distribution of Y is a negative binomial if α is an integer.

For y = 0, 1, . . . , we may write the conditional distribution of Y = y as:

$$P(Y = y|\lambda) = \sum_{n=y}^{\infty} P(Y = y|N = n, \lambda)P(N = n|\lambda) = \sum_{n=y}^{\infty} \binom{n}{y} p^y (1-p)^{n-y} \frac{e^{-\lambda}\lambda^n}{n!}$$

$$P(Y = y|\lambda) = \sum_{n=y}^{\infty} \frac{1}{y!(n-y)!} (\frac{p}{1-p})^y [(1-p)\lambda]^n e^{-\lambda}$$

Define $m = n - y$, such that we may rewrite the above as:

$$P(Y = y|\lambda) = \sum_{n=y}^{\infty} \frac{e^{-\lambda}}{y!m!} (\frac{p}{1-p})^y [(1-p)\lambda)^m] = \sum_{n=y}^{\infty} \frac{e^{-\lambda}}{y!} (\frac{p}{1-p})^y \frac{[(1-p)\lambda)^m]}{m!}$$

After gathering the terms, we see quite a lot of this does not depend on m, such that we may take it out of the summation and write:

$$P(Y = y|\lambda) = \frac{e^{-\lambda}}{y!} (\frac{p}{1-p})^y \sum_{n=y}^{\infty} \frac{[(1-p)\lambda)^m]}{m!}$$

After simplifying, we then take advantage that

$$\sum_{n=y}^{\infty} \frac{[(1-p)\lambda)^m]}{m!} = e^{(1-p)\lambda}$$

And may write:

$$P(Y = y|\lambda) = e^{-\lambda}(p\lambda)^y e^{(1-p)\lambda} = \frac{(p\lambda)^y e^{-p\lambda}}{y!}$$

Note the above is a type of Poisson, specifically:

$$Y|\Lambda \sim Poisson(p\lambda)$$

From this we may "extract" the pmf of Y (pmf as both the conditional of Y and Λ are both Poisson distributed), specifically for $y = 0, 1, ...,$

$$f_Y(y) = \frac{1}{\Gamma(\alpha)y!(p\beta)^\alpha} \Gamma(y+\alpha)(\frac{p\beta}{1+p\beta})^{y+\alpha}$$

For a positive integer α, the above provides a pmf for a negative binomial distribution, specifically:

$$Y \sim NB(\alpha, \frac{1}{1+p\beta}$$

Q3

Expectation

(a)

Show that any random variable X (with finite mean) has zero covariance with any real constant c, i.e. $Cov(X, c) = 0$

The covariance of X and c may be written:

$$Cov(X, c) = E[(X - E[X])(c - E[c])] = E[(X - E[X])(c - c)] = E[(X - E[X])0] = E[0] = 0$$

Such that we conclude:

$$Cov(X, c) = 0$$

And we must have the condition that X has a finite mean as $\infty * 0$ is undefined.

(b)

Using the definition of conditional expectation, show that

$$E[g(X)h(Y)|X = x] = g(x)E[h(Y)|X = x]$$

for an x with pdf $f_X(x) > 0$ (You may also assume (X, Y) are jointly discrete).

To show that

$$E[g(X)h(Y) \mid X = x] = g(x)E[h(Y) \mid X = x]$$

For jointly discrete random variables X and Y, the conditional expectation of h(Y) | X = x is:

$$E[h(Y) \mid X = x] = \sum_y h(y)P(Y = y \mid X = x)$$

Similarly, the conditional expectation of g(X)h(Y) | X = x is:

$$E[g(X)h(Y) \mid X = x] = \sum_y g(x)h(y)P(Y = y \mid X = x)$$

We can simplify by recognizing there are terms in the above equations that do not depend on the index of the summation, specifically:

$$E[g(X)h(Y) \mid X = x] = \sum_y g(x)h(y)P(Y = y \mid X = x) = g(x)\sum_y h(y)P(Y = y \mid X = x)$$

However, this is a very familiar formula to us!

$$E[g(X)h(Y) \mid X = x] = g(x)\sum_y h(y)P(Y = y \mid X = x) = g(x)E[h(Y) \mid X = x]$$

Note:

The condition $f_X(x) > 0$ is necessary as it ensures that $P(Y = y \mid X = x)$ is defined, because:

$$P(Y = y \mid X = x) = \frac{P(X = x, Y = y)}{P(X = x)} \equiv \frac{P(X = x, Y = y)}{f_X(x)}$$

Q4

Suppose that X_i has mean μ_i and variance σ_i^2, for i = 1, 2, and that the covariance of X_1 and X_2 is σ_{12}. Compute the covariance between $X_1 - 2X_2 + 8$, and then compute the covariance of $3X_1 + X_2$.

(a)

$X_1 - 2X_2 + 8$

$$Var(X_1 - 2X_2 + 8) = Cov(X_1 - 2X_2 + 8, X_1 - 2X_2 + 8) = Cov(X_1 - 2X_2, X_1 - 2X_2)$$

$$Cov(X_1 - 2X_2 + 8, X_1 - 2X_2 + 8) = Cov(X_1, X_1) - 2Cov(X_1, X_2) - 2Cov(X_2, X_1) + 4Cov(X_2, X_2) = \sigma_1^2 - 4\sigma_{12} + 4\sigma_2^2$$

$$Cov(X_1 - 2X_2 + 8, X_1 - 2X_2 + 8) = \sigma_1^2 - 4\sigma_{12} + 4\sigma_2^2.$$

(b)

$3X_1 + X_2$

$$Cov(3X_1 + X_2, 3X_1 + X_2) = Cov(3X_1, 3X_1) + Cov(3X_1, X_2) + Cov(X_2, 3X_1) + Cov(X_2, X_2)$$

$$Cov(3X_1 + X_2, 3X_1 + X_2) = 9\sigma_1^2 + 3\sigma_{12} + 3\sigma_{12} + \sigma_2^2$$

Q5

The joint distribution of X, Y is given by the joint pdf:

$$f(x, y) = 3(x + y) \text{ for } 0 < x < 1, 0 < y < 1, 0 < x + y < 1$$

(a)

Find the marginal distribution of $f_X(x)$

To find the marginal distribution $f_X(x)$, we need to integrate the joint probability density function $f(x, y)$ with respect to y:

$$f_X(x) = \int_0^1 f(x, y)\, dy$$

Given the joint pdf:

$$f(x, y) = 3(x + y) \quad \text{for } 0 < x < 1,\ 0 < y < 1,\ 0 < x + y < 1,$$

the region where the pdf is nonzero is bounded by $0 < x < 1$, $0 < y < 1$, and $0 < x + y < 1$. We need to integrate within these bounds.

For a fixed x, y must satisfy $0 < y < 1 - x$ to ensure $0 < x + y < 1$.

The marginal distribution $f_X(x)$ is given by:

$$f_X(x) = \int_0^{1-x} 3(x + y)\, dy.$$

$$f_X(x) = 3\int_0^{1-x} (x + y)\, dy = 3\left[\int_0^{1-x} x\, dy + \int_0^{1-x} y\, dy\right].$$

Evaluating these integrals:

1. $$\int_0^{1-x} x\, dy = x(1 - x).$$

2. $$\int_0^{1-x} y\, dy = \frac{(1 - x)^2}{2}.$$

So, we have:

$$f_X(x) = 3\left[x(1 - x) + \frac{(1 - x)^2}{2}\right] = 3\left[(1 - x)\left(x + \frac{1 - x}{2}\right)\right].$$

Simplifying further:

$$f_X(x) = 3(1 - x)\left(\frac{2x + 1 - x}{2}\right) = 3(1 - x)\left(\frac{x + 1}{2}\right) = \frac{3}{2}(1 - x)(x + 1).$$

Thus, the marginal distribution is:

$$f_X(x) = \frac{3}{2}(1 - x)(x + 1), \quad \text{for } 0 < x < 1.$$

(b)

Find the conditional pdf of Y | X = x, given some 0<x<1.

To find the conditional probability density function of Y given $X = x$, we use the definition:

$$f_{Y|X}(y|x) = \frac{f(x, y)}{f_X(x)},$$

where $f(x, y)$ is the joint pdf and $f_X(x)$ is the marginal pdf of X.

The joint pdf is:

$$f(x, y) = 3(x + y), \quad \text{for } 0 < x < 1,\ 0 < y < 1,\ 0 < x + y < 1.$$

We found that:

$$f_X(x) = \frac{3}{2}(1 - x)(x + 1), \quad \text{for } 0 < x < 1.$$

The conditional pdf is given by:

$$f_{Y|X}(y|x) = \frac{f(x, y)}{f_X(x)} = \frac{3(x + y)}{\frac{3}{2}(1 - x)(x + 1)}.$$

Simplifying the expression:

$$f_{Y|X}(y|x) = \frac{2(x + y)}{(1 - x)(x + 1)}.$$

Given $0 < x < 1$, the support for y is $0 < y < 1 - x$ to satisfy $0 < x + y < 1$.

Thus, the conditional pdf of Y given $X = x$ is:

$$f_{Y|X}(y|x) = \frac{2(x + y)}{(1 - x)(x + 1)}, \quad \text{for } 0 < y < 1 - x.$$

(c)

Find $E[Y|X = x]$

To find the conditional expectation $E[Y \mid X = x]$, we use the conditional probability density function $f_{Y|X}(y|x)$:

$$E[Y \mid X = x] = \int_0^{1-x} y\, f_{Y|X}(y|x)\, dy.$$

From the previous result, the conditional pdf is:

$$f_{Y|X}(y|x) = \frac{2(x + y)}{(1 - x)(x + 1)}, \quad \text{for } 0 < y < 1 - x.$$

The conditional expectation becomes:

$$E[Y \mid X = x] = \int_0^{1-x} y \left(\frac{2(x+y)}{(1-x)(x+1)} \right) dy.$$

We have:

$$E[Y \mid X = x] = \frac{2}{(1-x)(x+1)} \int_0^{1-x} y(x+y)\, dy.$$

Expanding $y(x+y)$, we get:

$$y(x+y) = xy + y^2.$$

So the integral becomes:

$$E[Y \mid X = x] = \frac{2}{(1-x)(x+1)} \left(\int_0^{1-x} xy\, dy + \int_0^{1-x} y^2\, dy \right).$$

1. Evaluate $\int_0^{1-x} xy\, dy$:

$$\int_0^{1-x} xy\, dy = x \int_0^{1-x} y\, dy = x \left[\frac{(1-x)^2}{2} \right] = \frac{x(1-x)^2}{2}.$$

2. Evaluate $\int_0^{1-x} y^2\, dy$:

$$\int_0^{1-x} y^2\, dy = \left[\frac{(1-x)^3}{3} \right].$$

The conditional expectation is:

$$E[Y \mid X = x] = \frac{2}{(1-x)(x+1)} \left(\frac{x(1-x)^2}{2} + \frac{(1-x)^3}{3} \right).$$

Factor out $(1-x)^2$:

$$E[Y \mid X = x] = \frac{2(1-x)^2}{(1-x)(x+1)} \left(\frac{x}{2} + \frac{1-x}{3} \right).$$

Simplify further:

$$E[Y \mid X = x] = \frac{2(1-x)}{x+1} \left(\frac{3x+2-2x}{6} \right) = \frac{2(1-x)}{x+1} \left(\frac{x+2}{6} \right).$$

Thus, the conditional expectation is:

$$E[Y \mid X = x] = \frac{(1-x)(x+2)}{3(x+1)}.$$

(d)

Given the results in (a), (b), and (c), explain how you know $E[X|Y=y]$ without any further calculation

We can determine $E[X \mid Y=y]$ using the symmetry of the joint distribution $f(x,y)$.

The given joint pdf is:

$$f(x,y) = 3(x+y), \quad \text{for } 0 < x < 1,\, 0 < y < 1,\, 0 < x+y < 1.$$

This joint distribution is symmetric in x and y, meaning that if we interchange x and y, the form of the joint pdf remains unchanged. Specifically, since $f(x,y)$ depends only on the sum $x+y$, it treats x and y symmetrically within the valid region.

Because of this symmetry, the roles of X and Y are interchangeable. Thus, the conditional expectation $E[X \mid Y=y]$ should have the same form as $E[Y \mid X=x]$, with x replaced by y.

Given that:

$$E[Y \mid X=x] = \frac{(1-x)(x+2)}{3(x+1)},$$

by symmetry, we can immediately conclude that:

$$E[X \mid Y=y] = \frac{(1-y)(y+2)}{3(y+1)}.$$

This conclusion follows without any further calculation because the joint distribution's symmetry ensures that the conditional expectation expressions for X and Y will be identical, with the variables swapped.

(e)

Find $E[E[2XY-Y|X]]$

To find $E[E[2XY-Y \mid X]]$, we use the law of iterated expectations, which states that:

$$E[E[Z \mid X]] = E[Z],$$

where $Z = 2XY - Y$.

According to the law of iterated expectations, we can rewrite $E[E[2XY-Y \mid X]]$ as:

$$E[E[2XY-Y \mid X]] = E[2XY-Y].$$

Using the linearity of expectation, we get:

$$E[2XY-Y] = 2E[XY] - E[Y].$$

The marginal pdf of Y, $f_Y(y)$, is symmetric to the marginal pdf of X, so it can be derived analogously. We previously found that the marginal pdf of X is:

$$f_X(x) = \frac{3}{2}(1-x)(x+1), \quad \text{for } 0 < x < 1.$$

Thus, $E[Y]$ can be obtained by integrating y with respect to the marginal pdf of Y, but given the symmetry of the joint pdf, we can directly conclude that:

$$E[Y] = E[X].$$

Now, we calculate $E[X]$:

$$E[X] = \int_0^1 x \cdot f_X(x)\,dx = \int_0^1 x \cdot \frac{3}{2}(1-x)(x+1)\,dx.$$

Expanding $(1-x)(x+1)$, we get:

$$(1-x)(x+1) = 1 + x - x - x^2 = 1 - x^2.$$

Thus,

$$E[X] = \frac{3}{2}\int_0^1 x(1-x^2)\,dx = \frac{3}{2}\left(\int_0^1 x\,dx - \int_0^1 x^3\,dx\right).$$

Evaluating these integrals:

$$\int_0^1 x\,dx = \frac{1}{2}, \quad \int_0^1 x^3\,dx = \frac{1}{4}.$$

So,

$$E[X] = \frac{3}{2}\left(\frac{1}{2} - \frac{1}{4}\right) = \frac{3}{2} \cdot \frac{1}{4} = \frac{3}{8}.$$

Therefore, $E[Y] = \frac{3}{8}$.

To find $E[XY]$, we integrate $xy \cdot f(x,y)$ over the region $0 < x < 1$, $0 < y < 1$, and $0 < x + y < 1$:

$$E[XY] = \int_0^1 \int_0^{1-x} xy \cdot 3(x+y)\,dy\,dx.$$

Expanding this integral will give the value of $E[XY]$.

After evaluating $E[XY]$ and $E[Y]$, we can find $E[2XY - Y] = 2E[XY] - E[Y]$, which gives us the final result.

Let's proceed to find the final result for $E[E[2XY - Y \mid X]] = E[2XY - Y]$, which requires calculating $2E[XY] - E[Y]$.

In the previous steps, we found:

$$E[Y] = \frac{3}{8}.$$

We need to evaluate:

$$E[XY] = \int_0^1 \int_0^{1-x} xy \cdot 3(x+y)\,dy\,dx.$$

Expanding this expression:

$$E[XY] = 3\int_0^1 \int_0^{1-x} xy(x+y)\,dy\,dx.$$

Expanding $xy(x+y)$, we get:

$$xy(x+y) = x^2y + xy^2.$$

Thus, the integral becomes:

$$E[XY] = 3\int_0^1 \int_0^{1-x} (x^2y + xy^2)\,dy\,dx.$$

We will now evaluate these integrals separately.

1. **Evaluate $\int_0^1 \int_0^{1-x} x^2y\,dy\,dx$:**

$$\int_0^1 \int_0^{1-x} x^2y\,dy\,dx = \int_0^1 x^2\left(\frac{(1-x)^2}{2}\right)dx = \frac{1}{2}\int_0^1 x^2(1-x)^2\,dx.$$

Expanding $(1-x)^2 = 1-2x+x^2$, we get:

$$\frac{1}{2}\int_0^1 x^2(1-2x+x^2)\,dx = \frac{1}{2}\left(\int_0^1 x^2\,dx - 2\int_0^1 x^3\,dx + \int_0^1 x^4\,dx\right).$$

Evaluating these integrals:

$$\int_0^1 x^2\,dx = \frac{1}{3}, \quad \int_0^1 x^3\,dx = \frac{1}{4}, \quad \int_0^1 x^4\,dx = \frac{1}{5}.$$

Thus,

$$\frac{1}{2}\left(\frac{1}{3} - 2\cdot\frac{1}{4} + \frac{1}{5}\right) = \frac{1}{2}\left(\frac{1}{3} - \frac{1}{2} + \frac{1}{5}\right) = \frac{1}{2}\left(\frac{10}{30} - \frac{15}{30} + \frac{6}{30}\right) = \frac{1}{2}\cdot\frac{1}{30} = \frac{1}{60}.$$

2. **Evaluate $\int_0^1 \int_0^{1-x} xy^2\,dy\,dx$:**

$$\int_0^1 \int_0^{1-x} xy^2\,dy\,dx = \int_0^1 x\left(\frac{(1-x)^3}{3}\right)dx = \frac{1}{3}\int_0^1 x(1-x)^3\,dx.$$

Expanding $(1-x)^3 = 1-3x+3x^2-x^3$, we get:

$$\frac{1}{3}\int_0^1 (x-3x^2+3x^3-x^4)\,dx = \frac{1}{3}\left(\frac{1}{2} - 3\cdot\frac{1}{3} + 3\cdot\frac{1}{4} - \frac{1}{5}\right).$$

Evaluating these terms:

$$\frac{1}{3}\left(\frac{1}{2} - 1 + \frac{3}{4} - \frac{1}{5}\right) = \frac{1}{3}\left(\frac{30}{60} - \frac{60}{60} + \frac{45}{60} - \frac{12}{60}\right) = \frac{1}{3} \cdot \frac{3}{60} = \frac{1}{60}.$$

Adding the results, we obtain:

$$E[XY] = 3\left(\frac{1}{60} + \frac{1}{60}\right) = \frac{3}{30} = \frac{1}{10}.$$

Now, we have:

$$2E[XY] = 2 \cdot \frac{1}{10} = \frac{1}{5},$$

and

$$E[Y] = \frac{3}{8}.$$

Thus,

$$2E[XY] - E[Y] = \frac{1}{5} - \frac{3}{8}.$$

Converting to a common denominator (40):

$$2E[XY] - E[Y] = \frac{8}{40} - \frac{15}{40} = -\frac{7}{40}.$$

Therefore, the final result is:

$$E[E[2XY - Y \mid X]] = -\frac{7}{40}.$$

Q6

Suppose that $f(x, y) = e^{-y}$ for $0 < x < y < \infty$

(a)

Find the joint moment generating function for (X, Y).

The joint moment generating function $M_{X,Y}(t_1, t_2)$ may be defined:

$$M_{X,Y}(t_1, t_2) = E\left[e^{t_1 X + t_2 Y}\right] = \int_0^\infty \int_0^y e^{t_1 x + t_2 y} e^{-y} \, dx \, dy = \int_0^\infty \int_0^y e^{t_1 x} e^{(t_2 - 1)y} \, dx \, dy$$

First, integrate with respect to x. The inner integral is:

$$\int_0^y e^{t_1 x} \, dx = \frac{1}{t_1} \left(e^{t_1 y} - 1\right),$$

assuming $t_1 \neq 0$.

Substitute the result into the outer integral:

$$M_{X,Y}(t_1, t_2) = \frac{1}{t_1} \int_0^\infty \left(e^{(t_1 + t_2 - 1)y} - e^{(t_2 - 1)y}\right) dy.$$

Now, integrate term by term:

For $e^{(t_1+t_2-1)y}$:

$$\int_0^\infty e^{(t_1 + t_2 - 1)y} \, dy = \frac{1}{1 - t_1 - t_2} \quad \text{for } t_1 + t_2 < 1.$$

For $e^{(t_2-1)y}$:

$$\int_0^\infty e^{(t_2 - 1)y} \, dy = \frac{1}{1 - t_2} \quad \text{for } t_2 < 1.$$

Now, combine the two results:

$$M_{X,Y}(t_1, t_2) = \frac{1}{t_1} \left(\frac{1}{1 - t_1 - t_2} - \frac{1}{1 - t_2}\right).$$

Thus, the joint moment generating function for (X, Y) is:

$$M_{X,Y}(t_1, t_2) = \frac{1}{t_1} \left(\frac{1}{1 - t_1 - t_2} - \frac{1}{1 - t_2}\right),$$

valid for $t_1 + t_2 < 1$ and $t_2 < 1$.

(b)

Use the joint moment generating function to find the variance of X, the variance of Y, and the covariance of X and Y.

To find the variances of X, Y, and the covariance between X and Y using the joint moment generating function (MGF), we will compute the necessary partial derivatives of the MGF.

The joint MGF we found is:

$$M_{X,Y}(t_1,t_2) = \frac{1}{t_1}\left(\frac{1}{1-t_1-t_2} - \frac{1}{1-t_2}\right),$$

valid for $t_1 + t_2 < 1$ and $t_2 < 1$.

To find the means of X and Y, we use the following formulas for the partial derivatives of the MGF:

- $\mathbb{E}[X] = \frac{\partial}{\partial t_1} M_{X,Y}(t_1,t_2)\Big|_{t_1=0,t_2=0}$,
- $\mathbb{E}[Y] = \frac{\partial}{\partial t_2} M_{X,Y}(t_1,t_2)\Big|_{t_1=0,t_2=0}$.

First, we differentiate $M_{X,Y}(t_1,t_2)$ with respect to t_1:

$$\frac{\partial}{\partial t_1} M_{X,Y}(t_1,t_2) = \frac{-1}{t_1^2}\left(\frac{1}{1-t_1-t_2} - \frac{1}{1-t_2}\right) + \frac{1}{t_1}\cdot\frac{1}{(1-t_1-t_2)^2}.$$

Taking the limit as $t_1 \to 0$ and $t_2 \to 0$, we get:

$$\mathbb{E}[X] = \frac{\partial}{\partial t_1} M_{X,Y}(t_1,t_2)\Big|_{t_1=0,t_2=0} = \frac{1}{1^2} = 1.$$

Now, we differentiate $M_{X,Y}(t_1,t_2)$ with respect to t_2:

$$\frac{\partial}{\partial t_2} M_{X,Y}(t_1,t_2) = \frac{1}{t_1}\left(\frac{1}{(1-t_1-t_2)^2} - \frac{1}{(1-t_2)^2}\right).$$

Taking the limit as $t_1 \to 0$ and $t_2 \to 0$, we get:

$$\mathbb{E}[Y] = \frac{\partial}{\partial t_2} M_{X,Y}(t_1,t_2)\Big|_{t_1=0,t_2=0} = 1.$$

The variance of X is given by:

$$\mathrm{Var}(X) = \frac{\partial^2}{\partial t_1^2} M_{X,Y}(t_1,t_2)\Big|_{t_1=0,t_2=0}.$$

From the first derivative:

$$\frac{\partial}{\partial t_1} M_{X,Y}(t_1,t_2) = \frac{-1}{t_1^2}\left(\frac{1}{1-t_1-t_2} - \frac{1}{1-t_2}\right) + \frac{1}{t_1}\cdot\frac{1}{(1-t_1-t_2)^2}.$$

The second derivative is:

$$\frac{\partial^2}{\partial t_1^2} M_{X,Y}(t_1, t_2) = \frac{2}{t_1^3}\left(\frac{1}{1 - t_1 - t_2} - \frac{1}{1 - t_2}\right) - \frac{2}{t_1^2} \cdot \frac{1}{(1 - t_1 - t_2)^2} + \frac{2}{t_1} \cdot \frac{1}{(1 - t_1 - t_2)^3}.$$

Evaluating at $t_1 = 0$ and $t_2 = 0$, we get:

$$\text{Var}(X) = 1.$$

Similarly, the variance of Y is:

$$\text{Var}(Y) = \frac{\partial^2}{\partial t_2^2} M_{X,Y}(t_1, t_2)\Big|_{t_1=0, t_2=0}.$$

This is:

$$\frac{\partial^2}{\partial t_2^2} M_{X,Y}(t_1, t_2) = \frac{2}{t_1}\left(\frac{1}{(1 - t_1 - t_2)^3} - \frac{1}{(1 - t_2)^3}\right).$$

Evaluating at $t_1 = 0$ and $t_2 = 0$, we get:

$$\text{Var}(Y) = 1.$$

The covariance of X and Y is given by:

$$\text{Cov}(X, Y) = \frac{\partial^2}{\partial t_1 \partial t_2} M_{X,Y}(t_1, t_2)\Big|_{t_1=0, t_2=0}.$$

From the derivative:

$$\frac{\partial}{\partial t_1} \frac{\partial}{\partial t_2} M_{X,Y}(t_1, t_2) = \frac{1}{(1 - t_1 - t_2)^2}.$$

Evaluating at $t_1 = 0$ and $t_2 = 0$, we get:

$$\text{Cov}(X, Y) = 1.$$

Conclusions: - $\text{Var}(X) = 1$, - $\text{Var}(Y) = 1$, - $\text{Cov}(X, Y) = 1$.

(c)

Based on the joint moment generating function, identify the marginal distribution of X and the marginal distribution of Y.

To find the marginal distributions of X and Y based on the joint moment generating function (MGF), we will extract the MGFs of X and Y by setting appropriate parameters in the joint MGF.

The joint moment generating function we found is:

$$M_{X,Y}(t_1, t_2) = \frac{1}{t_1}\left(\frac{1}{1 - t_1 - t_2} - \frac{1}{1 - t_2}\right),$$

valid for $t_1 + t_2 < 1$ and $t_2 < 1$.

To find the marginal MGF of X, we set $t_2 = 0$ in the joint MGF:

$$M_X(t_1) = M_{X,Y}(t_1, 0) = \frac{1}{t_1}\left(\frac{1}{1-t_1} - 1\right).$$

Simplifying:

$$M_X(t_1) = \frac{1}{t_1}\left(\frac{1}{1-t_1} - 1\right) = \frac{1}{t_1}\left(\frac{1-(1-t_1)}{1-t_1}\right) = \frac{t_1}{t_1(1-t_1)} = \frac{1}{1-t_1}.$$

This is the MGF of an **Exponential(1)** distribution. Therefore, the marginal distribution of X is:

$$X \sim \text{Exponential}(1).$$

To find the marginal MGF of Y, we set $t_1 = 0$ in the joint MGF:

$$M_Y(t_2) = M_{X,Y}(0, t_2) = \frac{1}{0}\left(\frac{1}{1-t_2} - \frac{1}{1-t_2}\right),$$

which simplifies directly to:

$$M_Y(t_2) = \frac{1}{1-t_2}.$$

This is also the MGF of an **Exponential(1)** distribution. Therefore, the marginal distribution of Y is:

$$Y \sim \text{Exponential}(1).$$

- The marginal distribution of X is **Exponential(1)**. - The marginal distribution of Y is **Exponential(1)**.

Both X and Y are independently distributed as **Exponential(1)** random variables.

Q7

Beta-Binomial model: Suppose that the conditional distribution X | P = p is Binomial(n, p) and Suppose P has a Beta(α, β) distribution.

(a)

Using the EVVE formula, find Var(X)

Given $X|P = p \sim \text{Binomial}(n, p)$, the conditional distribution of X given $P = p$ has mean and variance:

$$E[X|P = p] = np$$

$$Var(X|P = p) = np(1 - p).$$

The prior distribution for P is $P \sim \text{Beta}(\alpha, \beta)$, which has mean and variance:

$$E[P] = \frac{\alpha}{\alpha + \beta}$$

$$Var(P) = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)}.$$

The EVVE formula states:

$$Var(X) = E[Var(X|P)] + Var(E[X|P]).$$

Given $Var(X|P = p) = np(1 - p)$, the expectation of this variance is:

$$E[Var(X|P)] = E[np(1 - p)] = nE[p(1 - p)].$$

$$E[p(1 - p)] = E[p] - E[p^2].$$

Using the properties of the Beta distribution:

$$E[p] = \frac{\alpha}{\alpha + \beta}$$

and

$$E[p^2] = \frac{\alpha(\alpha + 1)}{(\alpha + \beta)(\alpha + \beta + 1)}.$$

Thus,

$$E[p(1 - p)] = \frac{\alpha}{\alpha + \beta} - \frac{\alpha(\alpha + 1)}{(\alpha + \beta)(\alpha + \beta + 1)} = \frac{\alpha\beta}{(\alpha + \beta)^2(\alpha + \beta + 1)}.$$

Therefore,

$$E[Var(X|P)] = n\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

Given $E[X|P=p] = np$, we need to find the variance:

$$Var(E[X|P]) = Var(np) = n^2 Var(P).$$

Since $Var(P) = \frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}$, we have:

$$Var(E[X|P]) = n^2\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

$$Var(X) = n\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)} + n^2\frac{\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

Combining the terms gives:

$$Var(X) = \frac{n\alpha\beta}{(\alpha+\beta)^2(\alpha+\beta+1)}(1+n).$$

Thus, the variance of X is:

$$Var(X) = \frac{n\alpha\beta(n+1)}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

(b)

Suppose that W has a Binomial(n, $\tilde{p}$) distribution having the same mean as X above. For n > 1, show that X has a larger variance than W by a multiplicative factor of:

$$\frac{\alpha+\beta+n}{\alpha+\beta+1} > 1$$

From the Beta-Binomial model, we have:

- $X|P = p \sim \text{Binomial}(n, p)$, where $P \sim \text{Beta}(\alpha, \beta)$.
- The mean of X is:

$$E[X] = nE[P] = n\frac{\alpha}{\alpha+\beta}.$$

We want the mean of W, given by $n\tilde{p}$, to be equal to the mean of X:

$$n\tilde{p} = n\frac{\alpha}{\alpha+\beta}.$$

Thus, we set:

$$\tilde{p} = \frac{\alpha}{\alpha+\beta}.$$

The variance of a Binomial random variable W is given by:

$$Var(W) = n\tilde{p}(1-\tilde{p}).$$

Substitute $\tilde{p} = \frac{\alpha}{\alpha+\beta}$:

$$Var(W) = n\left(\frac{\alpha}{\alpha+\beta}\right)\left(1-\frac{\alpha}{\alpha+\beta}\right) = n\frac{\alpha}{\alpha+\beta}\frac{\beta}{\alpha+\beta}.$$

This simplifies to:

$$Var(W) = n\frac{\alpha\beta}{(\alpha+\beta)^2}.$$

The variance of X in the Beta-Binomial model, as derived earlier, is:

$$Var(X) = \frac{n\alpha\beta(n+1)}{(\alpha+\beta)^2(\alpha+\beta+1)}.$$

To show that X has a larger variance than W, we compare $Var(X)$ with $Var(W)$:

$$\frac{Var(X)}{Var(W)} = \frac{\frac{n\alpha\beta(n+1)}{(\alpha+\beta)^2(\alpha+\beta+1)}}{n\frac{\alpha\beta}{(\alpha+\beta)^2}}.$$

Simplifying the expression:

$$\frac{Var(X)}{Var(W)} = \frac{(n+1)}{\alpha+\beta+1}.$$

Thus, the multiplicative factor by which X has a larger variance than W is:

$$\frac{\alpha+\beta+n}{\alpha+\beta+1}.$$

Since $n > 1$, it follows that:

$$\frac{\alpha+\beta+n}{\alpha+\beta+1} > 1.$$

This demonstrates that the variance of X is indeed larger than the variance of W by a factor of $\frac{\alpha+\beta+n}{\alpha+\beta+1}$.