

# Problem Set 4

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June 14, 2017

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# 1 References and License

We are answering questions in the material from MIT OpenCourseWare course 18.05, Introduction to Probability and Statistics.

In this document we are answering questions Orloff and Bloom ask in [5].

Please see the references section for detailed citation information.

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We use documentation in `[logicNot]`, `[proofs]`, `[bars]`, `[packageClash]`, `[curlyBrace]`, `[cases]` to write the L<sup>A</sup>T<sub>E</sub>X source code for this document.

# 2 Time to failure

The first group of problems Orloff and Bloom have for us involve some random variables that follow an exponential distribution.

The exponential distribution they give us to work with has probability density function (pdf):

$$f(x) = \lambda e^{-\lambda x}, x \geq 0. \quad (1)$$

## 2.1 $P(X \geq x)$

We know how to calculate  $P(X < x)$  as a definite integral [1], therefore we will find  $P(X < x)$ , and our final result will be to find  $P(X \geq x) = 1 - P(X < x)$ .

In order to calculate this probability, we will do a change of variable similar to the technique Orloff and Bloom show in section 3.4 of [2].

We change the variable in the pdf  $f(x)$  to  $u$ ; therefore we rewrite the pdf as  $f(u)$ :

$$f(u) = \lambda e^{-\lambda u}. \quad (2)$$

We use this definition, the fact that  $f$  is defined for  $x \geq 0$ , and the definition of probability of continuous random variables [1] to write this equation:

$$P(X < x) = \int_0^x \lambda e^{-\lambda u} du. \quad (3)$$

We substitute the integral on the right hand side of the previous equation with its antiderivative to get:

$$P(X < x) = -e^{-\lambda u} \Big|_{u=0}^x. \quad (4)$$

We evaluate the the antiderivative at the limits of integration:

$$P(X < x) = -e^{-\lambda x} - -e^{-\lambda 0}. \quad (5)$$

Now we simplify the previous equation:

$$P(X < x) = -e^{-\lambda x} + 1. \quad (6)$$

Now, we apply the identity:

$$P(X \geq x) = 1 - P(X < x). \quad (7)$$

Therefore

$$P(X \geq x) = 1 - (-e^{-\lambda x} + 1). \quad (8)$$

The previous equation simplifies to:

$$P(X \geq x) = e^{-\lambda x}. \quad (9)$$

## 2.2 CDF of Minimum of two exponential random variables

In this section Orloff and Bloom ask us to find the cumulative distribution function (CDF) of two independent random variables  $X_1$ , and  $X_2$  that both follow an exponential distribution, and that both have mean  $\frac{1}{\lambda}$ .

In [4] Orloff and Bloom state that the mean of a random variable that has probability mass function (pmf)  $\lambda e^{-\lambda x}$  is  $\frac{1}{\lambda}$ .

Therefore  $X_1$ , and  $X_2$  both have pmf's  $\lambda e^{-\lambda x}$ .

For this problem, Orloff and Bloom let  $T = \min(X_1, X_2)$ .

They ask us for the cdf of  $T$ .

The cdf of  $T$  is a function  $F(t) = P(T < t)$ .

In the previous section, we found that for a random variable  $X$  that has pdf  $\lambda e^{-\lambda x}$ ,

$$P(X \geq x) = e^{-\lambda x}. \quad (10)$$

We use the definition of  $T$  to write the equation:

$$P(T \geq t) = P(\min(X_1, X_2) \geq t). \quad (11)$$

$T = \min(X_1, X_2)$ , so  $T \geq t$  if, and only if,  $X_1 \geq t$ , and  $X_2 \geq t$ .

**Lemma 1.** *If two events  $A$  and  $B$  have a biconditional relation, then*

$$P(A) = P(B). \quad (12)$$

*Proof.* The proof is by contradiction. Assume events  $A$  and  $B$  are biconditionally related, but  $P(A) \neq P(B)$ . Then there would be unequal chances of events  $A$  and  $B$

occurring, which means that one event would occur while the other does not. But  $A$  and  $B$  are biconditionally related, so event  $A$  occurs when, and only when, event  $B$  occurs. This is a contradiction, so  $P(A) = P(B)$ .  $\square$

Therefore

$$P(T \geq t) = P(X_1 \geq t, X_2 \geq t). \quad (13)$$

$X_1$  and  $X_2$  are independent events. In [2] Orloff and Bloom state that random variables  $X_1$  and  $Y_1$  are independent if and only if:

$$P(X_1, X_2) = F_{X_1}(x_1) F_{X_2}(x_2). \quad (14)$$

$F(X_1, X_2)$  is the cdf of  $X_1$ , and  $X_2$ .  $F_{X_1}(x_1)$ , and  $F_{X_2}(x_2)$  are the marginal cumulative distribution functions of  $X_1$ , and  $X_2$ .

We know that  $X_1$ , and  $Y_1$  are exponentially distributed random variables with mean  $\frac{1}{\lambda}$ . The answer we find in the previous section implies that the cdf of  $X_1$  is  $F_{X_1}(x_1) = e^{-\lambda x_1}$ , and the cdf of  $X_2$  is  $F_{X_2}(x_2) = e^{-\lambda x_2}$ .

Since  $X_1$ , and  $X_2$  are independent,

$$F(X_1, X_2) = e^{-\lambda x_1} e^{-\lambda x_2}. \quad (15)$$

We add the exponents of the base  $e$  to simplify the previous equation to:

$$F(X_1, X_2) = e^{-\lambda(x_1+x_2)}. \quad (16)$$

We are finding the cdf of  $T$ .

Consider  $F(X_1 < t, X_2 < t)$ . We use the previous equation to write:

$$F(X_1 < t, X_2 < t) = e^{-\lambda 2t}. \quad (17)$$

Since  $P(T < t) = P(X_1 < t, X_2 < t)$ :

$$F(T < t, X_2 < t) = e^{-\lambda 2t}. \quad (18)$$

## 2.3 Three lightbulbs

In this section we answer a question about three lightbulbs,  $B_1$ ,  $B_2$ , and  $B_3$ , where each lightbulb's lifetime is an exponential random variable with mean values  $\frac{1}{2}$ ,  $\frac{1}{3}$ , and  $\frac{1}{5}$ , respectively. The unit for each mean value is years.

Furthermore, Orloff and Bloom state that the lifetimes of the lightbulbs are independent.

Let  $X_1$ ,  $X_2$ , and  $X_3$  be the random variables equal to the lifetimes of  $B_1$ ,  $B_2$ , and  $B_3$ , respectively.

Since the mean value of  $X_1$  is  $\frac{1}{2}$ , and  $X_1$  follows an exponential distribution,  $X_1 \sim 2e^{-2t}$ .

Similarly,  $X_2 \sim 3e^{-3t}$ , and  $X_3 \sim 5e^{-5t}$

We apply logic similar to what we use in the previous question to state that the cdf of a random variable  $T = \min(X_1, X_2, X_3)$  is

$$F(T < t) = e^{-1(2+3+5)t} = e^{-10t}. \quad (19)$$

The expected value of a random variable with cdf  $e^{-10t}$  is  $\frac{1}{10}$  year.

### 3 Aching Joints

We deal with the joint distribution of two continuous random variables  $X$ , and  $Y$ . The probability density function for  $X$ , and  $Y$  is  $f(x) = c(x^2 + xy)$ . Furthermore,  $f$  is defined on  $[0, 1] \times [0, 1]$ .

#### 3.1 Value of $c$

The first thing Orloff and Bloom ask us for is the value of  $c$  in  $f$  as defined above.

In order for  $f(x, y)$  to be a probability distribution function (PDF),

$$c \int_0^1 \int_0^1 x^2 + xy \, dx \, dy = 1. \quad (20)$$

This is true, if and only if:



$$c \int_0^1 \frac{x^3}{3} + \frac{x^2 y}{2} dy \Big|_{x=0}^1 = 1. \quad (21)$$

We evaluate the anti-derivative over the interval indicated in the equation above to obtain:

$$c \int_0^1 \frac{1}{3} + \frac{y}{2} dy = 1. \quad (22)$$

We now replace the integral of the function of  $y$  above with its anti-derivative:

$$c \frac{y}{3} + \frac{y^2}{4} \Big|_{y=0}^1 = 1. \quad (23)$$

And, we now evaluate the anti-derivative over the interval indicated in the equation above:

$$c \frac{1}{3} + \frac{1}{4} = 1. \quad (24)$$

Now, we simplify the previous equation:

$$c \frac{7}{12} = 1. \quad (25)$$

And, we solve for  $c$ :

$$c = \frac{12}{7}. \quad (26)$$

### 3.2 Marginal cumulative distribution, and probability density functions

Orloff and Bloom are asking us to find four functions

- the marginal CDF  $F_Y(y)$ ,
- the marginal CDF  $F_X(x)$ .
- the marginal PDF  $f_Y(y)$ , and
- the marginal PDF  $f_X(x)$ .

The definition of marginal CDF dictates that we evaluate the CDF at the upper limit of the variable that we are not finding the marginal CDF for.

Therefore,

$$F_Y(y) = F(1, y). \quad (27)$$

In order to find the marginal CDF's, we need to find the anti-derivative of the PDF:

$$F(x, y) = \int \int \frac{12}{7}xy + x^2 dx dy. \quad (28)$$

First we find the anti-derivative with respect to  $x$ :

$$F(x, y) = \int \frac{12}{7}frac{x^2y}{2} + frac{x^3}{3} dy. \quad (29)$$

Next, we find the anti-derivative with respect to  $y$ :

$$F(x, y) = \frac{12}{7} \frac{x^2 y^2}{2} + \frac{x^2 y}{2}. \quad (30)$$

Now that we have the CDF, we can partially evaluate it to obtain the marginal CDF's.

$$F_Y(y) = F(1, y). \quad (31)$$

We replace the right hand side of the equation above with the CDF we found, and replace  $x$  with the value 1 to find the CDF for  $y$ .

$$F_Y(y) = \frac{12}{7} \frac{y^2}{2} + \frac{2y}{2}. \quad (32)$$

$$F_X(x) = F(x, 1). \quad (33)$$

We replace the right hand side of the equation above with the CDF we found, and replace  $y$  with the value 1 to find the CDF for  $X$ .

$$F_X(x) = \frac{12}{7} \left( \frac{x^2}{2} + \frac{x^2}{2} \right). \quad (34)$$

The expression above simplifies to:

$$F_X(x) = \frac{12x^2}{7}. \quad (35)$$

Now we move on to deriving the marginal PDF's. We use the definition of marginal PDF from [2].

First we tackle the marginal PDF  $f_X(x)$ .

$$f_X(x) = \int_0^1 \frac{12}{7} (x^2 + xy) dy \quad (36)$$

We replace the function with its anti-derivative:

$$f_X(x) = \frac{12}{7} \left( x^2 y + \frac{xy^2}{2} \right) \Big|_{y=0}^1. \quad (37)$$

Now we evaluate the anti-derivative for the interval  $[0, 1]$ .

$$f_X(x) = \frac{12}{7} \left( x^2 + \frac{x^2}{2} \right). \quad (38)$$

This is the marginal PMF  $f_X(x)$ .

We do a similar integration to derive the marginal PDF  $f_Y(y)$ .

$$f_Y(y) = \frac{12}{7} \left( \int_0^1 x^2 + xy dx \right). \quad (39)$$

We replace the integral in the equation above with its anti-derivative.

$$f_Y(y) = \frac{12}{7} \left( \frac{x^3}{3} + \frac{1}{2} x^2 y \right) \Big|_0^1. \quad (40)$$

We evaluate the anti-derivative over the interval  $[0, 1]$ .

$$f_Y(y) = \frac{12}{7} \left( \frac{1}{3} + \frac{y}{2} \right). \quad (41)$$

This is the marginal PDF for  $f_Y(y)$ .

### 3.3 $E(X)$ , and $\text{Var}(X)$

In order to calculate  $E(X)$ , we integrate the product of the PDF  $f(x, y)$ , and  $x$ .

$$E(X) = \int_0^1 \int_0^1 x \frac{12}{7} (x + xy) dx dy. \quad (42)$$

We distribute  $x$  in the expression above.

$$E(X) = \int_0^1 \int_0^1 \frac{12}{7} (x^2 + x^2 y) dx dy. \quad (43)$$

First, we integrate with respect to  $x$ .

$$E(X) = \int_0^1 \frac{12}{7} \left( \frac{x^3}{3} + \frac{x^3 y}{3} \Big|_{x=0}^1 \right) dy. \quad (44)$$

Next we integrate with respect to  $y$ :

$$E(X) = \frac{12}{7} \left( \frac{x^3 y}{3} + \frac{x^3 y^2}{6} \Big|_{x=0}^1 \Big|_{y=0}^1 \right). \quad (45)$$

We evaluate the expression at the limits of integration specified to compute:

$$E(X) = \frac{12}{7} \left( \frac{1}{3} + \frac{1}{6} \right) = \frac{6}{7}. \quad (46)$$

In order to compute the variance of  $X$ , we use the identity

$$\text{Var}(X) = E(X^2) + E(X)^2 \quad (47)$$

We integrate the product of  $X^2$ , and the PDF Orloff and Bloom give us in order to calculate  $E(X^2)$ .

$$E(X^2) = \int_0^1 \int_0^1 x^2 \frac{12}{7} (x + xy) dx dy. \quad (48)$$

We distribute the  $x^2$  term in the expression above to aid in determining the anti-derivative of the integrals.

$$E(X^2) = \int_0^1 \int_0^1 \frac{12}{7} (x^3 + x^2y) dx dy. \quad (49)$$

First we replace the inner integral with its anti-derivative with respect to  $x$ :

$$E(X^2) = \int_0^1 \frac{12}{7} \left( \frac{x^4}{4} + \frac{x^3y}{3} \right) \Big|_{x=0}^1 dy. \quad (50)$$

Next, we replace the remaining integral with its anti-derivative:

$$E(X^2) = \frac{12}{7} \left( \frac{x^4 y}{4} + \frac{x^3 y^2}{6} \right) \Big|_{x=0}^1 \Big|_{y=0}^1. \quad (51)$$

Now we evaluate the anti-derivatives to complete the integration:

$$E(X^2) = \frac{12}{7} \left( \frac{1}{4} + \frac{1}{6} \right). \quad (52)$$

We simplify the expression above to:

$$E(X^2) = \frac{5}{7}. \quad (53)$$

Now that we know  $E(X^2)$ , we can calculate  $\text{Var}(X)$ .

$$\text{Var}(X) = E(X^2) - E(X)^2. \quad (54)$$

We substitute the values for  $E(X^2)$ , and  $E(X)^2$  in the equation above to obtain:

$$\text{Var}(X) = \frac{5}{7} - \left( \frac{6}{7} \right)^2 \quad (55)$$

### 3.4 Variance and Covariance of $X$ and $Y$

In order to compute the variance and covariance of  $X$ , and  $Y$ , we will use the property of covariance:

$$\text{Cov} = E(XY) - \mu_x \mu_y \quad (56)$$

However, in order to use the property, we must calculate  $\mu_y$ , and  $E(XY)$ . Note that we computed  $\mu_x$ , in the previous section.

We use the definition of expected value from [3] to compute  $\mu_y$ .

$$\mu_y = \int_0^1 \int_0^1 y \frac{12}{7} (x^2 + xy) dx dy. \quad (57)$$

We distribute  $y$  in order to determine what the anti-derivative is for the integral above:

$$\mu_y = \int_0^1 \int_0^1 y \frac{12}{7} (x^2 y + xy^2) dx dy. \quad (58)$$

We replace the integrals above with their anti-derivatives:

$$\mu_y = \frac{12}{7} \left( \frac{x^3 y^2}{6} + \frac{x^2 y^3}{6} \Big|_{x=0}^1 \Big|_{y=0}^1 \right). \quad (59)$$

And we evaluate the anti-derivative at the limits above to obtain:

$$\mu_y = \frac{12}{7} \left( \frac{1}{6} + \frac{1}{6} \right). \quad (60)$$

The equation above simplifies to:



$$/mu_y = \frac{4}{42}. \quad (61)$$

We continue to collect components of the sum we will compute in order to calculate  $\text{Cov}(X, Y)$ .

We resort to the definition of expected value in order to compute  $E(X, Y)$

$$E(X, Y) = \int_0^1 \int_0^1 \frac{12}{7} xy (x^2 + xy) dx dy. \quad (62)$$

We distribute  $xy$  in order to find the anti-derivatives of the integrals above:

$$E(X, Y) = \int_0^1 \int_0^1 \frac{12}{7} (x^3y + x^2y^2) dx dy. \quad (63)$$

Now we replace the integrals above with their anti-derivatives:

$$E(X, Y) = \frac{12}{7} \left( \frac{x^4y^2}{8} + \frac{x^3y^3}{9} \Big|_{x=0}^1 \Big|_{y=0}^1 \right). \quad (64)$$

We now evaluate the expression above at the limits of integration to find:

$$E(X, Y) = \frac{12}{7} \left( \frac{1}{8} + \frac{1}{9} \right). \quad (65)$$

This equation above simplifies to:

$$E(X, Y) = \frac{17}{42} \quad (66)$$

We now have all the components we need to compute  $\text{Cov}(X, Y)$ .

$$\text{Cov} = E(XY) - \mu_x \mu_y \quad (67)$$

We substitute the values we computed previously into the equation above:

$$\text{Cov} = \frac{2}{63} - \frac{5}{7} \frac{5}{7} \quad (68)$$

The above simplifies to:

$$\text{Cov} = \frac{211}{567} \quad (69)$$

## 4 Elections

In this section we deal with an election scenario, and a poll of 400 people. In the population: 0.5 of the people support Erika, 0.2 support Ruthi, and the remaining 0.3 support Peter, John or Jerry.

## 4.1 Apply Central Limit Theorem

We treat the response of each person polled  $X_i$  as a Bernoulli(0.5) random variable.

## References

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