
40.017 PROBABILITY & STATISTICS

Homework 1

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Question 1

(a)

Let A be the random variable denoting the number of questions chosen from section A. Since the student 'samples' the question without replacement, A follows a hypergeometric distribution $A \sim \text{hypgeo}(12, 9, 9)$. The pmf $f(x)$ is given by:

$$f(x) = \mathbb{P}(X = x) = \frac{\binom{j}{x} \binom{k}{n-x}}{\binom{j+k}{n}}$$

for 6 questions from section A, we have $\mathbb{P}(X = 6)$:

$$\begin{aligned}\mathbb{P}(X = 6) &= \frac{\binom{9}{6} \binom{9}{6}}{\binom{18}{12}} \\ &= 0.380090 \\ &\boxed{\approx 0.380}\end{aligned}$$

(b)

Now we need to consider two cases, one where 5 questions come from Section A and the other 7 from Section B, and vice versa. i.e.

$$\begin{aligned}\mathbb{P}(A = 5) + \mathbb{P}(A = 7) &= \frac{\binom{9}{5} \binom{9}{7}}{\binom{18}{12}} + \frac{\binom{9}{7} \binom{9}{5}}{\binom{18}{12}} \\ &= 0.4886877 \\ &\boxed{\approx 0.489}\end{aligned}$$

Question 2

(a)

To find the probability that at least 1 man receives his own hat, we consider the complementary case of no man receiving his own hat, given by D_6 . Thus:

$$\begin{aligned}\mathbb{P}(\text{'at least 1 man receives his own hat'}) &= 1 - \frac{D_6}{6!} \\ &= 1 - \frac{6!(1 - \frac{1}{1!} + \frac{1}{2!} - \frac{1}{3!} + \frac{1}{4!} - \frac{1}{5!} + \frac{1}{6!})}{6!} \\ &= \boxed{\frac{91}{144}}\end{aligned}$$

(b)

Again we consider the complementary case that no man receives his own hat, or only 1 man receives his own hat. Thus:

$$\begin{aligned}\mathbb{P}(\text{'at least 2 men receives their own hats'}) &= 1 - \underbrace{\frac{D_6}{6!}}_{\text{no man receives their own hat}} - \underbrace{\frac{6 \times D_5}{6!}}_{\text{1 man receives his own hat}} \\ &= \frac{91}{144} - 6 \times \frac{5!(1 - \frac{1}{1!} + \frac{1}{2!} - \frac{1}{3!} + \frac{1}{4!} - \frac{1}{5!})}{6!} \\ &= \boxed{\frac{191}{720}}\end{aligned}$$

(c)

The probability that at least 5 men receive their own hats can be interpreted as every man receiving their own hats, since if 5 men receive their own hats, the last man will automatically also receive his own hat. There is only 1 way for all 6 men to receive their own hats, so we have:

$$\begin{aligned}\mathbb{P}(\text{'at least 5 men receives their own hats'}) &= \frac{1}{6!} \\ &= \boxed{\frac{1}{720}}\end{aligned}$$

Question 3

(a)

Since X is the number of coin tosses upon completion, we model X as a geometric distribution with the "success" being obtaining a T: $X \sim \text{geometric}(\frac{1}{2})$, $X \in \{1, 2, \dots, n\}$. For $x \in \{1, 2, \dots, n-1\}$, we thus have: $\mathbb{P}(X = x) = (1 - \frac{1}{2})^{x-1}(\frac{1}{2}) = (\frac{1}{2})^x$. As for $x = n$, we take the complement of all the other probabilities (since they sum to 1):

$$\begin{aligned}\mathbb{P}(X = n) &= 1 - \left(\sum_{i=1}^{n-1} \mathbb{P}(X = i) \right) \\ &= 1 - \left(\sum_{i=1}^{n-1} \left(\frac{1}{2} \right)^i \right) \\ &= 1 - \frac{\frac{1}{2}(1 - (\frac{1}{2})^{n-1-1+1})}{1 - \frac{1}{2}} \\ &= \left(\frac{1}{2} \right)^{n-1}\end{aligned}$$

The p.m.f. table is shown below:

x	1	2	3	...	n
$\mathbb{P}(X = x)$	$\frac{1}{2}$	$(\frac{1}{2})(\frac{1}{2})$	$(\frac{1}{2})(\frac{1}{2})(\frac{1}{2})$...	$(\frac{1}{2})^{n-1}$

and in piecewise notation:

$$\mathbb{P}(X = x) = \begin{cases} \left(\frac{1}{2} \right)^x, & x \in \{1, 2, \dots, n-1\} \\ \left(\frac{1}{2} \right)^{x-1}, & x = n \end{cases}$$

(b)

To find $\mathbb{E}(X)$, we sum over both cases of the p.m.f:

$$\begin{aligned}\mathbb{E}(X) &= \sum_{i=1}^{n-1} i \cdot \mathbb{P}(X = i) + n \cdot \left(\frac{1}{2} \right)^{n-1} \\ &= \sum_{i=1}^{n-1} i \cdot \left(\frac{1}{2} \right)^i + n \cdot \left(\frac{1}{2} \right)^{n-1} \\ &= \frac{1}{2} \sum_{i=1}^{n-1} i \cdot \left(\frac{1}{2} \right)^{i-1} + n \cdot \left(\frac{1}{2} \right)^{n-1}\end{aligned}\tag{1}$$

Using the hint, we differentiate the finite geometric series from the fact that $\frac{d}{dx}x^a = ax^{a-1}$. Letting $r = \frac{1}{2}$:

$$\begin{aligned}\frac{d}{dr} \left[\sum_{i=0}^{n-1} r^i \right] &= \frac{d}{dr} \left[\frac{1-r^n}{1-r} \right] \\ \sum_{i=1}^{n-1} i \cdot r^{i-1} &= \frac{1-r^n}{(1-r)^2} - \frac{nr^{n-1}}{1-r}\end{aligned}$$

Now, substituting back into Equation (1), we have:

$$\begin{aligned}\mathbb{E}(X) &= \frac{1}{2} \left[\frac{1 - \left(\frac{1}{2}\right)^n}{\left(1 - \frac{1}{2}\right)^2} - \frac{n\left(\frac{1}{2}\right)^{n-1}}{1 - \frac{1}{2}} \right] + n \cdot \left(\frac{1}{2}\right)^{n-1} \\ &= \frac{1}{2} \left[4 \left(1 - \left(\frac{1}{2}\right)^n \right) - 2n \left(\frac{1}{2}\right)^{n-1} \right] + n \cdot \left(\frac{1}{2}\right)^{n-1} \\ &= 2 - \left(\frac{1}{2}\right)^{n-1} - n \cdot \left(\frac{1}{2}\right)^{n-1} + n \cdot \left(\frac{1}{2}\right)^{n-1} \\ &= \boxed{2 - \left(\frac{1}{2}\right)^{n-1}}\end{aligned}$$

Question 4

Chebyshev's inequality in the standard form gives the **upper bound** for the probability of being k standard deviations ($\sigma = 5$) away from the mean $\mu = 50$.

$$\mathbb{P}(|X - \mu| \geq k\sigma) \leq \frac{1}{k^2} \quad (2)$$

Let X be the weekly production of the factory (in tons). We want to find the probability $\mathbb{P}(41 \leq X \leq 61)$. Since the bounds are not symmetric about μ , we need the tighter bound $\mathbb{P}(41 \leq X \leq 59)$. Then, the value of k is now $k = \frac{9}{5}$ standard deviations away from the mean.

Graphically, we can see that

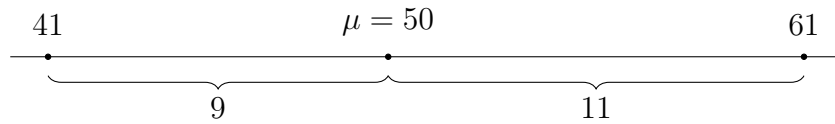


Figure 1: Illustration of bounds

From Equation (2), to find a *lower* bound, we need to take the complement:

$$\mathbb{P}(|X - \mu| < k\sigma) \geq 1 - \frac{1}{k^2} \quad (3)$$

Thus the lower bound for the probability that the weekly production is between 41 and 61 tons is:

$$\begin{aligned} \mathbb{P}(41 \leq X \leq 61) &\geq \mathbb{P}\left(|X - \mu| < \frac{9}{5}\sigma\right) \\ &\geq 1 - \frac{1}{\left(\frac{9}{5}\right)^2} \\ &= \boxed{\frac{56}{81}} \end{aligned}$$

Question 5

Let $X \sim \text{negbin}(n, p)$. In the recitation, to find the MGF of X , since the negative binomial distribution is the sum of n independent geometric distributions, let $Y \sim \text{Geometric}(p)$, and $q = 1 - p$.

$$M_Y(t) = \frac{pe^t}{1 - qe^t} \quad (4)$$

We have $Y_1 + Y_2 + \dots + Y_n \sim \text{negbin}(n, p)$. Since each Y_i 's are independent, by the sum property, the MGF of X is given by:

$$\begin{aligned} M_{Y_1+Y_2+\dots+Y_n}(t) &= M_{Y_1}(t) \cdot M_{Y_2}(t) \dots M_{Y_n}(t) \\ &= [M_Y(t)]^n \\ &= M_X(t) \\ &= \left[\frac{pe^t}{1 - qe^t} \right]^n \end{aligned}$$

Proof. To find $\mathbb{E}(X)$, we need to find the first moment, which requires the derivative:

$$\begin{aligned} M_X(t) &= \left[\frac{pe^t}{1 - qe^t} \right]^n \\ M'_X(t) &= n \left[\frac{pe^t}{1 - qe^t} \right]^{n-1} \cdot \frac{d}{dt} \left[\frac{pe^t}{1 - qe^t} \right] \\ &= n \left[\frac{pe^t}{1 - qe^t} \right]^{n-1} \cdot \left[\frac{pe^t(qe^t + (1 - qe^t))}{(1 - qe^t)^2} \right] \\ &= n \left[\frac{pe^t}{1 - qe^t} \right]^{n-1} \cdot \left[\frac{pe^t}{(1 - qe^t)^2} \right] \\ &= \left[\frac{pe^t}{1 - qe^t} \right] \cdot \frac{n}{(1 - qe^t)} \end{aligned}$$

Now, to find $\mathbb{E}(X)$, we set $t = 0$:

$$\begin{aligned} M'_X(0) &= \left[\frac{p}{1 - q} \right]^n \cdot \frac{n}{1 - q} \\ &= \left[\frac{p}{1 - (1 - p)} \right]^n \cdot \frac{n}{1 - (1 - p)} \\ &= \boxed{\frac{n}{p}} = \mathbb{E}(X) \end{aligned}$$

□

Question 6

(a)

To find the MGF of X , since X is continuous, we need to integrate over all X , taking note that the MGF is only defined on $-1 < t < 1$:

$$\begin{aligned}
 M_X(t) &= \int_{-\infty}^{\infty} e^{tx} f(x) dx \\
 &= \int_{-\infty}^{\infty} e^{tx} \frac{1}{2} e^{-|x|} dx \\
 &= \int_{-\infty}^0 e^{tx} \cdot \frac{1}{2} e^x dx + \int_0^{\infty} e^{tx} \cdot \frac{1}{2} e^{-x} dx \\
 &= \frac{1}{2} \left[\int_{-\infty}^0 e^{(t+1)x} dx + \int_0^{\infty} e^{(t-1)x} dx \right] \\
 &= \frac{1}{2} \left[\left. \frac{1}{t+1} e^{(t+1)x} \right|_{-\infty}^0 + \left. \frac{1}{t-1} e^{(t-1)x} \right|_0^{\infty} \right] \\
 &= \frac{1}{2} \left[\frac{1}{t+1} - \frac{1}{t-1} \right] \quad \because (-1 < t < 1) \\
 &= \frac{1}{2} \left[\frac{t-1-t-1}{(t+1)(t-1)} \right] \\
 &= \frac{1}{2} \left[\frac{-2}{t^2-1} \right] \\
 &= \boxed{\frac{1}{1-t^2}}
 \end{aligned}$$

(b)

Note that $\text{Var}(X) = \mathbb{E}(X^2) - \mathbb{E}(X)^2$, so we need to find the first and second moments. For the first moment we need the derivative:

$$\begin{aligned}
 \mathbb{E}(X) &= M'_X(0) \\
 &= \left. \frac{d}{dt} \left(\frac{1}{1-t^2} \right) \right|_{t=0} \\
 &= \left. -(1-t^2)^{-2}(-2t) \right|_{t=0} \\
 &= \left. \frac{2t}{(1-t^2)^2} \right|_{t=0} \\
 &= 0
 \end{aligned}$$

For the second moment:

$$\begin{aligned}\mathbb{E}(X^2) &= M_X''(0) \\ &= \left. \frac{d}{dt} \left(\frac{2t}{(1-t^2)^2} \right) \right|_{t=0} \\ &= 2t(-2(1-t^2)^{-3}(-2t)) + (1-t^2)^{-2}(2) \Big|_{t=0} \\ &= \left(\frac{8t^3}{(1-t^2)^3} \right) + \frac{2}{(1-t^2)^2} \Big|_{t=0} \\ &= 2\end{aligned}$$

Thus, we have

$$\begin{aligned}\text{Var}(X) &= \mathbb{E}(X^2) - \mathbb{E}(X)^2 \\ &= 2 - 0^2 \\ &= \boxed{2}\end{aligned}$$

Question 7

(a)

Manipulating the right tail probability of a standard normal r.v. Z , we have

$$\mathbb{P}(Z \geq t) = \mathbb{P}(tZ \geq t^2) = \mathbb{P}(e^{tZ} \geq e^{t^2}) \quad (5)$$

Markov's Inequality gives an upper bound on the tail probability, subject to any constant $a > 0$:

$$\mathbb{P}(X \geq a) \leq \frac{\mathbb{E}(X)}{a} \quad (6)$$

Proof. Applying Equation (6) on Equation (5), we have $a = e^{t^2}$.

$$\begin{aligned} \mathbb{P}(e^{tZ} \geq e^{t^2}) &\leq \frac{\mathbb{E}(e^{tZ})}{e^{t^2}} \\ &= \frac{M_Z(t)}{e^{t^2}} \\ &= \frac{e^{\frac{t^2}{2}}}{e^{t^2}} \\ &= e^{-\frac{t^2}{2}} \end{aligned}$$

Where $M_Z(t) = e^{\frac{t^2}{2}}$ was obtained from Week 2 Class 2 Example 3 (too lazy to typeset). From here, we have:

$$\boxed{\mathbb{P}(Z \geq t) = \mathbb{P}(e^{tZ} \geq e^{t^2}) \leq e^{-\frac{t^2}{2}}} \quad (7)$$

□

(b)

From Equation (7), we substitute $t = -7$ to get:

$$\begin{aligned} \mathbb{P}(Z \leq -7) &= \mathbb{P}(Z \geq 7) \quad (Z \text{ is symmetric about } \mu = 0) \\ &\leq e^{-\frac{7^2}{2}} \\ &\leq e^{-\frac{49}{2}} \\ &\leq 22.897\,348 \times 10^{-12} \\ &\approx \boxed{22.8 \times 10^{-12}} \end{aligned}$$