

MATH 368/621 Fall 2020 Homework #1

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Saturday 12th September, 2020

Problem 1

These exercises give you practice with sums and indicator functions.

(a) [easy] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} \mathbb{1}_{x=17}$.

$$\sum_{x \in \mathbb{R}} \mathbb{1}_{x=17} = 1$$

(b) [easy] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} c \mathbb{1}_{x=17}$ where $c \in \mathbb{R}$ is a constant.

$$\sum_{x \in \mathbb{R}} c \mathbb{1}_{x=17} = c$$

(c) [easy] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} \mathbb{1}_{x \in \{1,2,3\}}$.

$$\sum_{x \in \mathbb{R}} \mathbb{1}_{x \in \{1,2,3\}} = 3$$

(d) [easy] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} x \mathbb{1}_{x \in \{1,2,3\}}$.

$$\begin{aligned} \sum_{x \in \mathbb{R}} x \mathbb{1}_{x \in \{1,2,3\}} &= 1(1) + 2(1) + 3(1) + 4(0) + 5(0) + \dots \\ &= 6 \end{aligned}$$

(e) [easy] Expand and simplify as much as you can: $\sum_{x \in \mathbb{N}_0} x^{\mathbb{1}_{x \in \{1,2,3\}}}$.

$$\begin{aligned}\sum_{x \in \mathbb{N}_0} x^{\mathbb{1}_{x \in \{1,2,3\}}} &= 1^1 + 2^1 + 3^1 + 4^0 + \dots \\ &= 6 + \infty \\ &= \infty\end{aligned}$$

(f) [easy] Expand and simplify as much as you can: $\prod_{x \in \mathbb{R}} \mathbb{1}_{x \in \{1,2,3\}}$.

$$\begin{aligned}\prod_{x \in \mathbb{R}} \mathbb{1}_{x \in \{1,2,3\}} &= 1 * 1 * 1 * 0 * \dots \\ &= 0\end{aligned}$$

(g) [easy] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} \mathbb{1}_{x \in \{1,2,3\}} \mathbb{1}_{x \in \{4,5,6\}}$.

$$\begin{aligned}\sum_{x \in \mathbb{R}} \mathbb{1}_{x \in \{1,2,3\}} \mathbb{1}_{x \in \{4,5,6\}} &= (1)(0) + (1)(0) + (1)(0) + (0)(1) + (0)(1) + (0)(1) + \dots \\ &= 0\end{aligned}$$

(h) [harder] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} c \mathbb{1}_{x \in \{1,2,\dots,t\}}$ where $c \in \mathbb{R}$ is a constant and $t \in \mathbb{N}$ is a constant.

$$\begin{aligned}\sum_{x \in \mathbb{R}} c \mathbb{1}_{x \in \{1,2,\dots,t\}} &= c \sum_{i=0}^t 1 \\ &= tc\end{aligned}$$

(i) [harder] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} t \mathbb{1}_{x \in \{1,2,\dots,t\}}$ where $c \in \mathbb{R}$ is a constant and $t \in \mathbb{N}$ is a constant.

$$\begin{aligned}\sum_{x \in \mathbb{R}} t \mathbb{1}_{x \in \{1,2,\dots,t\}} &= t \sum_{i=1}^t i \\ &= t^2\end{aligned}$$

- (j) [harder] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} x \mathbb{1}_{x \in \{1, 2, \dots, t\}}$ where $c \in \mathbb{R}$ is a constant and $t \in \mathbb{N}$ is a constant.

$$\begin{aligned} \sum_{x \in \mathbb{R}} x \mathbb{1}_{x \in \{1, 2, \dots, t\}} &= \sum_{i=1}^t i \\ &= \frac{(t-1)(t)}{2} \end{aligned}$$

- (k) [harder] Expand and simplify as much as you can: $\sum_{x \in \mathbb{R}} \frac{1}{x!} \mathbb{1}_{x \in \mathbb{N}}$.

$$\begin{aligned} \sum_{x \in \mathbb{R}} \frac{1}{x!} \mathbb{1}_{x \in \mathbb{N}} &= \sum_{x \in \mathbb{N}} \frac{1}{x!} \\ &= \exp(1) - 1 \end{aligned}$$

- (l) [harder] Prove $\mathbb{E}[\mathbb{1}_{X \in A}] = \mathbb{P}(X \in A)$.

$$\begin{aligned} \mathbb{E}[\mathbb{1}_{X \in A}] &= \mathbb{P}(X \in A) \\ \mathbb{1}_{X \in A} &= \text{Deg}(\mathbb{1}_{X \in A}) \end{aligned}$$

Problem 2

These exercises review convolutions.

- (a) [easy] Is a JMF a type of PMF or PMF a type of JMF? Explain.

A JMF is a type of PMF because a JMF is derived from 2 or more PMF's

- (b) [easy] Let $X_1, X_2 \stackrel{iid}{\sim} \text{Bernoulli}(p)$. Find the PMF of the sum of $T = X_1 + X_2$ using the appropriate discrete convolution formula that would make the problem easiest.

$$\begin{aligned} \mathbb{P}(t) &= \sum_{x \in \mathbb{R}} \binom{1}{x} p^x (1-p)^{1-x} \binom{1}{t-x} p^{t-x} (1-p)^{1-t-x} \\ &= p^t (1-p)^{2-t} \sum_{x \in \mathbb{R}} \binom{1}{x} \binom{1}{t-x} \end{aligned}$$

$$\begin{aligned}
&= p^t(1-p)^{2-t} \left(\binom{1}{t} \binom{1}{t-1} \right) \\
&= \binom{2}{t} p^t(1-p)^{2-t}
\end{aligned}$$

- (c) [easy] Let $X_1 \sim \text{Bernoulli}(p_1)$ independent of $X_2 \sim \text{Bernoulli}(p_2)$. Find the JMF of for X_1, X_2 . Denote it using a 2×2 grid or the piecewise function notation.

$$\begin{cases} 1 & \text{w.p. } (p_1)(p_2) \\ 0 & \text{w.p. } (1-p_1)(1-p_2) \end{cases}$$

- (d) [difficult] Let

$$X_1 \sim \begin{cases} 3 & \text{w.p. } 0.3 \\ 6 & \text{w.p. } 0.7 \end{cases} \quad \text{independent of} \quad X_2 \sim \begin{cases} 4 & \text{w.p. } 0.4 \\ 8 & \text{w.p. } 0.6 \end{cases}$$

Find the PMF of $T = X_1 + X_2$ using a convolution. Denote it using the piecewise function notation.

$$T \sim \begin{cases} 7 & \text{w.p. } 0.12 \\ 10 & \text{w.p. } 0.18 \\ 11 & \text{w.p. } 0.28 \\ 14 & \text{w.p. } 0.42 \end{cases}$$

- (e) [difficult] Prove the PMF of a binomial inductively using convolutions on the sequence of r.v.'s $X_1, \dots, X_n \stackrel{iid}{\sim} \text{Bernoulli}(p)$. You will need to use Pascal's Triangle combinatorial identity we employed in class.

$$\text{Let } T_n = X_1 + X_2 + \dots + X_n \text{ and } T_n = X_n + T_{n-1}$$

$$\begin{aligned}
\mathbb{P}(t) &= \sum_{x \in \{0,1\}} p^x(1-p)^{1-x} \binom{n-1}{t-x} p^{t-x}(1-p)^{n-1-t+x} \\
&= \sum_{x \in \{0,1\}} p^t(1-p)^{n-t} \binom{n-1}{t-x}
\end{aligned}$$

$$\begin{aligned}
&= p^t(1-p)^{n-t} \sum_{x \in \{0,1\}} \binom{n-1}{t-x} \\
&= p^t(1-p)^{n-t} \left(\binom{n-1}{t} + \binom{n-1}{t-1} \right) \\
&= p^t(1-p)^{n-t} \binom{n}{t}
\end{aligned}$$

- (f) [difficult] [MA] Prove the PMF of a negative binomial inductively using convolutions on the sequence of r.v.'s $X_1, \dots, X_n \stackrel{iid}{\sim} \text{Geometric}(p)$. You will need to use the “hockey stick identity” [click here].

$$\text{Let } T_n = X_n + T_{n-1}$$

$$\begin{aligned}
\mathbb{P}(t) &= \sum \mathbb{P}(X_n) \mathbb{P}(T_n - X_n) \\
&= \sum_{x \in \{0,1,\dots\}} (1-p)^x \binom{(t-x) + n - 2}{n-2} (1-p)^{t-x} p^{n-1} \mathbb{1}_{t-x \in \{0,1,\dots\}} \\
&= (1-p)^t p^n \sum_{x \in \{0,1,\dots\}} \binom{(t-x) + n - 2}{n-2} \\
&= (1-p)^t p^n \sum_{x=0}^t \binom{t + n - x - 2}{n-2} \\
&= (1-p)^t p^n \binom{t + n - 1}{n-1}
\end{aligned}$$

- (g) [difficult] Let $X_1 \sim \text{Binomial}(n_1, p)$ independent of $X_2 \sim \text{Binomial}(n_2, p)$. Find the PMF of the sum of $T = X_1 + X_2$ using a convolution.

$$\begin{aligned}
\mathbb{P}(t) &= \sum_{x \in \mathbb{R}} \binom{n_1}{x} p^x (1-p)^{n_1-x} \binom{n_2}{t-x} p^{t-x} (1-p)^{n_2-t+x} \mathbb{1}_{t-x \in \text{Supp}[X_1]} \\
&= p^t (1-p)^{n_1+n_2-t} \sum_{x \in \{0,\dots,t\}} \binom{n_1}{x} \binom{n_2}{t-x} \\
&= p^t (1-p)^{n_1+n_2-t} \binom{n_1+n_2}{t}
\end{aligned}$$

(h) [easy] Prove the PMF of $X \sim \text{Poisson}(\lambda)$ using the limit as $n \rightarrow \infty$ and let $p = \frac{\lambda}{n}$.

Let $X \sim \text{Binomial}(n, p)$ where $n \rightarrow \infty$ and $p = \frac{\lambda}{n}$

$$\begin{aligned}
 \mathbb{P}(x) &= \lim_{n \rightarrow \infty} \frac{n!}{x!(n-x)!} \left(\frac{\lambda}{n}\right)^x \left(1 - \frac{\lambda}{n}\right)^{n-x} \mathbb{1}_{x \in \{0, \dots, n\}} \\
 &= \lim_{n \rightarrow \infty} \binom{n}{x} p^x (1-p)^{1-x} \mathbb{1}_{x \in \{0, \dots, n\}} \\
 &= \frac{\lambda^x}{x!} \lim_{n \rightarrow \infty} \frac{n!}{(n-x)n^x} \lim_{n \rightarrow \infty} \left(1 - \frac{\lambda}{n}\right)^n \lim_{n \rightarrow \infty} \left(1 - \frac{\lambda}{n}\right)^{-x} \mathbb{1}_{x \in \{0, \dots, n\}} \\
 &= \frac{\lambda^x}{x!} \lim_{n \rightarrow \infty} \frac{n(n-1) \dots (n-x+1)}{n \cdot n \dots n} \exp(-\lambda) \mathbb{1}_{x \in \{0, 1, \dots\}} \\
 &= \frac{\lambda^x e^{-\lambda}}{x!} \mathbb{1}_{x \in \{0, 1, \dots\}} \\
 &= \text{Poisson}(\lambda)
 \end{aligned}$$

(i) [difficult] Let $X_1 \sim \text{Poisson}(\lambda_1)$ independent of $X_2 \sim \text{Poisson}(\lambda_2)$. Find the PMF of the sum of $T = X_1 + X_2$ using a convolution.

$$\begin{aligned}
 \mathbb{P}(t) &= \sum_{x_1 \in \{0, \dots\}} = \sum \frac{\exp(-\lambda_1) \lambda_1^{x_1}}{x_1!} \frac{\exp(-\lambda_2) \lambda_2^{t-x_1}}{(t-x_1)!} \mathbb{1}_{t-x \in \text{Supp}[X_1]} \\
 &= \sum_{x_1 \in \{0, \dots, t\}} \frac{\exp(-\lambda_1) \lambda_1^{x_1}}{x_1!} \frac{\exp(-\lambda_2) \lambda_2^{t-x_1}}{(t-x_1)!} \\
 &= \sum_{x_1 \in \{0, \dots, t\}} \left(\frac{1}{x_1!(t-x_1)!} \exp(-\lambda_1) \lambda_1^{x_1} \exp(-\lambda_2) \lambda_2^{t-x_1} \right) \frac{t!}{t!} \\
 &= \sum_{x_1 \in \{0, \dots, t\}} \binom{t}{x_1} \frac{\exp(-\lambda_1) \lambda_1^{x_1} \exp(-\lambda_2) \lambda_2^{t-x_1}}{t!} \\
 &= \frac{\exp(-\lambda_1 - \lambda_2)}{t!} \sum_{x_1 \in \{0, \dots, t\}} \binom{t}{x_1} \lambda_1^{x_1} \lambda_2^{t-x_1} \\
 &= \frac{\exp(-\lambda_1 - \lambda_2) (\lambda_2 + \lambda_1)^t}{t!}
 \end{aligned}$$

Problem 3

These exercises introduce probabilities of conditional subsets of the supports of multiple r.v.'s.

- (a) [difficult] Let $X \sim \text{Geometric}(p_x)$ independent of $Y \sim \text{Geometric}(p_y)$. Find $\mathbb{P}(X > Y)$ using the method we did in class.

$$\begin{aligned}
\mathbb{P}(X > Y) &= \sum_{x \in \mathbb{N}_0} \sum_{y \in \mathbb{N}_0} (1 - p_x)^x p_x (1 - p_y)^y p_y \mathbf{1}_{x > y} \\
&= p_x p_y \sum_{y \in \mathbb{N}_0} (1 - p_y)^y \sum_{x \in \mathbb{N}_0} (1 - p_x)^x \mathbf{1}_{x > y} \\
&= p_x p_y \sum_{y \in \mathbb{N}_0} (1 - p_y)^y \sum_{x \in \{y+1, \dots\}} (1 - p_x)^x \\
&= p_x p_y \sum_{y \in \mathbb{N}_0} (1 - p_y)^y \sum_{x' \in \mathbb{N}_0} (1 - p_x)^{x'+y+1} \\
&= p_x p_y (1 - p_x) \sum_{y \in \mathbb{N}_0} (1 - p_y)^y \sum_{x' \in \mathbb{N}} (1 - p_x)^{x'-1} \\
&= p_y (1 - p_x) \sum_{y \in \mathbb{N}_0} (1 - p_y)^y (1 - p_x)^y \\
&= p_y (1 - p_x) \sum_{y \in \mathbb{N}_0} [(1 - p_y)(1 - p_x)]^y \\
&= p_y (1 - p_x) \sum_{y \in \mathbb{N}} [(1 - p_y)(1 - p_x)]^{y-1} \\
&= \frac{p_y - p_x p_y}{p_x + p_y - p_x p_y}
\end{aligned}$$

- (b) [easy] [MA] Prove this a different way by finding $\mathbb{P}(X = Y)$ and then using the law of total probability.

$$\begin{aligned}
1 - \mathbb{P}(X \leq Y) &= \mathbb{P}(X > Y) \\
\mathbb{P}(X \leq Y) &= 1 - \mathbb{P}(X > Y) \\
&= 1 - \frac{p_y - p_x p_y}{p_x + p_y - p_x p_y} \\
&= \frac{p_x}{p_x + p_y - p_x p_y}
\end{aligned}$$

$$\frac{p_y - p_x p_y}{p_x + p_y - p_x p_y} + \frac{p_x}{p_x + p_y - p_x p_y} = 1$$

- (c) [easy] [MA] As both p_x and p_y are reduced to zero, but $r = \frac{p_x}{p_y}$, what is the asymptotic probability you found in (a)?

Let $p_x = rp_y$

$$\begin{aligned}
 \mathbb{P}(X > Y) &= \frac{p_y - p_x p_y}{p_x + p_y - p_x p_y} \\
 &= \frac{1 - rp_y}{r + 1 - rp_y} \\
 &= \lim_{p_y \rightarrow 0} \frac{1 - rp_y}{r + 1 - rp_y} \\
 &= \frac{1}{1 + r} \\
 &= \frac{p_x}{p_y + p_x}
 \end{aligned}$$

- (d) [difficult] Let $X \sim \text{Poisson}(\lambda)$ independent of $Y \sim \text{Poisson}(\lambda)$. Find an expression for $\mathbb{P}(X > Y)$ as best as you are able to answer. Part of this exercise is identifying where you cannot go any further.

$$\begin{aligned}
 \mathbb{P}(X > Y) &= \sum_{x \in \mathbb{R}} \sum_{y \in \mathbb{R}} \mathbb{P}(x) \mathbb{P}(y) \mathbf{1}_{x > y} \\
 &= \sum_{x \in \mathbb{N}_0} \sum_{y \in \mathbb{N}_0} \frac{e^{-\lambda} \lambda^x}{x!} \frac{e^{-\lambda} \lambda^y}{y!} \mathbf{1}_{x > y} \\
 &= e^{-2\lambda} \sum_{y \in \mathbb{N}_0} \frac{\lambda^y}{y!} \sum_{x \in \{y+1, \dots\}} \frac{\lambda^x}{x!} \\
 &= e^{-2\lambda} \sum_{y \in \mathbb{N}_0} \frac{\lambda^y}{y!} \sum_{x' \in \mathbb{N}_0} \frac{\lambda^{x'+y+1}}{x'!} \\
 &= \lambda e^{2\lambda} \sum_{y \in \mathbb{N}_0} \frac{\lambda^{2y}}{y!} \sum_{x' \in \mathbb{N}_0} \frac{\lambda^{x'}}{x'!} \\
 &= \lambda e^{-\lambda} \sum_{y \in \mathbb{N}_0} \frac{\lambda^{2y}}{y!}
 \end{aligned}$$

Problem 4

These exercises will introduce the Multinomial distribution.

- (a) [easy] If $\mathbf{X} \sim \text{Multinomial}(n, \mathbf{p})$ where $\dim[\mathbf{X}] = k$, what is the parameter space for both n and \mathbf{p} ?

$$n \in \mathbb{N}, \quad \mathbf{p} \in \{\vec{v} : \vec{v} \cdot \mathbf{1}, v_1 \in (0, 1), \dots, v_k \in (0, 1)\}$$

(b) [easy] If $\mathbf{X} \sim \text{Multinomial}(n, \mathbf{p})$ where $\dim[\mathbf{X}] = k$, what is the $\text{Supp}[\mathbf{X}]$?

$$\text{Supp}[\mathbf{X}] = \{\vec{x} : \vec{x} \cdot \mathbf{1} = n, x_1 \in \{0, \dots, n\}, \dots, x_k \in \{0, \dots, n\}\}$$

(c) [easy] If $\mathbf{X} \sim \text{Multinomial}(n, \mathbf{p})$ where $\dim[\mathbf{X}] = k$, what is $\dim[\mathbf{p}]$?

$$\dim[\mathbf{p}] = k$$

(d) [easy] If $\mathbf{X} \sim \text{Multinomial}(n, \mathbf{p})$ where $\dim[\mathbf{X}] = 2$, express p_2 as a function of p_1 .

$$p_1 = 1 - p_2$$

(e) [easy] If $\mathbf{X} \sim \text{Multinomial}(n, \mathbf{p})$ where $\dim[\mathbf{X}] = 2$, how are both X_1 and X_2 distributed?

$$X_1 \sim \text{Binomial}(n, p_1), \quad X_2 \sim \text{Binomial}(n, p_2)$$

(f) [easy] If $\mathbf{X} \sim \text{Multinomial}(n, \mathbf{p})$ and $n = 10$ and $\dim[\mathbf{X}] = 7$ as a column vector, give an example value of \mathbf{x} , a realization of the r.v. \mathbf{X} .

$$\mathbf{x} = [1, 1, 1, 1, 1, 2, 3]^T$$

(g) [easy] If $\mathbf{X} \sim \text{Multinomial}\left(9, [0.1 \ 0.2 \ 0.7]^\top\right)$, find $\mathbb{P}\left(\mathbf{X} = [3 \ 2 \ 4]^\top\right)$ to the nearest two decimal places.

$$\begin{aligned} \mathbb{P}(X = [3, 2, 4]^T) &= \binom{9}{3, 2, 4} \cdot (0.1) \cdot (0.2) \cdot (0.7) \\ &= \frac{9!}{3!2!4!} \cdot (0.1) \cdot (0.2) \cdot (0.7) \\ &= 17.64 \end{aligned}$$

- (h) [difficult] [MA] If $\mathbf{X}_1 \sim \text{Multinomial}(n, \mathbf{p})$ and independently $\mathbf{X}_2 \sim \text{Multinomial}(n, \mathbf{p})$ where $\dim[\mathbf{X}_1] = \dim[\mathbf{X}_2] = k$. Find the JMF of $\mathbf{T}_2 = \mathbf{X}_1 + \mathbf{X}_2$ from the definition of convolution. This looks harder than it is! First, use the definition of convolution and factor out the terms that are not a function of x_1, \dots, x_k . Finally, use Theorem 1 in this paper: [\[click here\]](#) for the summation.

$$\begin{aligned}
\mathbb{P}(t_1, \dots, t_k) &= \sum_{x_1, \dots, x_k} \binom{n}{x_1, \dots, x_k} \prod_{k=1}^k p_k^{x_k} \binom{n}{(t_1 - x_1), \dots, (t_k - x_k)} \prod_{k=1}^k p_k^{t_k - x_k} \\
&= \prod_{i=1}^k p_i^{t_i} \sum_{x_1, \dots, x_k} \binom{n}{x_1, \dots, x_k} \binom{n}{(t_1 - x_1), \dots, (t_k - x_k)} \\
&= \prod_{i=1}^k p_i^{t_i} \binom{2n}{t_1, t_2, \dots, t_k}
\end{aligned}$$