

STAT 111: Mathematical Statistics II

DAVID YANG

Spring 2024

Abstract

These notes arise from my studies in STAT 111: Mathematical Statistics II, taught by Professor [Phil Everson](#), at Swarthmore College, following the material of Munkre's *Topology*. I am responsible for all faults in this document, mathematical or otherwise. Feel free to message me with any suggestions or corrections at dyang5@swarthmore.edu.

Contents

1	Discrete Probability Distributions	2
1.2	Indicator Variables	2
2	Continuous Random Variables	5
2.2	The Differential Argument and the Gamma Distribution	5

1 Discrete Probability Distributions

1.2 Indicator Variables

- a) Define $I(A)$ to be an indicator variable for the event A , meaning $I(A) = 1$ if A occurs and $I(A) = 0$ if A^c occurs. Relate this to a Bernoulli random variable. Show how an indicator variable is the *fundamental bridge* between probability and expected value, in that $P(A) = E(I(A))$. Use this to prove Boole's inequality: $P(A_1 \cup A_2 \cup \dots \cup A_n) \leq P(A_1) + P(A_2) + \dots + P(A_n)$. Try to think of a non-trivial example.

We can write $I(A)$ as

$$I(A) = \begin{cases} 1 & \text{if } A \\ 0 & \text{if } A^c \end{cases}$$

where A occurs with probability of $P(A)$, and A^c occurs with probability $1 - P(A)$. This is equivalent to a $\text{Bern}(P(A))$ random variable.

For the fundamental bridge, note that $E[I(A)] = P(A) \cdot 1 + (1 - P(A)) \cdot 0 = P(A)$.

To prove Boole's Inequality, we will show that $P(A_1 \cup A_2 \cup \dots \cup A_n) \leq P(A_1) + P(A_2) + \dots + P(A_n)$. Rewriting the probability values on the left and right hand sides as expected values of indicator variables, we know that

$$P(A_1 \cup A_2 \cup \dots \cup A_n) = E[I_{A_1 \cup A_2 \cup \dots \cup A_n}].$$

On the other hand,

$$P(A_1) + P(A_2) + \dots + P(A_n) = E[I_{A_1}] + E[I_{A_2}] + \dots + E[I_{A_n}] = E[I_{A_1} + I_{A_2} + \dots + I_{A_n}]$$

Thus, to prove Boole's inequality, it suffices to show that

$$E[I_{A_1 \cup A_2 \cup \dots \cup A_n}] \leq E[I_{A_1} + I_{A_2} + \dots + I_{A_n}].$$

Note that $I_{A_1 \cup A_2 \cup \dots \cup A_n}$ can only be either 0 or 1, since it is an indicator. In the former case, none of A_1 to A_n have occurred, so $I_{A_1} + I_{A_2} + \dots + I_{A_n} = 0$. In the latter case, if $I_{A_1 \cup A_2 \cup \dots \cup A_n} = 1$, then at least one of A_1 to A_n has occurred, so $I_{A_1} + I_{A_2} + \dots + I_{A_n} \geq 1$.

It follows that

$$I_{A_1 \cup A_2 \cup \dots \cup A_n} \leq I_{A_1} + I_{A_2} + \dots + I_{A_n}.$$

Taking the expected value of both sides, we arrive at Boole's Inequality.

Example of Boole's Inequality: Let A represent the event of a fair coin flip; $A_i = 1$ if flip i is heads, and $A_i = 0$ if it is tails. Boole's Inequality tells us that if we flip the coin 5 times, the probability we flip at least one heads is less than or equal to 5 times the probability we flip a heads on any single coin flip. Thus, the probability we flip at least one heads is at most $5 \cdot \frac{1}{2} = \frac{5}{2}$; this is trivial as this is greater than 1.

- b) A special case of Boole's inequality occurs when the events all have the same probability. Suppose n graduates all throw their caps in the air and then retrieve a cap at random. Find an expression for the probability that none of the students retrieve their own cap (a derangement). Find the limit of this probability if the number of caps $n \rightarrow \infty$. *Hint: For $i = 1, \dots, n$, let A_i represent the event that person i retrieves their own cap. Then $(A_1 \cup A_2 \cup \dots \cup A_n)^c$ is the event that nobody ends up with their own cap.*

The probability of a derangement is

$$P(A_1 \cup A_2 \cup \dots \cup A_n)^c = 1 - P(A_1 \cup A_2 \cup \dots \cup A_n).$$

Taking the limit of this expression as $n \rightarrow \infty$ and using the Principle of Inclusion Exclusion, we know that this

$$\begin{aligned} \lim_{n \rightarrow \infty} 1 - P(A_1 \cup A_2 \cup \dots \cup A_n) &= 1 - \left[\sum_{k=1}^n P(A_i) - \sum_{i < j} P(A_i \cap A_j) + \sum_{i < j < k} P(A_i \cap A_j \cap A_k) - \dots \right] \\ &= \lim_{n \rightarrow \infty} 1 - \left[n \cdot \frac{1}{n} - \binom{n}{2} \left(\frac{1}{n} \cdot \frac{1}{n-1} \right) + \binom{n}{3} \left(\frac{1}{n} \cdot \frac{1}{n-1} \cdot \frac{1}{n-2} \right) \right] \end{aligned}$$

Simplifying, this becomes

$$\lim_{n \rightarrow \infty} 1 - \left[1 - \frac{1}{2!} + \frac{1}{3!} - \frac{1}{4!} + \dots \right] = \lim_{n \rightarrow \infty} \frac{1}{2!} - \frac{1}{3!} + \frac{1}{4!} - \dots$$

Recall the Taylor Expansion of e^x : $e^x = \sum_{k=0}^{\infty} \frac{x^k}{k!}$. We recognize the above expression as e^{-1} :

$$\begin{aligned} e^{-1} &= \sum_{k=0}^{\infty} \frac{(-1)^k}{k!} = \lim_{n \rightarrow \infty} \left(1 - 1 + \frac{1}{2!} - \frac{1}{3!} + \frac{1}{4!} - \dots \right) \\ &= \lim_{n \rightarrow \infty} \frac{1}{2!} - \frac{1}{3!} + \frac{1}{4!} - \dots \end{aligned}$$

Thus,

$$\lim_{n \rightarrow \infty} P(A_1 \cup A_2 \cup \dots \cup A_n)^c = \boxed{\frac{1}{e}}.$$

- c) In the caps example, let X represent the number of graduates who retrieve their own cap. Explain why the distribution of X is approximately Poisson(1) when n is large (see 1(c)). Compare the exact probabilities of $X = 0$ and $X = 1$ to the corresponding Poisson probabilities when $n = 5$.

Note that the probability that a given graduate receives their own cap (assuming nothing about all other graduate cap arrangements) is $p = \frac{1}{n}$. Though we are essentially sampling without replacement when throwing all the graduate caps in the air and retrieving them at random, we know from problem 1(b) that the distribution X for the number of graduates who receive their own cap converges to Binom(n, p) when n is large.

Furthermore, note that $\lambda = np = n \frac{1}{n} = 1$ is fixed. Consequently, the limit of $P(X = x)$ as n is large, by problem 1(c), is simply $\text{Poisson}(\lambda) = \text{Poisson}(1)$. We conclude that the distribution of X is approximately $\text{Poisson}(1)$ when n is large.

Using the approximation $X \sim \text{Poisson}(1)$ for large n , we can approximate the probability of a derangement

$$f_x(x = 0, \lambda = 1) = \frac{1^0 e^{-1}}{0!} = \frac{1}{e}$$

and the probability that exactly one graduate gets their own cap:

$$f_x(x = 1, \lambda = 1) = \frac{1^1 e^{-1}}{1!} = \frac{1}{e}.$$

We can also compare these approximations with the exact probabilities of $X = 0$ and $X = 1$ for $n = 5$. Note that the probability of a derangement for $n = 5$ can be calculated using the formula from 2(b):

$$\begin{aligned} P(X = 0) &= 1 - \left[5 \cdot \frac{1}{5} - \binom{5}{2} \frac{1}{5} \cdot \frac{1}{4} + \binom{5}{3} \frac{1}{5} \cdot \frac{1}{4} \cdot \frac{1}{3} - \binom{5}{4} \frac{1}{5} \cdot \frac{1}{4} \cdot \frac{1}{3} \cdot \frac{1}{2} + \binom{5}{5} \frac{1}{5} \cdot \frac{1}{4} \cdot \frac{1}{3} \cdot \frac{1}{2} \cdot \frac{1}{1} \right] \\ &= \frac{11}{30} \approx 0.3\bar{6} \end{aligned}$$

Note that the probability that $X = 1$ can be calculated by “picking” the graduate to get their own cap (of which there are 5 possibilities), multiplying this by the probability that the chosen graduate gets their own hat ($\frac{1}{5}$), and then multiplying this by the probability of a derangement with $n = 4$ (each of the remaining four graduates does not get their own cap):

$$\begin{aligned} P(X = 1) &= 5 \cdot \frac{1}{5} \cdot P(\text{derangement for } n = 4 \text{ students}) \\ &= 1 - \left[4 \cdot \frac{1}{4} - \binom{4}{2} \frac{1}{4} \cdot \frac{1}{3} + \binom{4}{3} \frac{1}{4} \cdot \frac{1}{3} \cdot \frac{1}{2} - \binom{4}{4} \frac{1}{4} \cdot \frac{1}{3} \cdot \frac{1}{2} \cdot \frac{1}{1} \right] \\ &= \frac{3}{8} = 0.375 \end{aligned}$$

We can see that even for small n (in our case, $n = 5$), the expected probabilities approach $\frac{1}{e} \approx 0.36788$.

2 Continuous Random Variables

2.2 The Differential Argument and the Gamma Distribution

a) By definition,

$$P(X \in [x, x + dx)) = \int_x^{x+dx} f_x(y) dy.$$

For small deviation dx , we can approximate the integral as $f_x(x) [(x + dx) - x] = f_x(x) dx$.

Note that this expression becomes exact when dx approaches 0: formally, we have

$$\lim_{dx \rightarrow 0} \frac{P(X \in [x, x + dx))}{dx} = \lim_{dx \rightarrow 0} \frac{F(x + dx) - F(x)}{dx} = f_x(x)$$

because the second expression is the limit form of the derivative of the CDF at x , which is precisely the value of the PDF at x : $f_x(x)$.

We can use the Differential argument to derive the Exponential density function. Since the CDF of an Exponential variable at time t measures the probability that an event has occurred by time t , we can measure the probability that the first Poisson event occurs in the time interval $[t, t + dt)$ by subtracting the CDF at times $t + dt$ and time t :

$$\begin{aligned} P(\text{first occurrence in } [t, t + dt)) &= (1 - e^{-\lambda(t+dt)}) - (1 - e^{-\lambda t}) \\ &= e^{-\lambda t} - e^{-\lambda(t+dt)} \end{aligned}$$

Dividing this expression by dt and taking the limit as dt approaches 0, we derive the Exponential variable density at time t :

$$f_t(t) = \lim_{dt \rightarrow 0} \frac{e^{-\lambda t} - e^{-\lambda(t+dt)}}{dt}.$$

Using L'Hopital's Rule, this becomes

$$\begin{aligned} f_t(t) &= \lim_{dt \rightarrow 0} \frac{e^{-\lambda t} - e^{-\lambda(t+dt)}}{dt} \\ &= \lim_{dt \rightarrow 0} \frac{\lambda e^{-\lambda(t+dt)}}{1} \\ &= \lambda e^{-\lambda t}. \end{aligned}$$

b) We can similarly use the differential argument to derive the Gamma(k, λ) density; let X be the time of the k th event for a Poisson process with rate λ . We can model the probability of $k - 1$ events occurring before time x using $\text{Pois}(\lambda x)$, where λx represents the expected number of events to occur in x units of time. Similarly, we can model the probability of 1 event occurring in the interval $[x, x + dx)$ using $\text{Pois}(\lambda dx)$.

Thus, the probability of $k - 1$ events occurring before time x and a k th event occurring in $[x, x + dx)$ is

$$\begin{aligned} & P(k - 1 \text{ events before time } x)P(1 \text{ event before time } t) \\ &= \frac{(\lambda x)^{k-1} e^{-\lambda x}}{(k-1)!} \frac{(\lambda dx)^1 e^{-\lambda dx}}{1!} \\ &= \frac{\lambda^k e^{-\lambda(x+dx)} dx}{(k-1)!} x^{k-1} \end{aligned}$$

Dividing this probability by dx and taking the limit as dx approaches 0, we find that

$$\begin{aligned} f_x(k, \lambda) &= \lim_{dx \rightarrow 0} \frac{\left(\frac{\lambda^k e^{-\lambda(x+dx)} dx}{(k-1)!} x^{k-1} \right)}{dx} \\ &= \lim_{dx \rightarrow 0} \frac{\lambda^k e^{-\lambda(x+dx)}}{(k-1)!} x^{k-1} \\ &= \frac{\lambda^k e^{-\lambda x}}{(k-1)!} x^{k-1} \end{aligned}$$

which matches the $\text{Gamma}(k, \lambda)$ density we expect.

Note that if $X_1 \sim \text{Gamma}(k_1, \lambda)$ and $X_2 \sim \text{Gamma}(k_2, \lambda)$ are independent, intuitively, $X_1 + X_2 \sim \text{Gamma}(k_1 + k_2, \lambda)$, as we can think of X_1 and X_2 representing the sum for waiting times in two non-overlapping time intervals. We will reserve discussion for why the sum of two independent Gamma variables with different λ values is not Gamma for part (d).

c) Recall the form of the Gamma PDF derived in part (b):

$$f_x(k, \lambda) = \frac{\lambda^k e^{-\lambda x}}{(k-1)!} x^{k-1}.$$

Note that our derivation measures the average wait time for k events to occur, where k is an integer. However, the Gamma Distribution also extends to values of k which are not necessarily integers – all positive real k , in fact. To understand the extension and subsequent definition of the Gamma Distribution, we introduce the notion of a Gamma Function, an extension of the factorial function for real numbers. For integer k , $\Gamma(k) = (k-1)!$, which matches with the normalizing constant in our present PDF.

In general, if α is a positive real value replacing our k parameter, we define the PDF of $X \sim \text{Gamma}(\alpha, \lambda)$ to be

$$f_x(\alpha, \lambda) = \frac{\lambda^\alpha e^{-\lambda x}}{\Gamma(\alpha)} x^{\alpha-1}.$$

We can derive the definition of Gamma Function by forcing this PDF to integrate to 1 as x ranges from 0 to ∞ . Note that

$$\int_0^\infty \frac{\lambda^\alpha e^{-\lambda x}}{\Gamma(\alpha)} x^{\alpha-1} dx = \frac{\lambda^\alpha}{\Gamma(\alpha)} \int_0^\infty e^{-\lambda x} x^{\alpha-1} dx.$$

Apply the change of variables $y = \lambda x$. It follows that $x = \frac{y}{\lambda}$ so $dx = \frac{1}{\lambda} dy$. Our integral now becomes

$$\frac{\lambda^\alpha}{\Gamma(\alpha)} \int_0^\infty e^{-\lambda x} x^{\alpha-1} dx = \frac{\lambda^\alpha}{\Gamma(\alpha)} \int_0^\infty e^{-y} \left(\frac{y}{\lambda}\right)^{\alpha-1} \left(\frac{1}{\lambda} dy\right).$$

Simplifying and setting the resulting expression to 1 (since our PDF should integrate to 1), we find that

$$\frac{\int_0^\infty e^{-y} y^{\alpha-1} dy}{\Gamma(\alpha)} = 1.$$

This inspires our definition of the **Gamma Function**:

$$\Gamma(\alpha) = \int_0^\infty e^{-y} y^{\alpha-1} dy$$

which is defined for any positive real values of the parameter α .

With the above definition of the Gamma Function, we can derive a nice recursive definition of the Gamma Function, one which will illuminate its relationship with the factorial function.

Note that by definition, $\Gamma(\alpha + 1) = \int_0^\infty e^{-y} y^\alpha dy$.

Using Integration by Parts, we find that

$$\begin{aligned} \Gamma(\alpha + 1) &= [y^\alpha (-e^{-y})]_0^\infty - \int_0^\infty (-e^{-y}) \alpha y^\alpha dy \\ &= 0 + \alpha \int_0^\infty (e^{-y}) y^\alpha dy \\ &= \alpha \Gamma(\alpha). \end{aligned}$$

Since $\Gamma(1) = \int_0^\infty e^{-y} y^{1-1} dy = 1$ by definition, it follows recursively that $\Gamma(\alpha) = (\alpha - 1)!$.

- d) A final powerful property of the Gamma distribution is that for any constant $c > 0$, if $X \sim \text{Gamma}(\alpha, \lambda)$, then $Y = cX \sim \text{Gamma}\left(\alpha, \frac{\lambda}{c}\right)$. This property can be thought of as a changing in the units for the λ parameter: intuitively, if X measures the waiting time for α events to occur given a rate of λ in some unit of time (e.g seconds), $Y = cX$ may measure the waiting time for α events to occur given a rate of λ in a new unit of time (e.g. minutes, where $c = \frac{1}{60}$).

This intuition, which relates the λ parameter to a given unit of time, also gives us an idea of why the sum of two Gamma variables with different λ values is not itself Gamma: we cannot sum the waiting times for events of processes measured in different units of time.