Poisson Merging

The Poisson distribution is used to model rare events, such as the number of customers who enter a store in the next hour. The theoretical justification for this modeling assumption is that the limit of the binomial distribution, as the number of trials $n$ goes to $\infty$ and the probability of success per trial $p$ goes to 0, such that $np \to \lambda > 0$, is the Poisson distribution with mean $\lambda$.

Now, suppose we have two independent streams of rare events (for instance, the number of female customers and male customers entering a store), and we do not care to distinguish between the two types of rare events. Can the combined stream of events be modeled as a Poisson distribution?

Mathematically, let $X$ and $Y$ be independent Poisson random variables with means $\lambda$ and $\mu$ respectively. Prove that $X + Y \sim \text{Poisson}(\lambda + \mu)$. (This is known as Poisson merging.) Note that it is not sufficient to use linearity of expectation to say that $X + Y$ has mean $\lambda + \mu$. You are asked to prove that the distribution of $X + Y$ is Poisson.

Note: This property will be extensively used when we discuss Poisson processes.

**Solution:**

For $z \in \mathbb{N}$,

$$P(X + Y = z) = \sum_{j=0}^{z} \frac{e^{-\lambda} \lambda^j}{j!} \frac{e^{-\mu} \mu^{z-j}}{(z-j)!} = \frac{e^{-\lambda - \mu} \sum_{j=0}^{z} \frac{z!}{j!(z-j)!} \lambda^j \mu^{z-j}}{z!}$$

$$= \frac{e^{-(\lambda + \mu)} \sum_{j=0}^{z} \binom{z}{j} \lambda^j \mu^{z-j} \frac{z!}{z!}}{z!} = \frac{e^{-\lambda - \mu} (\lambda + \mu)^z}{z!}.$$

Here is some intuition for why Poisson merging holds. If we are interested in the number of customers entering a store in the next hour, we can discretize the hour into $n$ time intervals, where $n$ is a positive integer. In each time interval, independently of other time intervals, the probability that a female customer enters the store is $\lambda/n$ and the probability that a male customer enters the store is $\mu/n$. Since the two types of customers are assumed to be independent, the probability that a customer, disregarding gender, enters the store is $\lambda/n + \mu/n - \lambda\mu/n^2$. As $n \to \infty$, the number of customers who enter the store in the hour is Poisson with mean $\lim_{n \to \infty} n[\lambda/n + \mu/n - \lambda\mu/n^2] = \lambda + \mu$.

We will be able to give a much easier proof of this result after we introduce transforms of random variables.
2. Sampling without Replacement

Suppose you have \( N \) items, \( G \) of which are good and \( B \) of which are bad (where \( B, G, \) and \( N \) are positive integers, \( B + G = N \)). You start to draw items without replacement, and suppose that the first good item appears on draw \( X \). Compute the mean and variance of \( X \).

**Solution:**

The expectation is computed with a clever trick: let \( X_i \) be the indicator that the \( i \)th bad item appears before the first good item, for \( i = 1, \ldots, B \). Then, \( X = 1 + \sum_{i=1}^{B} X_i \), and by linearity of expectation,

\[
\mathbb{E}[X] = 1 + B \mathbb{E}[X_1] = 1 + \frac{B}{G+1} = \frac{N+1}{G+1}.
\]

Observe that \( \text{var} \ X = \text{var}(X - 1) \). Using the same indicators, we compute \( \mathbb{E}[(X - 1)^2] \).

\[
\mathbb{E}[(X - 1)^2] = B \mathbb{E}[X_1^2] + B(B - 1) \mathbb{E}[X_1 X_2]
\]

\[
= \frac{B}{G+1} + \frac{2B(B - 1)}{(G+1)(G+2)}
\]

Therefore, our answer is

\[
\text{var} \ X = \frac{B}{G+1} + \frac{2B(B - 1)}{(G+1)(G+2)} - \left( \frac{B}{G+1} \right)^2.
\]

With a little algebra, we can actually simplify the result.

\[
\text{var} \ X = \frac{B(G + 1)(G + 2) + 2B(B - 1)(G + 1) - B^2(G + 2)}{(G+1)^2(G+2)}
\]

\[
= \frac{BG(N + 1)}{(G + 1)^2(G + 2)}
\]

3. Clustering Coefficient

This problem will explore an important probabilistic concept of clustering that is widely used in machine learning applications today. Consider \( n \) students, where \( n \) is a positive integer. For each pair of students \( i, j \in \{1, \ldots, n\}, i \neq j \), they are friends with probability \( p \), independently of other pairs. We assume that friendship is mutual. We can see that the friendship among the \( n \) students can be represented by an undirected graph \( G \). Let \( N(i) \) be the number of friends of student \( i \) and \( T(i) \) be the number of triangles attached to student \( i \). We define the **clustering coefficient** \( C(i) \) for student \( i \) as follows:

\[
C(i) = \frac{T(i)}{\binom{N(i)}{2}}.
\]
The clustering coefficient is not defined for the students who have no friends. An example is shown in Figure 1. Student 3 has 4 friends (1, 2, 4, 5) and there are two triangles attached to student 3, i.e., triangle 1-2-3 and triangle 2-3-4. Therefore $C(3) = 2/\binom{4}{2} = 1/3$.

Find $\mathbb{E}[C(i) \mid N(i) \geq 2]$.

**Solution:**

First, we compute $\mathbb{E}[C(i) \mid N(i) = k]$, for $k \in \{2, \ldots, n-1\}$. Suppose that student $i$ has friends $f_1, \ldots, f_k$. We can see that $T(i)$ equals the number of friend pairs among $\{f_1, \ldots, f_k\}$. Since there are $\binom{k}{2}$ possible pairs and each pair of students are friends with probability $p$, independently of other pairs, we know that the expected number of friend pairs among $\{f_1, \ldots, f_k\}$ is $\binom{k}{2}p$. Then we have

$$\mathbb{E}[C(i) \mid N(i) = k] = \frac{\binom{k}{2}p}{\binom{k}{2}} = p.$$

Since this is true for all $k \geq 2$, we have $\mathbb{E}[C(i) \mid N(i) \geq 2] = p$. 

![Figure 1: Friendship and clustering coefficient.](image)