

DAI Assignment-2

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1 Mathemagic

1.1 Task A

For a Bernoulli random variable $X \sim Ber(p)$, $P[X = 0] = 1 - p$, $P[X = 1] = p$ and $P[X = n] = 0 \forall n \geq 2$.

$$\begin{aligned} G_{Ber}(z) &= \sum_{n=0}^{\infty} P[X = n] z^n \\ &= P[X = 0] + P[X = 1]z \\ G_{Ber} &= (1 - p) + pz \end{aligned}$$

1.2 Task B

When $X \sim Bin(n, p)$, $P[X = k] = \binom{n}{k} p^k (1 - p)^{n-k} \forall k \in \mathbb{Z}, 0 \leq k \leq n$. $P[X = k] = 0 \forall k > n$.

$$\begin{aligned} G_{Bin}(z) &= \sum_{k=0}^{\infty} P[X = k] z^k \\ &= \sum_{k=0}^n \binom{n}{k} p^k (1 - p)^{n-k} z^k \\ &= \sum_{k=0}^n \binom{n}{k} (pz)^k (1 - p)^{n-k} \\ &= (pz + (1 - p))^n \\ G_{Bin}(z) &= G_{Ber}(z)^n \end{aligned}$$

1.3 Task C

Let X_1 and X_2 be two random variables which take up non-negative integers and let $X = X_1 + X_2$.

$$\begin{aligned}
G_X(z) &= \sum_{n=0}^{\infty} P[X = n]z^n \\
&= \sum_{n=0}^{\infty} \sum_{i=0}^n (P[X_1 = i]P[X_2 = n - i])z^n \\
&= \sum_{i=0}^{\infty} \sum_{n=i}^{\infty} (P[X_1 = i]P[X_2 = n - i])z^n \\
&= \sum_{i=0}^{\infty} \sum_{n=i}^{\infty} (P[X_1 = i]z^i)(P[X_2 = n - i]z^{n-i}) \\
&= \sum_{i=0}^{\infty} P[X_1 = i]z^i \sum_{n=i}^{\infty} P[X_2 = n - i]z^{n-i} \\
&= \sum_{i=0}^{\infty} P[X_1 = i]z^i \sum_{n=0}^{\infty} P[X_2 = n]z^n \\
G_X(z) &= G_{X_1}(z)G_{X_2}(z)
\end{aligned}$$

For $k = 1$, $G_{\Sigma}(z) = G(z)^k$.

If for $k = n - 1$, $G_{\Sigma}(z) = G(z)^k$, then for $k = n$,

$$\begin{aligned}
G_{\Sigma}(z) &= G_{X_1+X_2+\dots+X_{n-1}}(z)G_{X_n}(z) \\
&= \prod_{i=1}^n G_{X_i}(z)G_{\Sigma}(z) = G(z)^k
\end{aligned}$$

From the *Principle of Mathematical Induction*, for all $k \in \mathbb{N}$, $G_{\Sigma}(z) = G(z)^k$

1.4 Task D

When $X \sim \text{Geo}(p)$, $P[X = n] = (1 - p)^{n-1}p$ and $P[X = 0] = 0$.

$$\begin{aligned}
G_{\text{Geo}}(z) &= \sum_{n=0}^{\infty} P[X = n]z^n \\
&= \sum_{n=1}^{\infty} (1 - p)^{n-1}pz^n \\
&= pz \sum_{n=1}^{\infty} ((1 - p)z)^{n-1} \\
&= \frac{pz}{1 - (1 - p)z}
\end{aligned}$$

1.5 Task E

$X \sim \text{Bin}(n, p)$ and $Y \sim \text{NegBin}(n, p)$. $Y = \sum_{k=1}^n Y_k$ where $Y_k \sim \text{Geo}(p)$.

$$\begin{aligned}
 G(Y) &= G(Y_1 + Y_2 + \dots + Y_n) \\
 &= G(Y_1)G(Y_2) \dots G(Y_n) \\
 &= \left(\frac{pz}{1 - (1-p)z} \right)^n \\
 G_Y^{(n,p)}(z) &= \left(\frac{pz}{1 - (1-p)z} \right)^n \\
 &= \left(\frac{1}{\frac{1}{pz} + (1 - \frac{1}{p})} \right)^n \\
 G_X^{(n,p^{-1})}(z^{-1}) &= \left(\frac{1}{pz} + (1 - \frac{1}{p}) \right)^n \\
 \implies G_Y^{(n,p)}(z) &= \left(G_X^{(n,p^{-1})}(z^{-1}) \right)^{-1}
 \end{aligned}$$

1.6 Task F

$$P[Y = k] = \binom{k-1}{n-1} p^n (1-p)^{k-n}.$$

$$\begin{aligned}
 G_Y^{(n,p)}(z) &= \sum_{k=0}^{\infty} P[Y = k] z^k \\
 &= \sum_{k=n}^{\infty} \binom{k-1}{n-1} p^n (1-p)^{k-n} z^k \\
 \left(\frac{1}{pz} + \left(1 - \frac{1}{p} \right) \right)^{-n} &= \sum_{k=n}^{\infty} \binom{k-1}{n-1} p^n (1-p)^{k-n} z^k
 \end{aligned}$$

Substitute $x = z$, $p = 2$

$$\begin{aligned}
\left(\frac{1}{2x} + \frac{1}{2}\right)^{-n} &= \sum_{k=n}^{\infty} \binom{k-1}{n-1} 2^n (-1)^{k-n} x^k \\
x^n (1+x)^{-n} &= \sum_{k=n}^{\infty} \binom{k-1}{n-1} (-1)^{k-n} x^k \\
(1+x)^{-n} &= \sum_{k=n}^{\infty} \binom{k-1}{n-1} (-1)^{k-n} x^{k-n} \\
(1+x)^{-n} &= \sum_{r=0}^{\infty} \binom{n+r-1}{n-1} (-1)^r x^r \\
(1+x)^{-n} &= \sum_{r=0}^{\infty} \binom{n+r-1}{r} (-1)^r x^r
\end{aligned}$$

1.7 Task G

$$\begin{aligned}
G(z) &= \sum_{n=0}^{\infty} P[X = n] z^n \\
G'(z) &= \sum_{n=0}^{\infty} n P[X = n] z^{n-1} \\
G'(1) &= \sum_{n=0}^{\infty} n P[X = n] \\
G'(1) &= E[X]
\end{aligned}$$

For Bernoulli random variable $X \sim \text{Ber}(p)$,

$$\begin{aligned}
G_{\text{Ber}}(z) &= (1-p) + pz \\
G'_{\text{Ber}}(z) &= p \\
G'_{\text{Ber}}(1) &= p \\
E[X] &= p
\end{aligned}$$

For Binomial random variable $X \sim \text{Bin}(n, p)$,

$$\begin{aligned}
G_{\text{Bin}}(z) &= (pz + (1-p))^n \\
G'_{\text{Bin}}(z) &= np(pz + (1-p))^{n-1} \\
G'_{\text{Bin}}(1) &= np \\
E[X] &= np
\end{aligned}$$

For Geometric random variable $X \sim Geo(p)$,

$$\begin{aligned} G_{Geo}(z) &= \frac{pz}{1 - (1-p)z} \\ G'_{Geo}(z) &= \frac{p}{(1 - (1-p)z)^2} \\ G'_{Geo}(1) &= \frac{p}{p^2} \\ E[X] &= \frac{1}{p} \end{aligned}$$

For Negative Binomial random variable $X \sim NegBin(n, p)$,

$$\begin{aligned} G_{NegBin}(z) &= \left(\frac{pz}{1 - (1-p)z} \right)^n \\ G'_{NegBin}(z) &= n \left(\frac{pz}{1 - (1-p)z} \right)^{n-1} \frac{p}{(1 - (1-p)z)^2} \\ G'_{NegBin}(1) &= n \left(\frac{p}{p} \right)^{n-1} \frac{p}{p^2} \\ E[X] &= \frac{n}{p} \end{aligned}$$

2 Normal Sampling

2.1 Task A

To prove that Y is uniformly distributed in $[0,1]$, we need to prove that for an arbitrary interval $[a,b]$ in $[0, 1]$, Y lies in $[a, b]$ with probability $b - a$.

The probability that $a \leq Y \leq b$ is the probability that the randomly chosen X is such that $a \leq F_X(x) \leq b$. The cumulative probability of x being in the interval $[a_0, b_0]$ such that $F_X(a_0) = a$ and $F_X(b_0) = b$ is $b - a$, since the cumulative probability that $x \leq b_0$ is b , and the cumulative probability of $x \leq a_0$ is a , hence probability that $a_0 \leq x \leq b_0$ is $b - a$. Our condition that $F_X()$ is invertible guarantees that the \leq can be replaced with $<$, since it cannot be that $\lim_{x \rightarrow a_0^-} \neq \lim_{x \rightarrow a_0^+}$, otherwise between a_0^- and a_0^+ , all elements would be mapped to by a_0 .

2.2 Task B

Given a sample y , let us return $F_X^{-1}(y)$. To prove that this has the same CDF as X , we need to prove that if $F_X(a_0) = a$ and $F_X(b_0) = b$, the probability of getting $a_0 \leq F_X^{-1}(y) \leq b_0$ is $b - a$.

But this is fairly straightforward, since $a_0 \leq F_X^{-1}(y) \leq b_0 \iff a \leq y \leq b$, and the probability of getting $a \leq y \leq b$ is $b - a$.

Thus, this is the required function.

2.3 Task C

Code provided in 2c.ipynb.

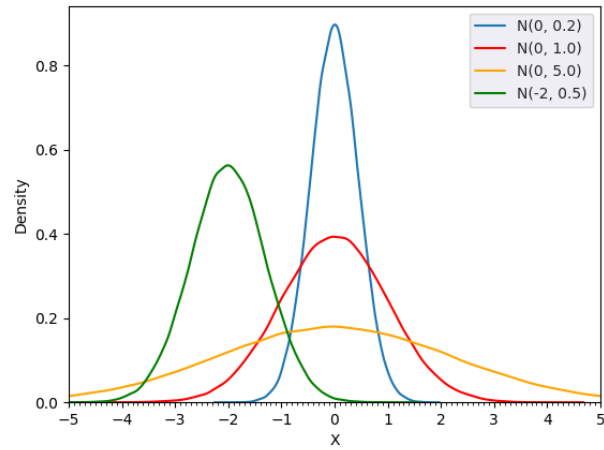


Figure 1: Histogram of the samples generated

2.4 Task D

Code provided in 2d.ipynb.

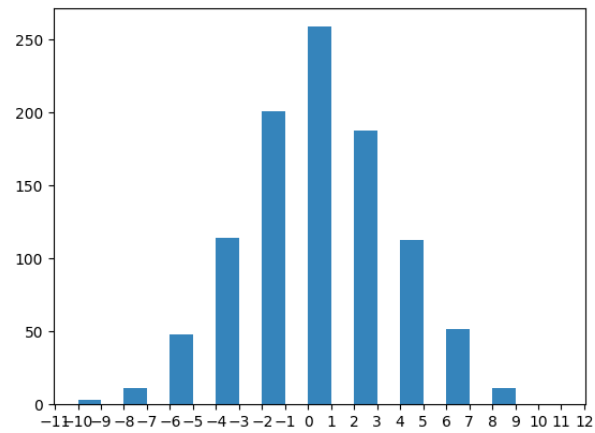


Figure 2: $h=10$

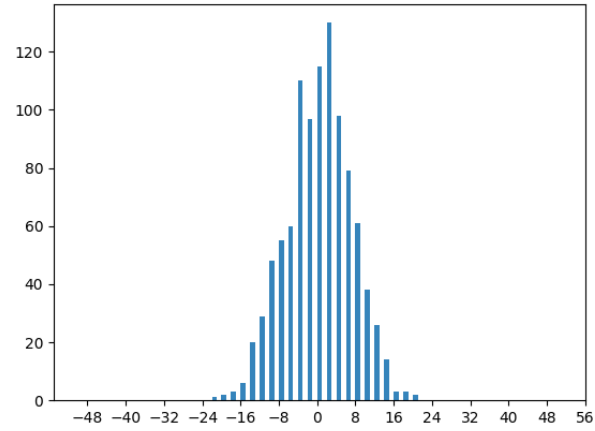


Figure 3: $h=50$

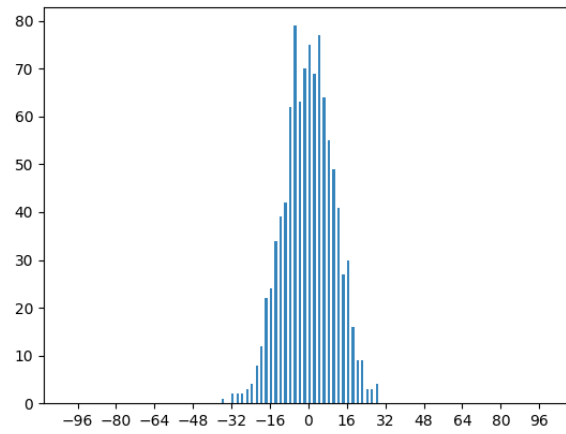


Figure 4: $h=100$

For $h=100$ alone, for better visibility, I have also written code with bins set to increment every 2 pockets. To observe the property of only even indexed bins being filled, simply replace `range(-100, 102, 2)` with `range(-100, 102, 1)`.

2.5 Task E

$$P_h[X = 2i] = \frac{\binom{2k}{i+k}}{2^{2k}}$$

Since the likelihood of a ball arriving at pocket i is equal to the likelihood of having $i+k$ collisions which move it to the right within the $2k$ possible collisions overall.

Applying Stirling's approximations,

$$\begin{aligned} P_h[X = 2j] &\approx \frac{k^{2k} \sqrt{4\pi k}}{(k+j)^{k+j} \sqrt{2\pi(k+j)} (k-j)^{k-j} \sqrt{2\pi(k-j)}} \\ &\approx \frac{k^{2k} \sqrt{2k} (k-j)^j}{(k^2 - j^2)^k \sqrt{2\pi(k^2 - j^2)} (k+j)^j} \\ &\approx \frac{1}{\sqrt{\pi k}} \frac{k^{2k} (k-j)^j}{(k^2)^k (k+j)^j} && \text{(By approximating } k^2 - j^2 \approx j^2) \\ &= \frac{1}{\sqrt{\pi k}} \left(1 - \frac{2j}{k+j}\right)^j \end{aligned}$$

Now, we independently approximate $\left(1 - \frac{2j}{k+j}\right)^j$ by taking its logarithm and using the property that for small x , $\ln(1-x) \approx -x$.

$$\begin{aligned} \ln \left(\left(1 - \frac{2j}{k+j}\right)^j \right) &= j \ln \left(1 - \frac{2j}{k+j}\right) \\ &\approx -\frac{2j^2}{k+j} \\ \left(1 - \frac{2j}{k+j}\right)^j &\approx e^{-\frac{2j^2}{k}} \end{aligned}$$

Setting $i = 2j$ as required, we get

$$\begin{aligned} P_h[X = i] &\approx \frac{1}{\sqrt{\pi k}} e^{-\frac{i^2}{2k}} \\ &= \frac{1}{\sqrt{2\pi k}} e^{-\frac{i^2}{h}} \end{aligned}$$

As required.

3 Quality in Inequalities

3.1 Task A

$$\begin{aligned}\mathbb{E}[X] &= \int_0^\infty X P(X) dX \\ &= \int_0^a X P(X) dX + \int_a^\infty X P(X) dX \\ &\geq \int_0^a X P(X) dX + \int_a^\infty a P(X) dX \\ &\geq \int_0^a X P(X) dX + a P[X \geq a] \\ &\geq a P[X \geq a]\end{aligned}$$

Here, we have used the fact that $\int_0^a X P(X) dX$ is ≥ 0 since $X \geq 0$ and $P(X) \geq 0$ everywhere in that interval.

From the above result, we get

$$\frac{\mathbb{E}[X]}{a} \geq P[X \geq a]$$

Intuitively, this corresponds to saying that if there is a high probability that $X \geq a$, then we can also expect that a random sample will give us a value greater than a .

3.2 Task B

First, we will prove a result which is useful later

$$\mathbb{E}\left[\left(X - \mathbb{E}[X] + \frac{\sigma^2}{\tau}\right)^2\right] = \text{Var}\left(X - \mathbb{E}[X] + \frac{\sigma^2}{\tau}\right) + \left(\mathbb{E}\left[X - \mathbb{E}[X] + \frac{\sigma^2}{\tau}\right]\right)^2$$

Now, since the variance of a distribution does not change on adding a constant to the distribution, and since the expectation value of the sum of terms is the sum of expectations of the terms, we get that this is equal to

$$\mathbb{E}\left[\left(X - \mathbb{E}[X] + \frac{\sigma^2}{\tau}\right)^2\right] = \sigma^2 + \left(\frac{\sigma^2}{\tau}\right)^2$$

Now, we notice that whenever $X - \mu \geq \tau$, it also holds that $\left(X - \mu + \frac{\sigma^2}{\tau}\right)^2 \geq \left(\tau + \frac{\sigma^2}{\tau}\right)^2$. Since we are assuming that $x - \mu + \frac{\sigma^2}{\tau} \geq \tau + \frac{\sigma^2}{\tau} \geq 0$, this result is proven by the fact that x^2 is an increasing function over the non-negative reals.

Thus, $P[X - \mu \geq \tau] \leq P\left[\left(X - \mu + \frac{\sigma^2}{\tau}\right)^2 \geq \left(\tau + \frac{\sigma^2}{\tau}\right)^2\right]$.

Using Markov's inequality on the above result, we get

$$\begin{aligned} P[X - \mu \geq \tau] &\leq P\left[\left(X - \mu + \frac{\sigma^2}{\tau}\right)^2 \leq \left(\tau + \frac{\sigma^2}{\tau}\right)^2\right] \leq \frac{\sigma^2 + \left(\frac{\sigma^2}{\tau}\right)^2}{\left(\tau + \frac{\sigma^2}{\tau}\right)^2} \\ &= \frac{\sigma^2}{\sigma^2 + \tau^2} \end{aligned}$$

Thus proving our desired result.

3.3 Task C

$$P[X \geq x] = \int_x^\infty P(X) dX$$

$$\begin{aligned} e^{-tx} E[e^{tx}] &= e^{-tx} \int_{-\infty}^\infty e^{tX} P(X) dX \\ &= e^{-tx} \int_{-\infty}^x e^{tX} P(X) dX + e^{-tx} \int_x^\infty e^{tX} P(X) dX \\ &\geq e^{-tx} \int_x^\infty e^{tX} P(X) dX && \text{(since both } P(X) \text{ and } e^{tX} \text{ are positive for all } X) \\ &\geq e^{-tx} e^{tx} \int_x^\infty P(X) dX && \text{(since } e^{tX} \text{ is increasing if } t \geq 0) \\ &= e^{-tx} e^{tx} P[X \geq x] \\ &= P[X \geq x] \end{aligned}$$

This proves that

$$P[X \geq x] \leq e^{-tx} E[e^{tx}] \tag{1}$$

Similarly,

$$P[X \leq x] = \int_{-\infty}^x P(X) dX$$

$$\begin{aligned} e^{-tx} E[e^{tx}] &= e^{-tx} \int_{-\infty}^\infty e^{tX} P(X) dX \\ &= e^{-tx} \int_{-\infty}^x e^{tX} P(X) dX + e^{-tx} \int_x^\infty e^{tX} P(X) dX \\ &\geq e^{-tx} \int_{-\infty}^x e^{tX} P(X) dX && \text{(since both } P(X) \text{ and } e^{tX} \text{ are positive for all } X) \\ &\geq e^{-tx} \cdot e^{tx} \cdot \int_{-\infty}^x P(X) dX && \text{(since } e^{tx} \leq e^{tx'} \text{ where } x \geq x' \text{ when } t \text{ is negative since } e^t \text{ is decreasing)} \\ &= \int_{-\infty}^x P(X) dX \\ &= P[X \leq x] \end{aligned}$$

as required.

3.4 Task D

1. We know, by the linearity of expectation, that

$$\mathbb{E}[Y] = \sum_{i=1}^n \mathbb{E}[X_i] = \sum_{i=1}^n p_i$$

2. For this question, we make use of the first result proved in Task C above.

$$\begin{aligned} P[Y \geq (1 + \delta)\mu] &\leq \frac{\mathbb{E}[e^{tY}]}{e^{(1+\delta)\mu t}} \\ &= \frac{\mathbb{E}[e^{(t \sum_{i=1}^n X_i)}]}{e^{(1+\delta)\mu t}} \end{aligned}$$

We will now prove that for independent random variables, $\mathbb{E}[e^{(t \sum_{i=1}^n X_i)}] = \prod_{i=1}^n \mathbb{E}[e^{tX_i}]$. To prove that, we prove the simpler result that for independent variables, $\mathbb{E}[XY] = \mathbb{E}[X]\mathbb{E}[Y]$.

$$\begin{aligned} \mathbb{E}[XY] &= \int_{-\infty}^{\infty} (xy) p_{X,Y}(x, y) dy dx \\ &= \int_{-\infty}^{\infty} (xy) p_X(x) p_Y(y) dy dx \\ &= \int_{-\infty}^{\infty} x p_X(x) \int_{-\infty}^{\infty} y p_Y(y) dy dx \\ &= \int_{-\infty}^{\infty} x p_X(x) dx \int_{-\infty}^{\infty} y p_Y(y) dy \\ &= \mathbb{E}[X] \mathbb{E}[Y] \end{aligned}$$

Since above, all X_i 's are independent, so are e^{tX_i} for all i . Thus,

$$\begin{aligned} E[e^{(t \sum_{i=1}^n X_i)}] &= \mathbb{E}[e^{tX_1}] E[e^{(t \sum_{i=2}^n X_i)}] \\ &= \mathbb{E}[e^{tX_1}] \mathbb{E}[e^{tX_2}] \mathbb{E}[e^{(t \sum_{i=3}^n X_i)}] \\ &\dots \\ &= \prod_{i=1}^n \mathbb{E}[e^{tX_i}] \end{aligned}$$

For each Bernoulli random variable X_i , it is easily observed that $E[e^{tX_i}] = 1 + (e^t - 1)p_i$. Using this result,

$$E[e^{(t \sum_{i=1}^n X_i)}] = \prod_{i=1}^n (1 + (e^t - 1)p_i)$$

We will now prove $\prod_{i=1}^n (1 + x_i) \leq e^{\sum_{i=1}^n x_i}$ for positive x_i 's.

$$\begin{aligned} \ln \left(\prod_{i=1}^n (1 + x_i) \right) &= \sum_{i=1}^n \ln(1 + x_i) \\ &\leq \sum_{i=1}^n x_i \quad (\text{Well known result that } \ln(1 + x) \leq x) \\ &= \ln \left(e^{\sum_{i=1}^n x_i} \right) \end{aligned}$$

Since our initial assumption in using 1 required $t > 0$ and hence $e^t > 1$, all $(e^t - 1)p_i$ values are positive and we can use the above result. Hence, $\mathbb{E}[e^{tY}] \leq e^{\mu(e^t - 1)}$. Plugging this into ??, we get

$$P[Y \geq (1 + \delta)\mu] \leq \frac{e^{\mu(e^t - 1)}}{e^{(1 + \delta)t\mu}}$$

as required.

3. Since this holds for arbitrary positive t , we can find the t for which the value of $e^{\mu e^t - 1 - (1 + \delta)t}$ is minimum. By differentiation, we observe the minima of the function is when $t = \ln(1 + \delta)$. At the minima, we have

$$e^t - 1 - (1 + \delta)t = \delta - (1 + \delta) \ln(1 + \delta)$$

Using the expansion $\ln(1 + \delta) = \sum_{i=1}^{\infty} \frac{\delta^i (-1)^{i-1}}{i}$,

$$\begin{aligned} \delta - (1 + \delta) \ln(1 + \delta) &= \delta + (1 + \delta) \left(\sum_{i=1}^{\infty} \frac{\delta^i (-1)^i}{i} \right) \\ &= \delta + \sum_{i=1}^{\infty} \frac{\delta^i (-1)^i}{i} + \sum_{i=2}^{\infty} \frac{\delta^i (-1)^{i-1}}{i-1} \\ &= \sum_{i=2}^{\infty} \frac{\delta^i (-1)^{i-1}}{i(i-1)} \end{aligned}$$

This is approximately $-\frac{\delta^2}{2} + \frac{\delta^3}{6}$ for small delta. Thus we get a good upper bound of $e^{-\frac{\mu\delta^2(3-\delta)}{6}}$ for $P[Y \geq (1 + \delta)\mu]$.

If $\delta > 0$, this can be simplified further, in a way that is more useful for us in question 5. Observe that for $x > 0$

$$\ln(1 + x) \geq \frac{2x}{2 + x}$$

This can be seen by observing that at $x=0$, $\ln(1 + x) - \frac{2x}{2+x}$ evaluates to 0 and that its derivative, $\frac{4}{(1+x)(2+x)^2}$ is always non-negative.

Thus,

$$\begin{aligned}\mu(\delta - (1 + \delta) \ln(1 + \delta)) &\leq \mu(\delta - \frac{2\delta(1 + \delta)}{2 + \delta}) \\ &= \frac{-\mu\delta^2}{2 + \delta}\end{aligned}$$

Thus, we get,

$$P[Y \geq (1 + \delta)\mu] \leq e^{\frac{-\mu\delta^2}{2 + \delta}} \quad (2)$$

For the last few steps of simplification, <https://math.mit.edu/~goemans/18310S15/bernoff-notes.pdf> was used as a guide.

3.5 Task E

Consider the random variable $B_n = nA_n$.

We need to prove $\lim_{n \rightarrow \infty} P[|B_n - n\mu| > n\epsilon] = 0$.

Note that we are done if we prove $\lim_{n \rightarrow \infty} P[B_n - n\mu > n\epsilon] = 0$ and $\lim_{n \rightarrow \infty} P[n\mu - B_n > n\epsilon] = 0$.

We will prove the first part first, assuming μ is not 0.

$$P[B_n \geq n\epsilon + n\mu] \leq e^{-\frac{n\epsilon^2}{2\mu + \epsilon}}$$

For a positive μ (since the distribution is the sum of Bernoulli RVs) and ϵ (given), $\frac{\epsilon^2}{2\mu + \epsilon}$ is a positive coefficient. e^{-n} tends to 0 as n tends to ∞ , which we will use henceforth.