CSE 312: Foundations of Computing II
Quiz Section #8: Normal Distribution, Central Limit Theorem, Tail Bounds

Review/Mini-Lecture/Main Theorems and Concepts From Lecture

Normal (Gaussian, "bell curve"): $X \sim N(\mu, \sigma^2)$ if X has the following probability density function:

$$f_X(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{(x-\mu)^2}{\sigma^2}}, \qquad x \in \mathbb{R}$$

$E[X] = \mu$ and $Var(X) = \sigma^2$. The "standard normal" random variable is typically denoted Z and has mean 0 and variance 1. If $X \sim N(\mu, \sigma^2)$, then $Z = \frac{X-\mu}{\sigma} \sim N(0,1)$. The CDF has no closed form, but we denote the CDF of the standard normal as $\Phi(z) = F_Z(z) = P(Z \le z)$. Note from symmetry of the probability density function about $z = 0$ that: $\Phi(-z) = 1 - \Phi(z)$.

Standardizing: Let X be any random variable (discrete or continuous, not necessarily normal), with $E[X] = \mu$ and $Var(X) = \sigma^2$. If we let $Y = \frac{X-\mu}{\sigma}$, then $E[Y] = 0$ and $Var(Y) = 1$.

Closure of the Normal Distribution: Let $X \sim N(\mu, \sigma^2)$. Then, $aX + b \sim N(a\mu + b, a^2\sigma^2)$. That is, linear transformations of normal random variables are still normal.

"Reproductive" Property of Normals: Let $X_1, \dots, X_n$ be independent normal random variables with $E[X_i] = \mu_i$ and $Var(X_i) = \sigma_i^2$. Let $a_1, \dots, a_n \in \mathbb{R}$ and $b \in \mathbb{R}$. Then,

$$X = \sum_{i=1}^{n} a_i X_i + b \sim N\left(\sum_{i=1}^{n} a_i \mu_i + b, \sum_{i=1}^{n} a_i^2 \sigma_i^2\right)$$

There's nothing special about the parameters – the important result here is that the resulting random variable is still normally distributed.

Central Limit Theorem (CLT): Let $X_1, \dots, X_n$ be iid random variables with $E[X_i] = \mu$ and $Var(X_i) = \sigma^2$. Let $X = \sum_{i=1}^{n} X_i$ which has $E[X] = n\mu$ and $Var(X) = n\sigma^2$. Let $\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i$, which has $E[\bar{X}] = \mu$ and $Var(\bar{X}) = \frac{\sigma^2}{n}$. $\bar{X}$ is called the sample mean. Then, as $n \to \infty$, $Y = \frac{\bar{X}-\mu}{\sigma/\sqrt{n}} \sim N(0,1)$ (same as $\bar{X} \sim N\left(\mu, \frac{\sigma^2}{n}\right)$). Equivalently, $Y' = \frac{X - n\mu}{\sigma\sqrt{n}} \sim N(0,1)$ (same as $X \sim N(n\mu, n\sigma^2)$). It is no surprise that $\bar{X}$ has mean μ and variance σ^2/n – this can be done with simple calculations. The importance of the CLT is that, for large n, regardless of what distribution X_i comes from, $\bar{X}$ is <u>approximately normally distributed with mean μ and variance σ^2/n</u>. Don't forget the continuity correction, only when $X_1, \dots, X_n$ are discrete random variables.

Markov's Inequality: Let X be a non-negative random variable, and $\alpha \in \mathbb{R}$. Then, $P(X \ge \alpha) \le \frac{E[X]}{\alpha}$.

Chebyshev's Inequality: Suppose Y is a random variable with $E[Y] = \mu$ and $Var(X) = \sigma^2$. Then, for any $\alpha \in \mathbb{R}$, $P(|Y - \mu| \ge \alpha) \le \frac{\sigma^2}{\alpha^2}$.

Chernoff Bound (for the Binomial): Suppose $X \sim Bin(n,p)$. Then, for any $0 < \delta < 1$,

- $P(X > (1+\delta)\mu) \leq e^{-\frac{\delta^2 \mu}{3}}$
- $P(X < (1-\delta)\mu) \leq e^{-\frac{\delta^2 \mu}{2}}$

Exercises

1. Suppose heights are normally distributed with some mean μ and variance σ^2. If 2.28% of people are under 48 inches and 15.87% of people are above 72 inches, what is the probability that a random person is over 84 inches tall? There is a standard normal cdf table on the last page.

2. Suppose $Z = X + Y$, where $X \perp Y$. Z is called the convolution of two random variables.
If X, Y, Z are discrete,

$$p_Z(z) = P(Z = z) = \sum_x P(X = x \cap Y = z - x) = \sum_x p_X(x) p_Y(z - x)$$

If X, Y, Z are continuous,

$$F_Z(z) = P(X + Y \leq z) = \int_{-\infty}^{\infty} P(Y \leq z - X \mid X = x) f_X(x) dx = \int_{-\infty}^{\infty} F_Y(z - x) f_X(x) dx$$

Suppose $X_1 \sim N(\mu_1, \sigma_1^2)$ and $X_2 \sim N(\mu_2, \sigma_2^2)$.

a) Find an expression for $P(X_1 < 2X_2)$ using a similar idea to convolution, in terms of $F_{X_1}, F_{X_2}, f_{X_1}, f_{X_2}$. (Your answer will be in the form of a single integral, and requires no calculations – do not evaluate it).

b) Find s, where $\Phi(s) = P(X_1 < 2X_2)$ using the “reproductive” property of normal distributions.

3. Suppose $X_1, \dots, X_n$ are iid $Poi(\lambda)$ random variables, and let $\bar{X}_n = \frac{1}{n}\sum_{i=1}^{n} X_i$, the sample mean. How large should we choose n to be such that $P\left(\frac{\lambda}{2} \le \bar{X}_n \le \frac{3\lambda}{2}\right) \ge 0.99$? Use the CLT and give an answer involving $\Phi^{-1}(\cdot)$. Then evaluate it exactly when $\lambda = 1/10$ and using the phi table below.

Z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.5000	0.5040	0.5080	0.5120	0.5160	0.5199	0.5239	0.5279	0.5319	0.5359
0.1	0.5398	0.5438	0.5478	0.5517	0.5557	0.5596	0.5636	0.5675	0.5714	0.5753
0.2	0.5793	0.5832	0.5871	0.5910	0.5948	0.5987	0.6026	0.6064	0.6103	0.6141
0.3	0.6179	0.6217	0.6255	0.6293	0.6331	0.6368	0.6406	0.6443	0.6480	0.6517
0.4	0.6554	0.6591	0.6628	0.6664	0.6700	0.6736	0.6772	0.6808	0.6844	0.6879
0.5	0.6915	0.6950	0.6985	0.7019	0.7054	0.7088	0.7123	0.7157	0.7190	0.7224
0.6	0.7257	0.7291	0.7324	0.7357	0.7389	0.7422	0.7454	0.7486	0.7517	0.7549
0.7	0.7580	0.7611	0.7642	0.7673	0.7704	0.7734	0.7764	0.7794	0.7823	0.7852
0.8	0.7881	0.7910	0.7939	0.7967	0.7995	0.8023	0.8051	0.8078	0.8106	0.8133
0.9	0.8159	0.8186	0.8212	0.8238	0.8264	0.8289	0.8315	0.8340	0.8365	0.8389
1.0	0.8413	0.8438	0.8461	0.8485	0.8508	0.8531	0.8554	0.8577	0.8599	0.8621
1.1	0.8643	0.8665	0.8686	0.8708	0.8729	0.8749	0.8770	0.8790	0.8810	0.8830
1.2	0.8849	0.8869	0.8888	0.8907	0.8925	0.8944	0.8962	0.8980	0.8997	0.9015
1.3	0.9032	0.9049	0.9066	0.9082	0.9099	0.9115	0.9131	0.9147	0.9162	0.9177
1.4	0.9192	0.9207	0.9222	0.9236	0.9251	0.9265	0.9279	0.9292	0.9306	0.9319
1.5	0.9332	0.9345	0.9357	0.9370	0.9382	0.9394	0.9406	0.9418	0.9429	0.9441
1.6	0.9452	0.9463	0.9474	0.9484	0.9495	0.9505	0.9515	0.9525	0.9535	0.9545
1.7	0.9554	0.9564	0.9573	0.9582	0.9591	0.9599	0.9608	0.9616	0.9625	0.9633
1.8	0.9641	0.9649	0.9656	0.9664	0.9671	0.9678	0.9686	0.9693	0.9699	0.9706
1.9	0.9713	0.9719	0.9726	0.9732	0.9738	0.9744	0.9750	0.9756	0.9761	0.9767
2.0	0.9772	0.9778	0.9783	0.9788	0.9793	0.9798	0.9803	0.9808	0.9812	0.9817
2.1	0.9821	0.9826	0.9830	0.9834	0.9838	0.9842	0.9846	0.9850	0.9854	0.9857
2.2	0.9861	0.9864	0.9868	0.9871	0.9875	0.9878	0.9881	0.9884	0.9887	0.9890
2.3	0.9893	0.9896	0.9898	0.9901	0.9904	0.9906	0.9909	0.9911	0.9913	0.9916
2.4	0.9918	0.9920	0.9922	0.9924	0.9927	0.9929	0.9931	0.9932	0.9934	0.9936
2.5	0.9938	0.9940	0.9941	0.9943	0.9945	0.9946	0.9948	0.9949	0.9951	0.9952
2.6	0.9953	0.9955	0.9956	0.9957	0.9958	0.9960	0.9961	0.9962	0.9963	0.9964
2.7	0.9965	0.9966	0.9967	0.9968	0.9969	0.9970	0.9971	0.9972	0.9973	0.9974
2.8	0.9974	0.9975	0.9976	0.9977	0.9977	0.9978	0.9979	0.9979	0.9980	0.9981
2.9	0.9981	0.9982	0.9982	0.9983	0.9984	0.9984	0.9985	0.9985	0.9986	0.9986