CSE 312

Foundations of Computing II

Lecture 12: Zoo of Discrete RVS part II
Poisson Distribution

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Midterm info

- Midterm info is posted on edstem
- I will post solutions to the practice midterm tomorrow.
- I will do a review in class next Friday.

hw 2 ~weeks

Zoo of Random Variables🦍🐘🦁🐅🦓🐪🦒

$X \sim \text{Unif}(a, b)$

$$P(X = k) = \frac{1}{b - a + 1}$$
$$E[X] = \frac{a+b}{2}$$
$$\text{Var}(X) = \frac{(b-a)(b-a+2)}{12}$$

$X \sim \text{Ber}(p)$

$$P(X = 1) = p, P(X = 0) = 1 - p$$
$$E[X] = p$$
$$\text{Var}(X) = p(1-p)$$

$X \sim \text{Bin}(n, p)$

$$P(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$$
$$E[X] = np$$
$$\text{Var}(X) = np(1-p)$$

$X \sim \text{Geo}(p)$

$$P(X = k) = (1-p)^{k-1} p$$
$$E[X] = \frac{1}{p}$$
$$\text{Var}(X) = \frac{1-p}{p^2}$$

$X \sim \text{NegBin}(r, p)$

$$P(X = k) = \binom{k-1}{r-1} p^r (1-p)^{k-r}$$
$$E[X] = \frac{r}{p}$$
$$\text{Var}(X) = \frac{r(1-p)}{p^2}$$

$X \sim \text{HypGeo}(N, K, n)$

$$P(X = k) = \frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$$
$$E[X] = n\frac{K}{N}$$
$$\text{Var}(X) = n\frac{K(N-K)(N-n)}{N^2(N-1)}$$

Agenda

- Zoo of Discrete RVs
  - Uniform Random Variables
  - Bernoulli Random Variables
  - Binomial Random Variables
  - Geometric Random variables
  - Examples
  - Poisson Distribution
    - Approximate Binomial distribution using Poisson distribution
  - Applications
  - Negative Binomial Random Variables
  - Hypergeometric Random Variables

Example

Sending a binary message of length 1024 bits over a network with probability 0.999 of correctly sending each bit in the message without corruption (independent of other bits).

Let X be the number of corrupted bits.

What kind of random variable is this and what is $\mathbb{E}[X]$?

$n = 1024$ $p = 0.001$

$n \cdot p$

$E(X)$

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a. 1022.99
b. 1.024
c. 1.02298
d. 1

Example: Music Lessons

Your music teacher requires you to play a 1000 note song without mistake. You have been practicing, so you have a probability of 0.999 of getting each note correct (independent of the others). If you mess up a single note in the song, you must start over and play from the beginning. Let X be the number of times you have to play the song from the start. What kind of random variable is this and what is $\mathbb{E}[X]$?

$X \sim Geo(p)$

$p = (0.999)^{1000}$

$E(X) = \frac{1}{p}$

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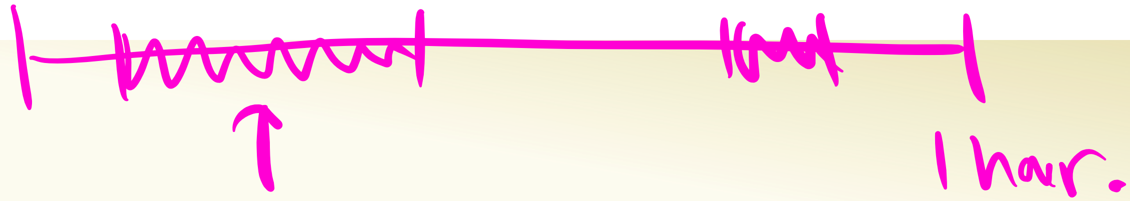


Preview: Poisson

X

Model: # events that occur in an hour

$E(X) = 3$

- Expect to see 3 events per hour (but will be random)
- The expected number of events in t hours, is $3t$
- Occurrence of events on disjoint time intervals is independent

Example – Modelling car arrivals at an intersection

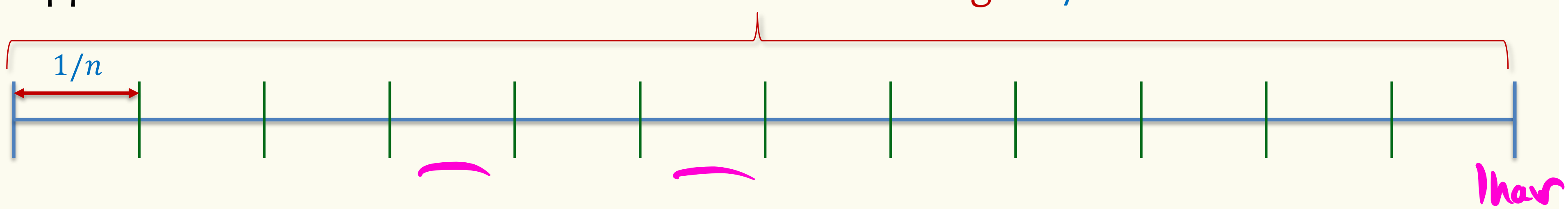
X = # of cars passing through a light in 1 hour

Example – Model the process of cars passing through a light in 1 hour

X = # cars passing through a light in 1 hour. $\mathbb{E}[X] = 3$

Assume: Occurrence of events on disjoint time intervals is independent

Approximation idea: Divide hour into n intervals of length $1/n$



Assume each interval either 0 or 1 car arrives

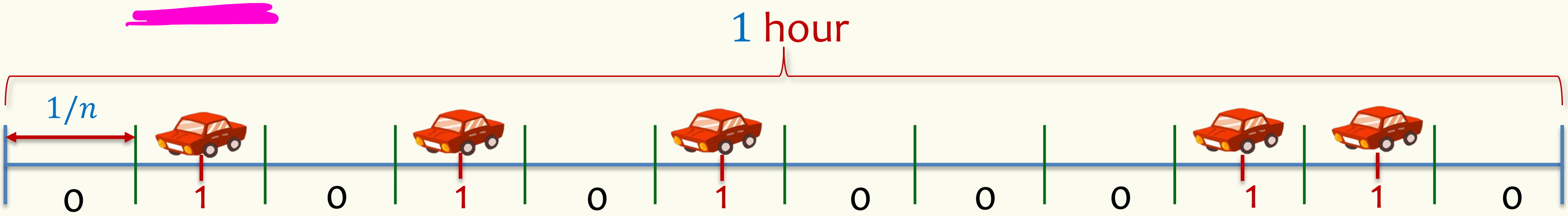
$p = P(\text{car arrives in } \frac{1}{n} \text{ intervals})$ $E(X) = 3$

$X \sim Bin(n, p)$

Example – Model the process of cars passing through a light in 1 hour

X = # cars passing through a light in 1 hour. Disjoint time intervals are independent.

Know: $\mathbb{E}[X] = \lambda$ for some given $\lambda > 0$



This gives us n independent intervals

Assume either zero or one car per interval

$p =$ probability car arrives in an interval

What should p be?
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A. $3/n$
B. $3n$
C. 3
D. $3/60$

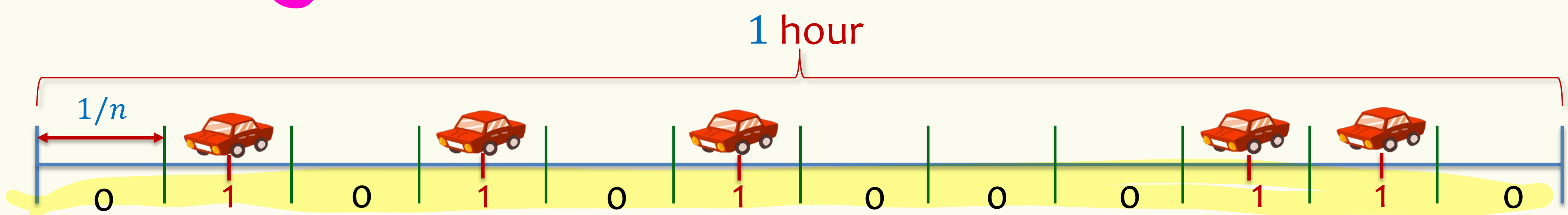
$X \sim Bin(n,p)$

$E(X) = np = 3$

Example – Model the process of cars passing through a light in 1 hour

X = # cars passing through a light in 1 hour. Disjoint time intervals are independent.

Know: $\mathbb{E}[X] = \lambda$ for some given $\lambda > 0$



Discrete version: n intervals, each of length $1/n$.

In each interval, there is a car with probability $p = \lambda/n$ (assume ≤ 1 car can pass by)

Each interval is Bernoulli: $X_i = 1$ if car in i^{th} interval (0 otherwise). $P(X_i = 1) = \lambda / n$

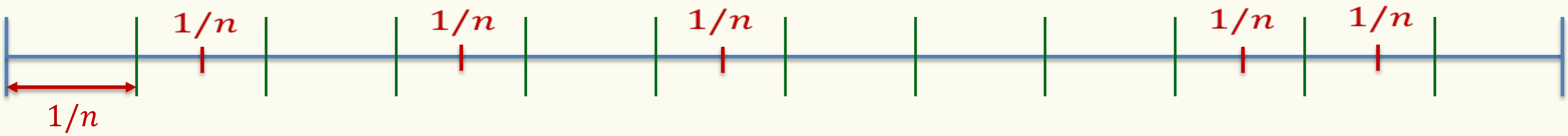
$X = \sum_{i=1}^{n} X_i$ $\quad X \sim \text{Bin}(n, p)$ $\quad P(X = i) = \binom{n}{i} \left(\frac{\lambda}{n}\right)^i \left(1 - \frac{\lambda}{n}\right)^{n-i}$

indeed! $\mathbb{E}[X] = pn = \lambda$

Don't like discretization

$n \quad p = \frac{\lambda}{n}$

X is binomial $P(X = i) = \binom{n}{i}\left(\frac{\lambda}{n}\right)^i\left(1 - \frac{\lambda}{n}\right)^{n-i}$



We want now $n \to \infty$

$$P(X=0) = \binom{n}{0}\left(\frac{\lambda}{n}\right)^0\left(1-\frac{\lambda}{n}\right)^{n-0} = \left(1-\frac{\lambda}{n}\right)^n$$

$$\lim_{n\to\infty}\left(1-\frac{\lambda}{n}\right)^n \quad \left(e^{-\frac{\lambda}{n}}\right)^n = e^{-\lambda}$$

$$e^{-x} = 1 - x + \frac{x^2}{2} - \frac{x^3}{3!} + \cdots \quad \approx (1-x)$$

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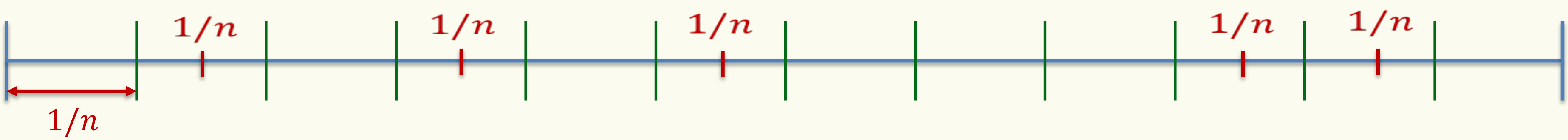
$$P(X=1) = \binom{n}{1}\left(\frac{\lambda}{n}\right)^1\left(1-\frac{\lambda}{n}\right)^{n-1} \quad n \cdot \frac{\lambda}{n} \quad e^{-\frac{\lambda}{n}(n-1)} \quad \lim_{n\to\infty} = \lambda e^{-\lambda}$$

Don't like discretization

X is <u>binomial</u> $P(X = i) = \binom{n}{i}\left(\frac{\lambda}{n}\right)^i\left(1 - \frac{\lambda}{n}\right)^{n-i}$



We want now $n \to \infty$

$$P(X = i) = \binom{n}{i}\left(\frac{\lambda}{n}\right)^i\left(1 - \frac{\lambda}{n}\right)^{n-i} = \underbrace{\frac{n!}{(n-i)!\,n^i}}_{\to 1}\frac{\lambda^i}{i!}\underbrace{\left(1 - \frac{\lambda}{n}\right)^n}_{\to e^{-\lambda}}\underbrace{\left(1 - \frac{\lambda}{n}\right)^{-i}}_{\to 1}$$

lim as $n \to \infty$

$$\to P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

$\Omega_X = \{0, 1, 2, \ldots \}$

Poisson Distribution

Siméon Denis Poisson
1781-1840

- Suppose "events" happen, independently, at an *average* rate of λ per unit time.
- Let X be the *actual* number of events happening in a given time unit. Then X is a *Poisson* r.v. *with parameter* λ (denoted $X \sim \text{Poi}(\lambda)$) and has distribution (PMF):

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

$i = 0, 1, 2, \ldots$

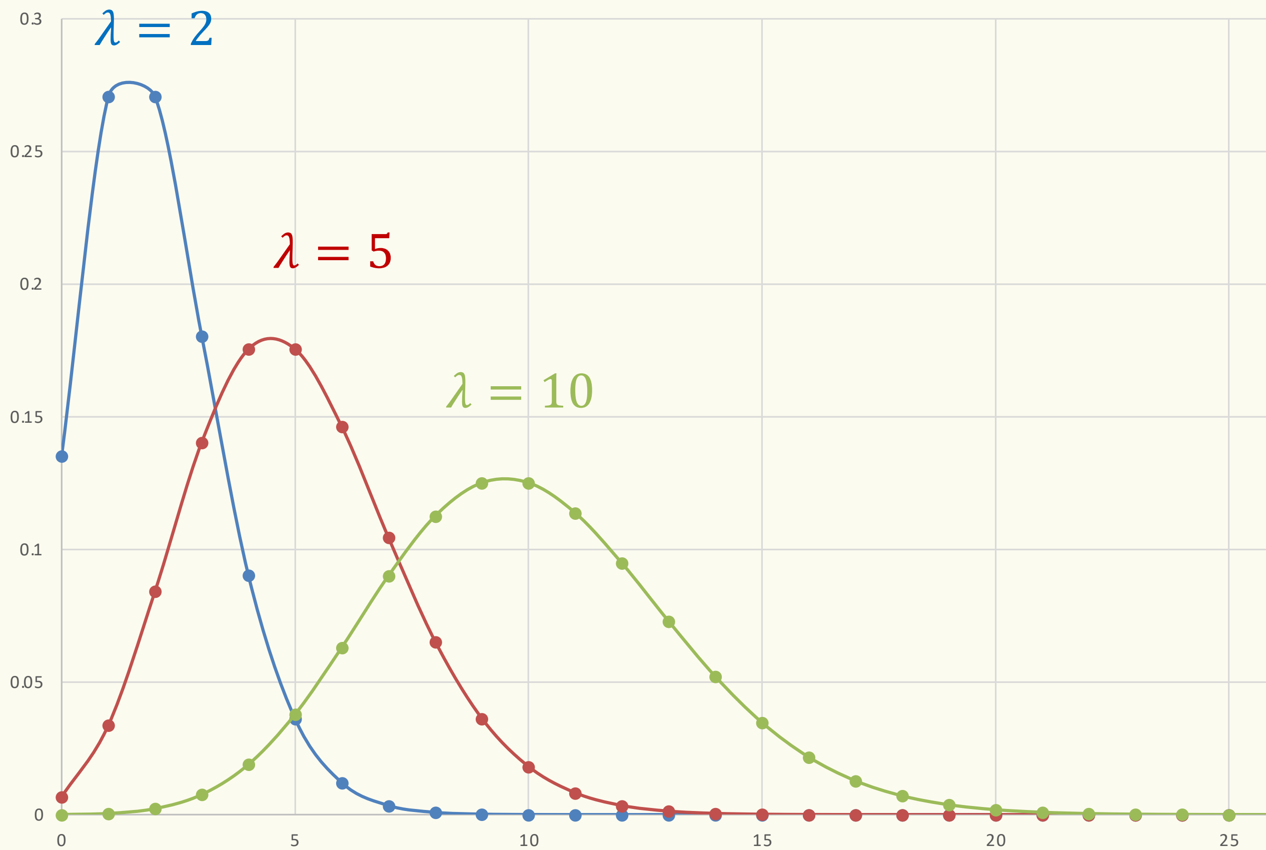
Several examples of "Poisson processes":

- # of cars passing through a traffic light in 1 hour
- # of requests to web servers in an hour
- # of photons hitting a light detector in a given interval
- # of patients arriving to ER within an hour

Assume fixed average rate

Probability Mass Function

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$



Validity of Distribution

$\lambda \geq 0$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!} \qquad i = 0, 1, 2, \ldots$$

Is this a valid probability mass function?

$$\sum_{i=0}^{\infty} e^{-\lambda} \frac{\lambda^i}{i!} = e^{-\lambda} \sum_{i=0}^{\infty} \frac{\lambda^i}{i!}$$

Validity of Distribution

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

We first want to verify that Poisson probabilities sum up to 1.

$$\sum_{i=0}^{\infty} P(X = i) = \sum_{i=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{i!} = e^{-\lambda} \sum_{i=0}^{\infty} \frac{\lambda^i}{i!} = e^{-\lambda} e^{\lambda} = e^{0} = 1$$

Fact (Taylor series expansion):

$$e^x = \sum_{i=0}^{\infty} \frac{x^i}{i!}$$

Validity of Distribution

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

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Fact (Taylor series expansion):

$$e^x = \sum_{i=0}^{\infty} \frac{x^i}{i!}$$

Expectation

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

Theorem. If X is a Poisson RV with parameter $\lambda \geq 0$, then

$$\mathbb{E}[X] = ?$$

Proof. $\mathbb{E}[X] = \sum_{i=0}^{\infty} P(X = i) \cdot i =$

Expectation

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

Theorem. If X is a Poisson RV with parameter λ, then

$$\mathbb{E}[X] = \lambda$$

Proof.

$$\mathbb{E}[X] = \sum_{i=0}^{\infty} P(X = i) \cdot i = \sum_{i=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{i!} \cdot i = \sum_{i=1}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{(i-1)!}$$

$$= \lambda \sum_{i=1}^{\infty} e^{-\lambda} \cdot \frac{\lambda^{i-1}}{(i-1)!}$$

$$= \lambda \sum_{i=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{i!} = \lambda \cdot 1 = \lambda$$

= 1 (see prior slides!)

Variance

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

Theorem. If X is a Poisson RV with parameter λ, then $\mathrm{Var}(X) = \lambda$

Proof. $$\mathbb{E}[X^2] = \sum_{i=0}^{\infty} P(X = i) \cdot i^2 = \sum_{i=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{i!} \cdot i^2 = \sum_{i=1}^{\infty} e^{-\lambda} \cdot \frac{\lambda^i}{(i-1)!} i$$

$$= \lambda \sum_{i=1}^{\infty} e^{-\lambda} \cdot \frac{\lambda^{i-1}}{(i-1)!} \cdot i = \lambda \sum_{j=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^j}{j!} \cdot (j+1)$$

$$= \lambda \left[\underbrace{\sum_{j=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^j}{j!} \cdot j}_{= \mathbb{E}[X] = \lambda} + \underbrace{\sum_{j=0}^{\infty} e^{-\lambda} \cdot \frac{\lambda^j}{j!}}_{= 1} \right] = \lambda^2 + \lambda$$

Similar to the previous proof
Verify offline.

$$\Rightarrow \quad \mathrm{Var}(X) = \mathbb{E}[X^2] - \mathbb{E}[X]^2 = \lambda^2 + \lambda - \lambda^2 = \lambda$$

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  - Bernoulli Random Variables, Part I
  - Binomial Random Variables, Part I
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  - Negative Binomial Random Variables
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Poisson Random Variables

Definition. A **Poisson random variable** X with parameter $\lambda \geq 0$ is such that for all $i = 0,1,2,3 \ldots,$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

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Poisson approximates binomial when:

n is very large, p is very small, and $\lambda = np$ is "moderate"

e.g. ($n > 20$ and $p < 0.05$), ($n > 100$ and $p < 0.1$)

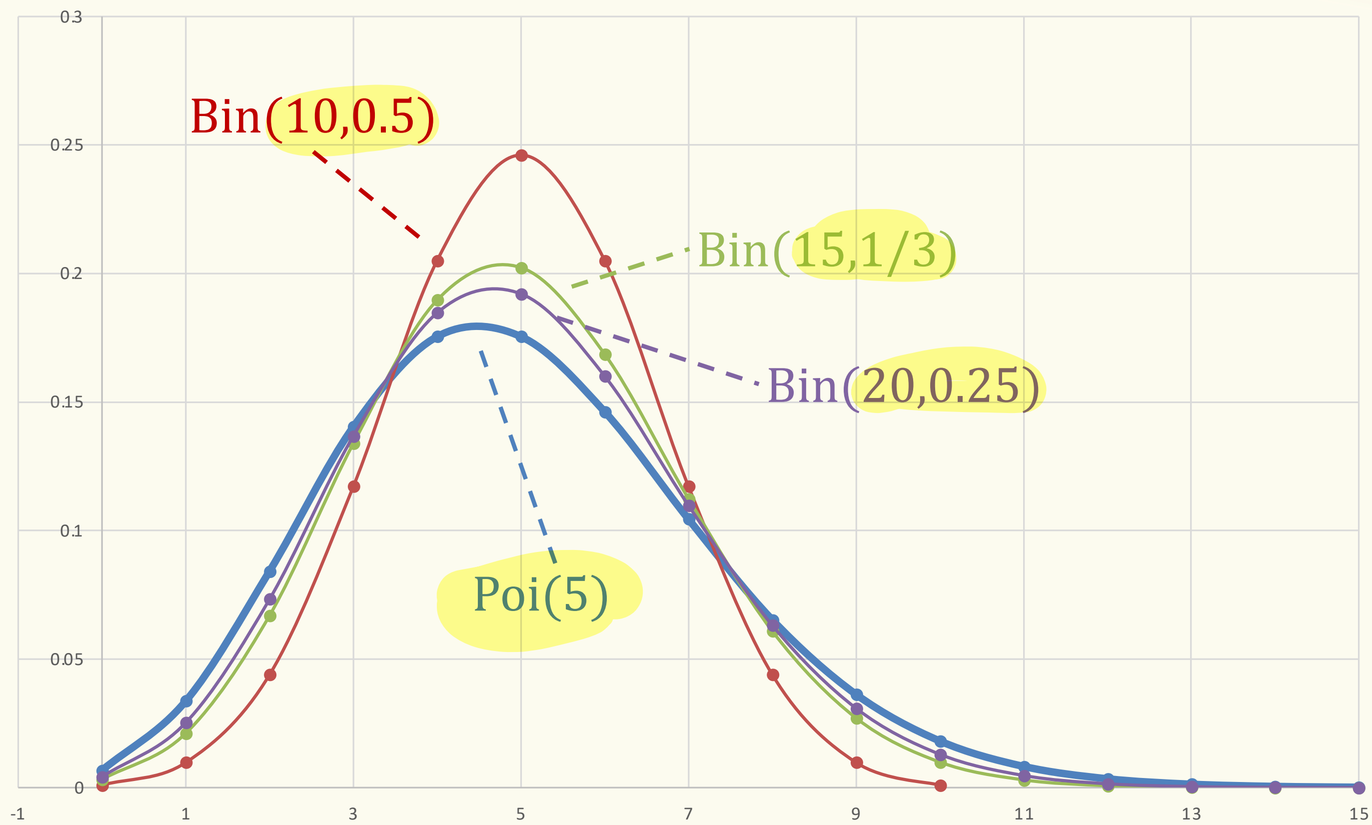
Formally, Binomial approaches Poisson in the limit as $n \to \infty$ (equivalently, $p \to 0$) while holding $np = \lambda$

Probability Mass Function – Convergence of Binomials

$\lambda = 5$

$p = \frac{5}{n}$

$n = 10,15,20$



$as\ n \to \infty,\ Binomial(n,\ p = \lambda/n) \to poi(\lambda)$

From Binomial to Poisson

$X \sim \text{Bin}(n, p)$

$$P(X = k) = \binom{n}{k} p^k (1-p)^{n-k}$$

$$E[X] = np$$

$$\text{Var}(X) = np(1-p)$$

$n \to \infty$

$np = \lambda$

$p = \frac{\lambda}{n} \to 0$

$X \sim \text{Poi}(\lambda)$

$$P(X = k) = e^{-\lambda} \cdot \frac{\lambda^k}{k!}$$

$$E[X] = \lambda$$

$$\text{Var}(X) = \lambda$$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

Example -- Approximate Binomial Using Poisson

Consider sending bit string over a network

- Send bit string of length $n = 10^4$
- Probability of (independent) bit corruption is $p = 10^{-6}$

What is probability that message arrives uncorrupted?

Using $X \sim \text{Poi}(\lambda = np = 10^4 \cdot 10^{-6} = 0.01)$

$$P(X = 0) = e^{-\lambda} \cdot \frac{\lambda^0}{0!} = e^{-0.01} \cdot \frac{0.01^0}{0!} \approx 0.990049834$$

Using $Y \sim \text{Bin}(10^4, 10^{-6})$

$$P(Y = 0) \approx 0.990049829$$

Sum of Independent Poisson RVs

Let $X \sim \text{Poi}(\lambda_1)$ and $Y \sim \text{Poi}(\lambda_2)$ such that $\lambda = \lambda_1 + \lambda_2$.

Let $Z = X + Y$. What kind of random variable is Z ?

Aka what is the "distribution" of Z ?

$$Z \sim \text{Poi}(\lambda_1 + \lambda_2)$$

Sum of Independent Poisson RVs

indep.

Theorem. Let $X \sim \text{Poi}(\lambda_1)$ and $Y \sim \text{Poi}(\lambda_2)$ such that $\lambda = \lambda_1 + \lambda_2$.
Let $Z = X + Y$. For all $z = 0,1,2,3 \ldots$,

$$P(Z = z) = e^{-\lambda} \cdot \frac{\lambda^z}{z!}$$

indep

More generally, let $X_1 \sim \text{Poi}(\lambda_1), \cdots, X_n \sim \text{Poi}(\lambda_n)$ such that $\lambda = \Sigma_i \lambda_i$.
Let $Z = \Sigma_i X_i$

$$P(Z = z) = e^{-\lambda} \cdot \frac{\lambda^z}{z!}$$

Sum of Independent Poisson RVs

Theorem. Let $X \sim \mathrm{Poi}(\lambda_1)$ and $Y \sim \mathrm{Poi}(\lambda_2)$ such that $\lambda = \lambda_1 + \lambda_2$.
Let $Z = X + Y$. For all $z = 0,1,2,3 \ldots,$

$$P(Z = z) = e^{-\lambda} \cdot \frac{\lambda^z}{z!}$$

$P(Z = z) = ?$

1. $P(Z = z) = \Sigma_{j=0}^{z} P(X = j, Y = z - j)$
2. $P(Z = z) = \Sigma_{j=0}^{\infty} P(X = j, Y = z - j)$
3. $P(Z = z) = \Sigma_{j=0}^{z} P(Y = z - j | X = j) \, P(X = j)$
4. $P(Z = z) = \Sigma_{j=0}^{z} P(Y = z - j | X = j)$

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A. All of them are right
B. The first 3 are right
C. Only 1 is right
D. Don't know

LTP

$$P(Z=z) = \sum_{j=0}^{\infty} P(Z=z \cap X=j)$$

$$= \sum_{j=0}^{\infty} P(X=j, Y=z-j)$$

$$= \sum_{j=0}^{z} P(X=j, Y=z-j)$$

$$= \sum_{j=0}^{z} P(Y=z-j \mid X=j) P(X=j)$$

$X \sim Poi(\lambda_1)$
$Y \sim Poi(\lambda_2)$

X, Y indep

$$= \sum_{j=0}^{z} P(X=j) P(Y=z-j)$$

$$= \sum_{j=0}^{z} e^{-\lambda_1} \frac{\lambda_1^j}{j!} e^{-\lambda_2} \frac{\lambda_2^{z-j}}{(z-j)!}$$

$$= \frac{e^{-\lambda_1} e^{-\lambda_2}}{z!} \sum_{j=0}^{z} \frac{z!}{j!(z-j)!} \lambda_1^j \lambda_2^{z-j}$$

$$= \frac{e^{-(\lambda_1+\lambda_2)}}{z!} \sum_{j=0}^{z} \binom{z}{j} \lambda_1^j \lambda_2^{z-j}$$

BT. $(\lambda_1+\lambda_2)^z$

$$= e^{-(\lambda_1+\lambda_2)} \frac{(\lambda_1+\lambda_2)^z}{z!}$$

Theorem. Let $X \sim \mathrm{Poi}(\lambda_1)$ and $Y \sim \mathrm{Poi}(\lambda_2)$ such that $\lambda = \lambda_1 + \lambda_2$.
Let $Z = X + Y$. For all $z = 0,1,2,3 \ldots,$

$$P(Z = z) = e^{-\lambda} \cdot \frac{\lambda^z}{z!}$$

Proof

$P(Z = z) = \Sigma_{j=0}^{z} P(X = j, Y = z - j)$ Law of total probability

Proof

$P(Z = z) = \Sigma_{j=0}^{z} P(X = j, Y = z - j)$ Law of total probability

$= \Sigma_{j=0}^{z} P(X = j)\, P(Y = z - j) = \Sigma_{j=0}^{z}\ e^{-\lambda_1} \cdot \frac{\lambda_1^j}{j!} \cdot e^{-\lambda_2} \cdot \frac{\lambda_2^{z-j}}{z - j!}$ Independence

$= e^{-\lambda_1 - \lambda_2} \left(\Sigma_{j=0}^{z}\ \cdot \frac{1}{j!\, z - j!} \cdot \lambda_1^j \lambda_2^{z-j} \right)$

$= e^{-\lambda} \left(\Sigma_{j=0}^{z}\ \frac{z!}{j!\, z - j!} \cdot \lambda_1^j \lambda_2^{z-j} \right) \frac{1}{z!}$

$= e^{-\lambda} \cdot (\lambda_1 + \lambda_2)^z \cdot \frac{1}{z!} = e^{-\lambda} \cdot \lambda^z \cdot \frac{1}{z!}$ Binomial Theorem

Poisson Random Variables

Definition. A **Poisson random variable** X with parameter $\lambda \geq 0$ is such that for all $i = 0,1,2,3 \ldots,$

$$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$$

General principle:

- Events happen at an average rate of λ per time unit
- Number of events happening at a time unit X is distributed according to Poi(λ)
- Poisson approximates Binomial when n is large, p is small, and np is moderate
- Sum of independent Poisson is still a Poisson

Zoo of Random Variables🦍🐘🦁🐅🦓🐪🦒

$X \sim \text{Poisson}(\lambda)$

$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$

$E[X] = \lambda$

$\text{Var}(X) = \lambda$

$X \sim \text{Ber}(p)$

$P(X = 1) = p, P(X = 0) = 1 - p$

$E[X] = p$

$\text{Var}(X) = p(1 - p)$

$X \sim \text{Bin}(n, p)$

$P(X = k) = \binom{n}{k} p^k (1 - p)^{n-k}$

$E[X] = np$

$\text{Var}(X) = np(1 - p)$

$X \sim \text{Geo}(p)$

$P(X = k) = (1 - p)^{k-1} p$

$E[X] = \frac{1}{p}$

$\text{Var}(X) = \frac{1 - p}{p^2}$

$X \sim \text{NegBin}(r, p)$

$P(X = k) = \binom{k - 1}{r - 1} p^r (1 - p)^{k-r}$

$E[X] = \frac{r}{p}$

$\text{Var}(X) = \frac{r(1 - p)}{p^2}$

$X \sim \text{HypGeo}(N, K, n)$

$P(X = k) = \frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$

$E[X] = n\frac{K}{N}$

$\text{Var}(X) = n\frac{K(N - K)(N - n)}{N^2(N - 1)}$

Negative Binomial Random Variables

A discrete random variable X that models the number of independent trials $Y_i \sim \text{Ber}(p)$ before seeing the r^{th} success.
Equivalently, $X = \sum_{i=1}^{r} Z_i$ where $\text{Z}_i \sim \text{Geo}(p)$.
X is called a Negative Binomial random variable with parameters r, p.

Notation: $X \sim \text{NegBin}(r, p)$

PMF: $P(X = k) =$

Expectation: $\mathbb{E}[X] =$

Negative Binomial Random Variables

A discrete random variable X that models the number of independent trials $Y_i \sim \mathrm{Ber}(p)$ before seeing the r^{th} success.
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Notation: $X \sim \mathrm{NegBin}(r, p)$

PMF: $P(X = k) = \binom{k-1}{r-1} p^r (1-p)^{k-r}$

Expectation: $\mathbb{E}[X] = \frac{r}{p}$

Variance: $\mathrm{Var}(X) = \frac{r(1-p)}{p^2}$

Hypergeometric Random Variables

A discrete random variable X that models the number of successes in n draws (without replacement) from N items that contain K successes in total. X is called a Hypergeometric RV with parameters N, K, n.

Notation: $X \sim \text{HypGeo}(N, K, n)$

PMF: $P(X = k) = \frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$

Expectation: $\mathbb{E}[X] = n\frac{K}{N}$

Variance: $\text{Var}(X) = n\frac{K(N-K)(N-n)}{N^2(N-1)}$

Hope you enjoyed the zoo! 🦍🐘🦁🐅🦓🐪🦒

$X \sim \mathrm{Unif}(a, b)$

$P(X = k) = \frac{1}{b - a + 1}$

$\mathbb{E}[X] = \frac{a + b}{2}$

$\mathrm{Var}(X) = \frac{(b - a)(b - a + 2)}{12}$

$X \sim \mathrm{Ber}(p)$

$P(X = 1) = p, P(X = 0) = 1 - p$

$\mathbb{E}[X] = p$

$\mathrm{Var}(X) = p(1 - p)$

$X \sim \mathrm{Bin}(n, p)$

$P(X = k) = \binom{n}{k} p^k (1 - p)^{n-k}$

$\mathbb{E}[X] = np$

$\mathrm{Var}(X) = np(1 - p)$

$X \sim \mathrm{Geo}(p)$

$P(X = k) = (1 - p)^{k-1} p$

$\mathbb{E}[X] = \frac{1}{p}$

$\mathrm{Var}(X) = \frac{1 - p}{p^2}$

$X \sim \mathrm{NegBin}(r, p)$

$P(X = k) = \binom{k - 1}{r - \ldots}$

$\mathbb{E}[X] = \frac{r}{p}$

$\mathrm{Var}(X) = \frac{r(1 - \ldots}{p^2}$

$X \sim \mathrm{HypGeo}(N, K, n)$

$\frac{\binom{K}{k}\binom{N-K}{n-k}}{\binom{N}{n}}$

$\frac{\ldots(N - K)(N - n)}{N^2(N - 1)}$

$X \sim \mathrm{Poisson}(\lambda)$

$P(X = i) = e^{-\lambda} \cdot \frac{\lambda^i}{i!}$

$E[X] = \lambda$

$\mathrm{Var}(X) = \lambda$