

Math Camp

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Where we're at

- Conditional Probability/Bayes' Rule

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- Today: Random Variables

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- A Brief Introduction to Markov Chains

Random Variable: Intuition

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Random variables: functions defined on the **sample space**

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- X 's **domain** are all outcomes (Sample Space)
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- Because X is defined on outcomes, makes sense to write $p(X)$ (we'll talk about this soon)

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Treatment assignment:

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Big Question: How do we compute $P(X=1)$, $P(X=0)$, etc?

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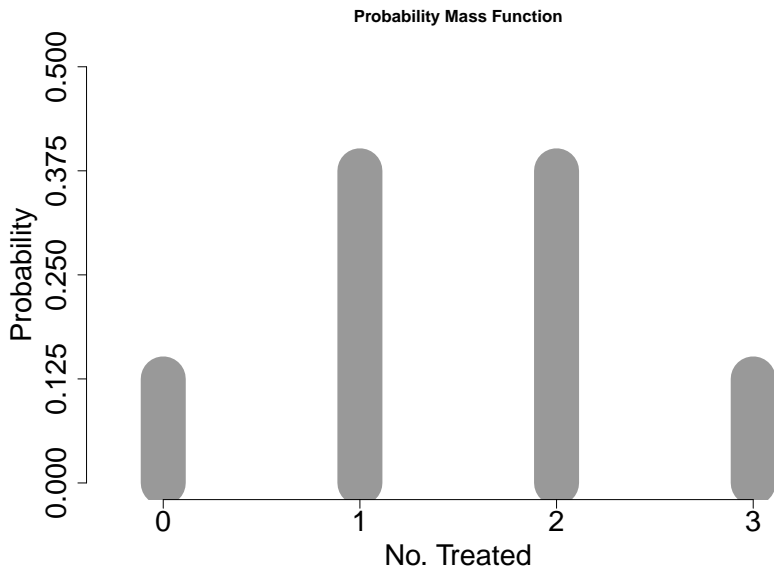
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$$p(X = a) = 0, \text{ for all } a \notin (0, 1, 2, 3)$$

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Consider outcome of election:

- $X(v) = 1$ if $v > 0.5$ otherwise $X(v) = 0$
- $P(X = 1)$ then is equal to $P(v > 0.5)$

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(Brief aside) Countable: A set is countable if there is a function that can map all its elements to the natural numbers $\{1, 2, 3, 4, \dots\}$ (one-to-one, injective). If it is onto (from S to all natural numbers, surjective), then we say the set is countably infinite

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Definition

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Topic 1 (say, **war**):

$P(\text{afghanistan}) = 0.3$; $P(\text{fire}) = 0.0001$; $P(\text{department}) = 0.0001$;

$P(\text{soldier}) = 0.2$; $P(\text{troop}) = 0.2$; $P(\text{war}) = 0.2997$; $P(\text{grant}) = 0.0001$

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Topic Models: take a set of documents and estimate topics.

Definition

Cumulative Mass (distribution) Function: For a random variable X , define the cumulative mass function $F(x)$ as,

$$F(x) = P(X \leq x)$$

- Characterizes how probability **cumulates** as X gets larger
- $F(x) \in [0, 1]$
- $F(x)$ is **non-decreasing**

Cumulative Mass Function: Example

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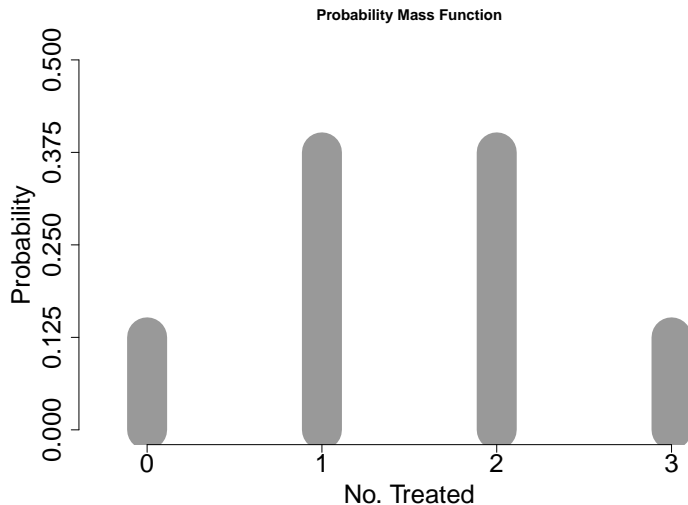
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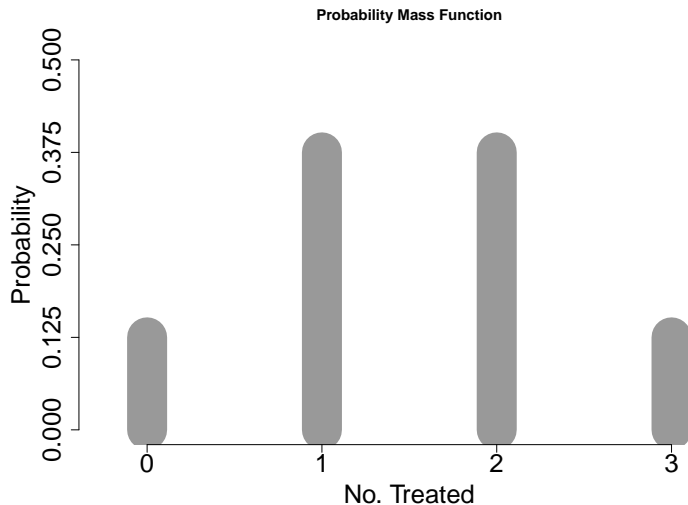
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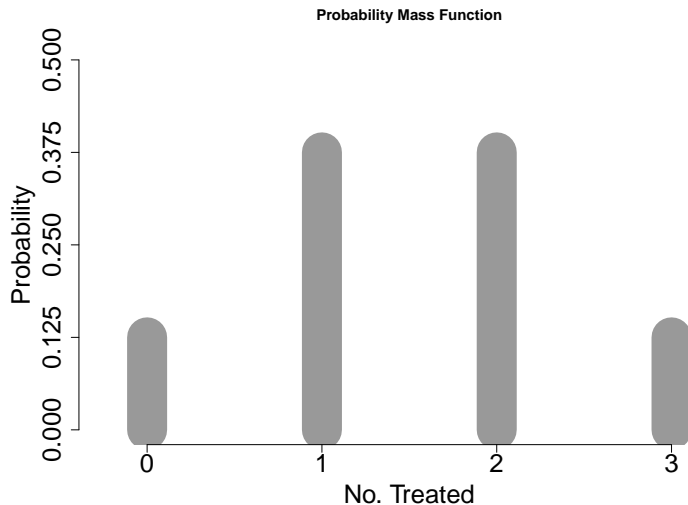
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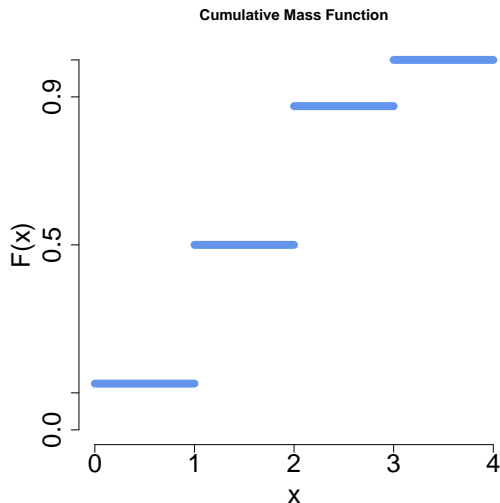
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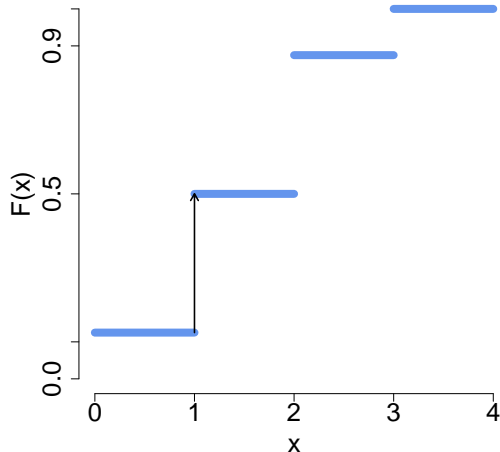


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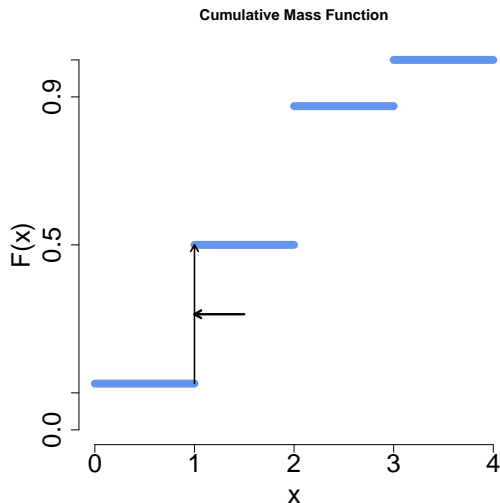
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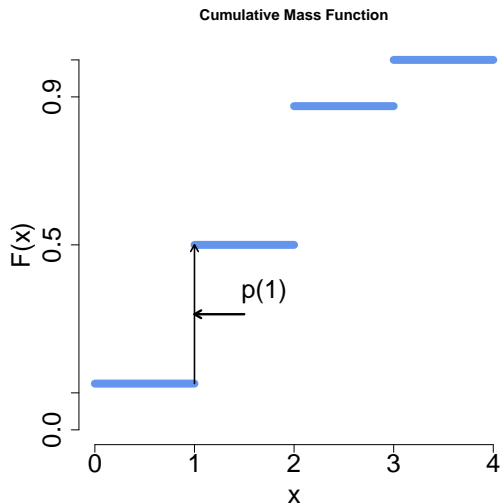
Consider Previous example:



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What can we **expect** from a trial?

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$$E[X] = \sum_{x:p(x)>0} xp(x)$$

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In words: for all values of x with $p(x)$ greater than zero, take the weighted average of the values

Expectation Example: Simple Experiment

Suppose again X is number of units assigned to treatment, in one of our previous examples.

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$$\begin{aligned} E[X] &= 0 \times \frac{1}{8} + 1 \times \frac{3}{8} + 2 \times \frac{3}{8} + 3 \times \frac{1}{8} \\ &= 1.5 \end{aligned}$$

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Indicator Variables and Probabilities



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Functions of Random Variables

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*Suppose X is a random variable and a and b are **constants** (not random variables). Then,*

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Variance

Definition

The variance of a random variable X , $\text{var}(X)$, is

$$\begin{aligned}\text{var}(X) &= E[(X - E[X])^2] \\ &= E[X^2] - E[X]^2\end{aligned}$$

- We will define the standard deviation of X , $\text{sd}(X) = \sqrt{\text{var}(X)}$
- $\text{var}(X) \geq 0$.

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$$\begin{aligned} E[X^2] &= 3 \\ E[X]^2 &= 1.5^2 = 2.25 \\ \text{Var}(X) &= E[X^2] - E[X]^2 \\ &= 3 - 2.25 = 0.75 \end{aligned}$$

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Famous Distributions

- Bernoulli
- Binomial
- Multinomial
- Poisson

Models of how world works.

Bernoulli Random Variable

Definition

*Suppose X is a random variable, with $X \in \{0, 1\}$ and $P(X = 1) = \pi$. Then we will say that X is **Bernoulli** random variable,*

$$p(k) = \pi^k(1 - \pi)^{1-k}$$

for $k \in \{0, 1\}$ and $p(k) = 0$ otherwise.

We will (equivalently) say that

$$Y \sim \text{Bernoulli}(\pi)$$

Bernoulli Random Variable

Suppose we flip a fair coin and $Y = 1$ if the outcome is Heads .

$$Y \sim \text{Bernoulli}(1/2)$$

$$p(1) = (1/2)^1(1 - 1/2)^{1-1} = 1/2$$

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$\text{var}(Y) = \pi(1 - \pi)$ What is the maximum variance?

Example: Winning a War

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Definition

Suppose X is a random variable that counts the number of successes in N independent and identically distributed Bernoulli trials. Then X is a **Binomial** random variable,

$$p(k) = \binom{N}{k} \pi^k (1 - \pi)^{1-k}$$

for $k \in \{0, 1, 2, \dots, N\}$ and $p(k) = 0$ otherwise.

Equivalently,

$$Y \sim \text{Binomial}(N, \pi)$$

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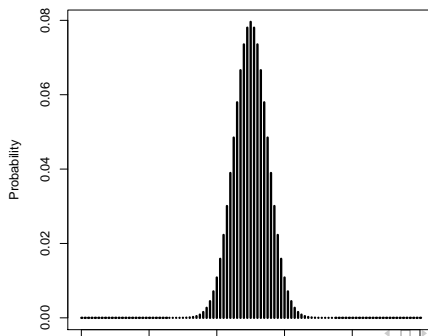
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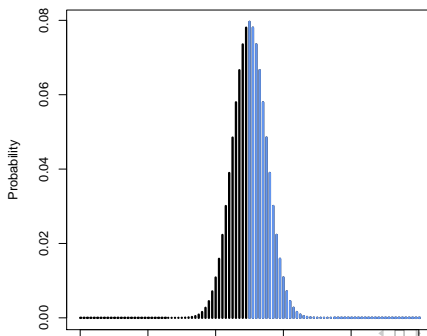
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R Code!

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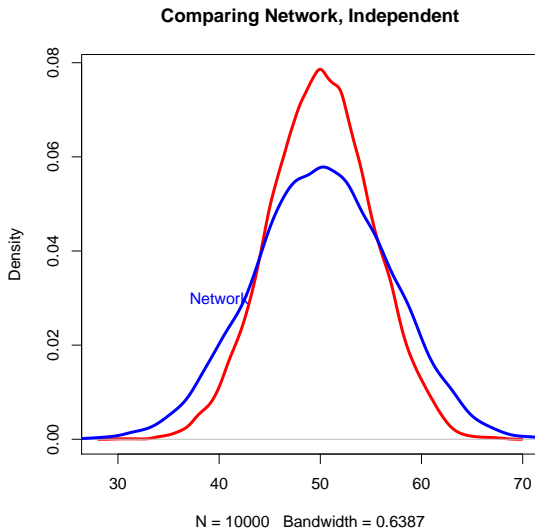
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Trials with More than Two Outcomes

Definition

Suppose we observe a trial, which might result in J outcomes.

And that $P(\text{outcome} = i) = \pi_i$

$\mathbf{Y} = (Y_1, Y_2, \dots, Y_J)$ where $Y_j = 1$ if outcome j occurred and 0 otherwise.

*Then \mathbf{Y} follows a **multinomial** distribution, with*

$$p(\mathbf{y}) = \pi_1^{y_1} \pi_2^{y_2} \dots \pi_k^{y_k}$$

if $\sum_{i=1}^k y_i = 1$ and the pmf is 0 otherwise.

Equivalently, we'll write

$$\mathbf{Y} \sim \text{Multinomial}(1, \boldsymbol{\pi})$$

$$\mathbf{Y} \sim \text{Categorical}(\boldsymbol{\pi})$$

Multinomial Properties + Notes

Computer scientists: commonly call Multinomial($1, \pi$) **Discrete**(π).

$$\begin{aligned} E[X_i] &= N\pi_i \\ \text{var}(X_i) &= N\pi_i(1 - \pi_i) \end{aligned}$$

Investigate Further in Homework!

Counting the Number of Events

Often interested in counting number of events that occur:

- 1) Number of wars started
- 2) Number of speeches made
- 3) Number of bribes offered
- 4) Number of people waiting for license

Generally referred to as **event counts**

Stochastic processes: a course provide introduction to many processes
(**Queing Theory**)

Poisson Distribution

Definition

Suppose X is a random variable that takes on values $X \in \{0, 1, 2, \dots\}$ and that $P(X = k) = p(k)$ is,

$$p(k) = e^{-\lambda} \frac{\lambda^k}{k!}$$

for $k \in \{0, 1, \dots\}$ and 0 otherwise. Then we will say that X follows a *Poisson* distribution with *rate* parameter λ .

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

Example: Poisson Distribution

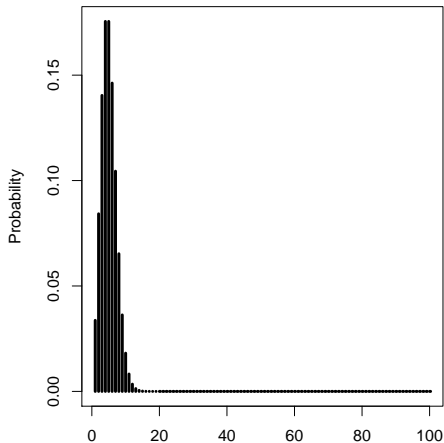
Suppose the number of threats a president makes in a term is given by $X \sim \text{Poisson}(5)$.

Example: Poisson Distribution

Suppose the number of threats a president makes in a term is given by $X \sim \text{Poisson}(5)$. What is the probability the president will make ten or more threats?

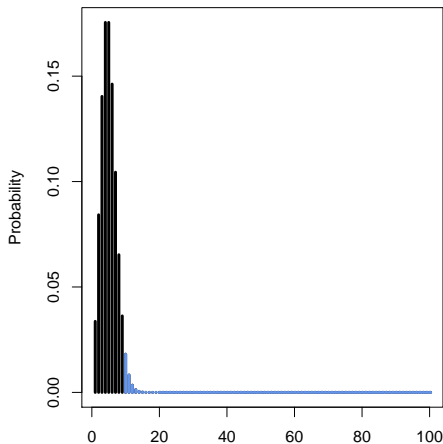
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R code!

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$$e^x = 1 + x + \frac{x^2}{2!} + \frac{x^3}{3!} + \dots$$

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$$e^{-\lambda} \sum_{k=0}^{\infty} \frac{\lambda^k}{k!} = e^{-\lambda} \left(1 + \lambda + \frac{\lambda^2}{2!} + \dots \right)$$

Poisson Distribution

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Recall the **Taylor expansion** of e^x

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

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$$\text{var}(X) = E[X^2] - E[X]$$

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Very useful distribution, with strong assumptions. We'll explore in homework!

Often interested in how processes evolve over time

- Given voting history, probability of voting in the future
- Given history of candidate support, probability of future support
- Given prior conflicts, probability of future war
- Given previous words in a sentence, probability of next word

Potentially complex history

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Potentially complex history

Stochastic Process

Definition

Suppose we have a sequence of random variables

$\{X\}_{i=0}^M = X_0, X_1, X_2, \dots, X_M$ that take on the countable values of S . We will call $\{X\}_{i=0}^M$ a stochastic process with state space S .

If index gives time, then we might condition on history to obtain probability

$$\text{PMF } X_t, \text{ given history} = P(X_t | X_{t-1}, X_{t-2}, \dots, X_1, X_0)$$

Still Complex

Markov Chain

Definition

Suppose we have a stochastic process $\{X\}_{i=0}^M$ with countable state space S . Then $\{X\}_{i=0}^M$ is a markov chain if:

$$P(X_t | X_{t-1}, X_{t-2}, \dots, X_1, X_0) = P(X_t | X_{t-1})$$

A Markov chain's future depends only on its current state

Transition Matrix

Habitual turnout?

$$\mathbf{T} = \begin{pmatrix} & \text{Vote}_t & \text{Not Vote}_t \\ \text{Vote}_{t-1} & 0.8 & 0.2 \\ \text{Not Vote}_{t-1} & 0.3 & 0.7 \end{pmatrix}$$

- Suppose someone starts as a voter—what is their behavior after
- 1 iteration?
- 2 iterations?
- The long run?

R Code!

Monday: Continuous Random Variables!