Conditional Independence; Random variables

CSE 312 Spring 26

Lecture 8

Conditional Independence

Definition. Two events A and B are **independent** conditioned on C if
$P(C) \neq 0$ and $P(A \cap B \mid C) = P(A \mid C) \cdot P(B \mid C)$.

- If $P(A \cap C) \neq 0$, equivalent to $P(B|A \cap C) = P(B \mid C)$
- If $P(B \cap C) \neq 0$, equivalent to $P(A|B \cap C) = P(A \mid C)$

Contrast to Plain Independence. Two events A and B are **independent** if

$$P(A \cap B) = P(A) \cdot P(B).$$

Example – Tossing Coins (1)

Suppose that Coin 1 has probability of heads 0.3
and Coin 2 has probability of head 0.9.
We choose one of the coins randomly with equal probability and flip that coin 2 times independently. What is the probability we get all heads?

C_i = coin i was selected

Tossing Coins (2)

Suppose that Coin 1 has probability of heads 0.3
and Coin 2 has probability of head 0.9.
We choose one of the coins randomly with equal probability and flip that coin 2 times independently. What is the probability we get all heads?

C_i = coin i was selected

$$P(HH) = P(HH \mid C_1) \cdot P(C_1) + P(HH \mid C_2) \cdot P(C_2)$$

Law of Total Probability (LTP)

$$= P(H|C_1)^2 \, P(C_1) + P(H \mid C_2)^2 \, P(C_2)$$

Conditional Independence

$$= 0.3^2 \cdot 0.5 + 0.9^2 \cdot 0.5 = 0.45$$

Tossing coins (3)

Suppose that Coin 1 has probability of heads 0.3

and Coin 2 has probability of head 0.9.

We choose one coin randomly with equal probability and flip that coin 2 times independently. How does the probability we get all heads compare to $P(H)^2$?

Example – Tossing coins (4)

Suppose that Coin 1 has probability of heads 0.3
and Coin 2 has probability of head 0.9.

We choose one coin randomly with equal probability and flip that coin 2 times independently. How does the probability we get all heads compare to $P(H)^2$?

$$P(HH \mid C_1) = P(H|C_1)^2$$

$$P(HH) \neq P(H)^2$$

$$P(HH) = P(H|C_1)^2\,P(C_1) + P(H \mid C_2)^2\,P(C_2) = 0.3^2 \cdot 0.5 + 0.9^2 \cdot 0.5 = 0.45$$

$$P(H) = P(H|C_1) \cdot P(C_1) + P(H|C_2) \cdot P(C_2) \doteq 0.6 \qquad P(HH) = 0.36$$

Pset 3 Coding – Naïve Bayes (Algorithm for Spam Detection)

Will compute probability an email is spam given the words in it

Say email contains words $\{x_1, x_2, \ldots, x_n\}$.
Want to compute probability it's spam: $\mathbb{P}(S \mid x_1, \ldots, x_n)$

$$\frac{\mathbb{P}(x_1, \ldots, x_n \mid S)\mathbb{P}(S)}{\mathbb{P}(x_1, \ldots, x_n)} = \frac{\mathbb{P}(x_1, \ldots, x_n \mid S)\mathbb{P}(S)}{\mathbb{P}(x_1, \ldots, x_n \mid S)\mathbb{P}(S) + \mathbb{P}(x_1, \ldots, x_n \mid H)\mathbb{P}(H)}$$

We will assume words in an email are conditionally independent, given email is spam or ham!

$$\begin{aligned} \mathbb{P}(x_1, \ldots, x_n, S) &= \mathbb{P}(x_1 \mid x_2, x_3, \ldots, x_n, S)\mathbb{P}(x_2 \mid x_3, \ldots, x_n, S) \ldots \mathbb{P}(x_{n-1} \mid x_n, S)\mathbb{P}(x_n \mid S)\mathbb{P}(S) \\ &\approx \mathbb{P}(x_1 \mid S)\mathbb{P}(x_2 \mid S) \ldots \mathbb{P}(x_{n-1} \mid S)\mathbb{P}(x_n \mid S)\mathbb{P}(S) \\ &= \mathbb{P}(S) \prod_{i=1}^{n} \mathbb{P}(x_i \mid S) \end{aligned}$$

Coding problem will be released on Ed at 11am today.

Agenda (1)

- Random Variables
- Probability Mass Function (PMF)
- Cumulative Distribution Function (CDF)

Random Variables (Idea)

Often: We want to **capture quantitative properties** of the outcome of a random experiment, e.g.:

- *What is the total of two dice rolls?*
- *What is the number of coin tosses needed to see the first head?*
- *What is the number of heads among 5 coin tosses?*

Random Variables

Definition. A **random variable (RV)** for a probability space $(\Omega, \mathbb{P})$ is a function $X: \Omega \to \mathbb{R}$.

The set of values that X can take on is called its range/support Ω_X

Example. Number of heads in 2 independent coin flips $\Omega = \{\mathrm{HH}, \mathrm{HT}, \mathrm{TH}, \mathrm{TT}\}$

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

Drawing Balls

20 balls labeled $1, 2, \ldots, 20$ in an urn

- Draw a subset of 3 uniformly at random
- What is $|\Omega|$?

Drawing Balls – new random variable

20 balls labeled 1, 2, … , 20 in an urn

– Draw a subset of 3 uniformly at random

– $|\Omega| = \binom{20}{3}$

– Let $X = \text{maximum of the 3 numbers on the balls}$

- Example: $X(2, 7, 5) = 7$
- Example: $X(15, 3, 8) = 15$

Drawing Balls – what is $|\Omega_X|$?

20 balls labeled 1, 2, … , 20 in an urn

- Draw a subset of 3 uniformly at random
- Let $X = \text{maximum of the 3 numbers on the balls}$
  - Example: $X(2,7,5) = 7$
  - Example: $X(15,3,8) = 15$
- What is $|\Omega_X|$?

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A. 20^3
B. 20
C. 18
D. $\binom{20}{3}$

Example: Returning Homeworks

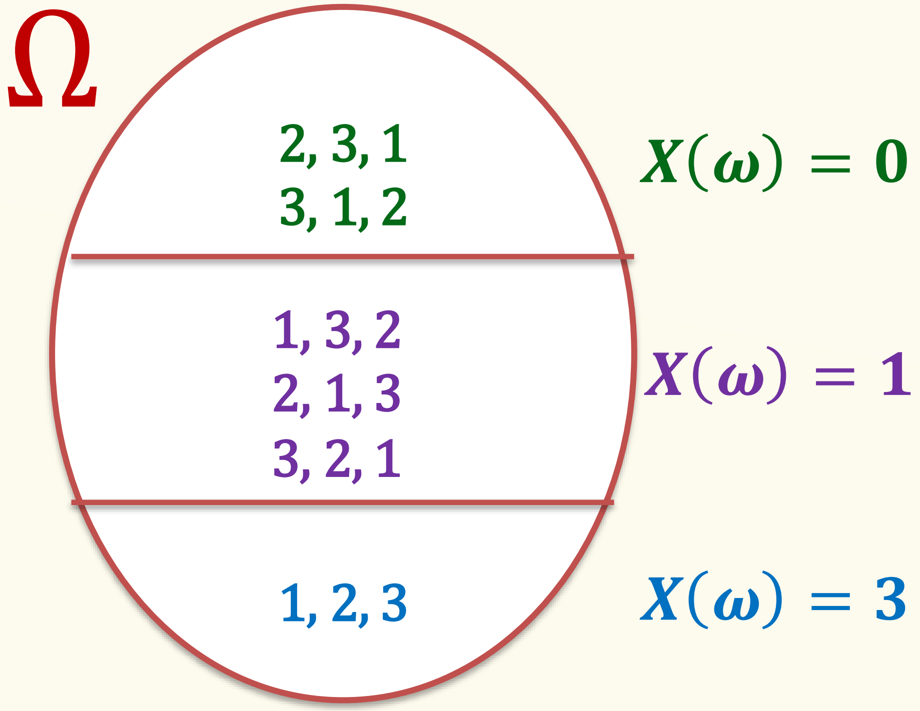
- Class with 3 students, randomly hand back homeworks. All permutations equally likely.
- Let X be the number of students who get their own HW

$\Pr(\omega)$	ω	$X(\omega)$
$1/6$	$1, 2, 3$	
$1/6$	$1, 3, 2$	
$1/6$	$2, 1, 3$	
$1/6$	$2, 3, 1$	
$1/6$	$3, 1, 2$	
$1/6$	$3, 2, 1$	

Example: Returning Homeworks (2)

- Class with 3 students, randomly hand back homeworks. All permutations equally likely.
- Let X be the number of students who get their own HW

$\Pr(\omega)$	ω	$X(\omega)$
1/6	1, 2, 3	3
1/6	1, 3, 2	1
1/6	2, 1, 3	1
1/6	2, 3, 1	0
1/6	3, 1, 2	0
1/6	3, 2, 1	1

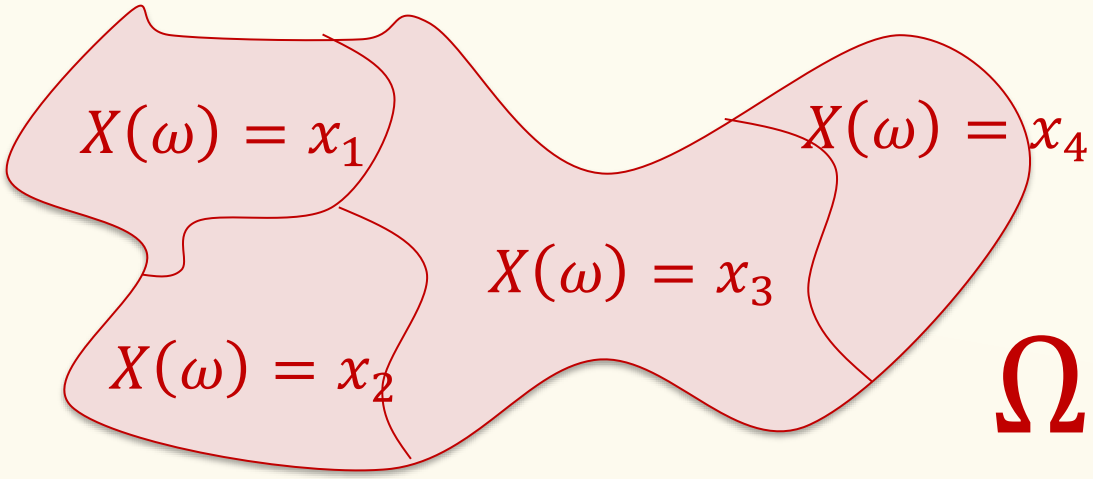


Random variables partition sample space

Definition. A **random variable (RV)** for a probability space $(\Omega, \mathbb{P})$ is a function $X: \Omega \to \mathbb{R}$.

The set of values that X can take on is called its range/support Ω_X

Random variables partition the sample space.



Definition. For a RV $X: \Omega \to \mathbb{R}$, we define the event

$$\{X = x\} \stackrel{\text{def}}{=} \{\omega \in \Omega \mid X(\omega) = x\}$$

Agenda (2)

- Random Variables
- Probability Mass Function (pmf)
- Cumulative Distribution Function (CDF)

Probability Mass Function (PMF)

Definition. For a RV $X: \Omega \to \mathbb{R}$, we define the event

$$\{X = x\} \overset{\text{def}}{=} \{\omega \in \Omega \mid X(\omega) = x\}$$

The **probability mass function** (PMF) of X tells us the probabilities of these events, i.e., the probability that X takes each value in Ω_X

We use the notation

$$p_X(x) = \mathbb{P}(X = x) = \mathbb{P}(\{\omega \in \Omega \mid X(\omega) = x\})$$

For the probability mass function

$$\sum_{x \in \Omega_X} \mathbb{P}(X = x) = 1$$

Probability Mass Function – example 1

Flipping two independent coins $\Omega = \{\mathrm{HH}, \mathrm{HT}, \mathrm{TH}, \mathrm{TT}\}$

X = number of heads in the two flips

$X(HH) = 2 \qquad X(HT) = 1 \qquad X(TH) = 1 \qquad X(TT) = 0$

$\Omega_{\mathrm{X}} = \{0, 1, 2\}$

What is the pmf of X?

Probability Mass Function

Flipping two independent coins

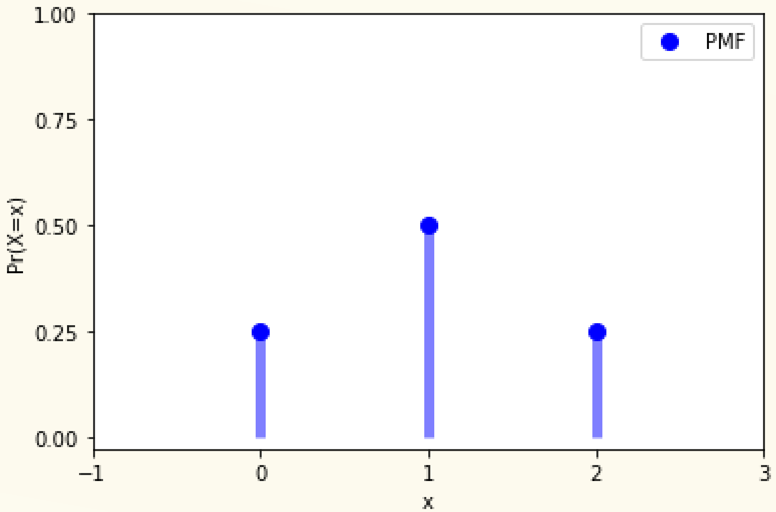
$$\Omega = \{\mathrm{HH, HT, TH, TT}\}$$

$$X = \text{number of heads in the two flips}$$

$$X(HH) = 2 \qquad X(HT) = 1 \qquad X(TH) = 1 \qquad X(TT) = 0$$

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

$$\mathrm{p}_X(\mathrm{x}) = \Pr(X = x) = \begin{cases} \frac{1}{4}, & x = 0 \\ \frac{1}{2}, & x = 1 \\ \frac{1}{4}, & x = 2 \\ 0, & o.w. \end{cases}$$



RV Example

20 balls labeled 1, 2, …, 20 in a bin

- Draw a subset of 3 uniformly at random
- Let $X = \text{maximum of the 3 numbers on the balls}$

What is $p_X(20) = P(X = 20)$?

Poll: https://pollev.com/ annakarlin185

A. $\binom{20}{2} / \binom{20}{3}$

B. $\binom{19}{2} / \binom{20}{3}$

C. $19^2 / \binom{20}{3}$

D. $19 \cdot 18 / \binom{20}{3}$

Agenda (3)

- Random Variables
- Probability Mass Function (PMF)
- Cumulative Distribution Function (CDF)

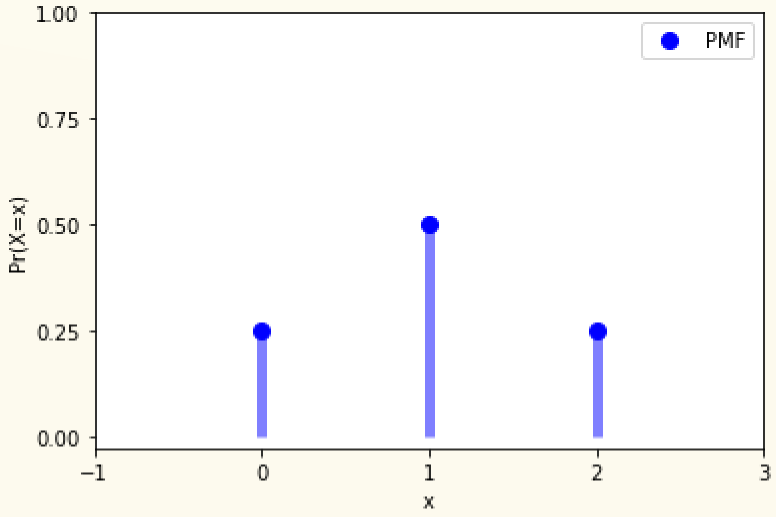
Cumulative Distribution Function (CDF)

Definition. For a RV $X: \Omega \to \mathbb{R}$, the cumulative distribution function of X specifies for any real number x, the probability that $X \leq x$.

$$\mathrm{F}_X(x) = \Pr(X \leq x)$$

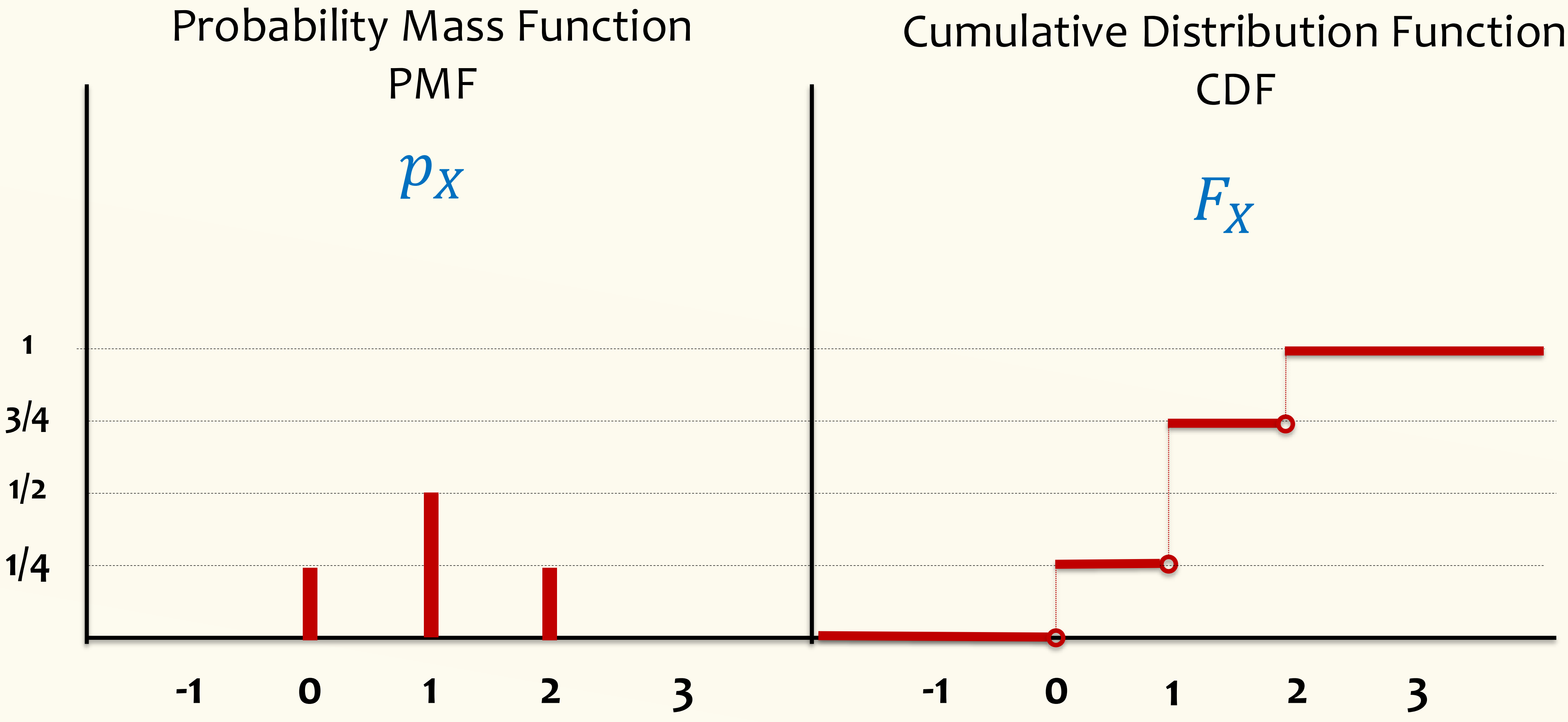
Recall the **probability mass function** of X, where X is the number of heads in 2 independent coin tosses.

$$\mathrm{p}_X(\mathrm{x}) = \Pr(X = x) = \begin{cases} \frac{1}{4}, & x = 0 \\ \frac{1}{2}, & x = 1 \\ \frac{1}{4}, & x = 2 \\ 0, & o.w. \end{cases}$$



Example – Two fair independent coin flips

X = number of heads



Cumulative Distribution Function (pmf and CDF for two coin tosses)

Definition. For a RV $X: \Omega \to \mathbb{R}$, the cumulative distribution function of X specifies for any real number x, the probability that $X \leq x$.

$$\mathrm{F}_X(x) = \Pr(X \leq x)$$

Go back to 2 coin clips, where X is the number of heads

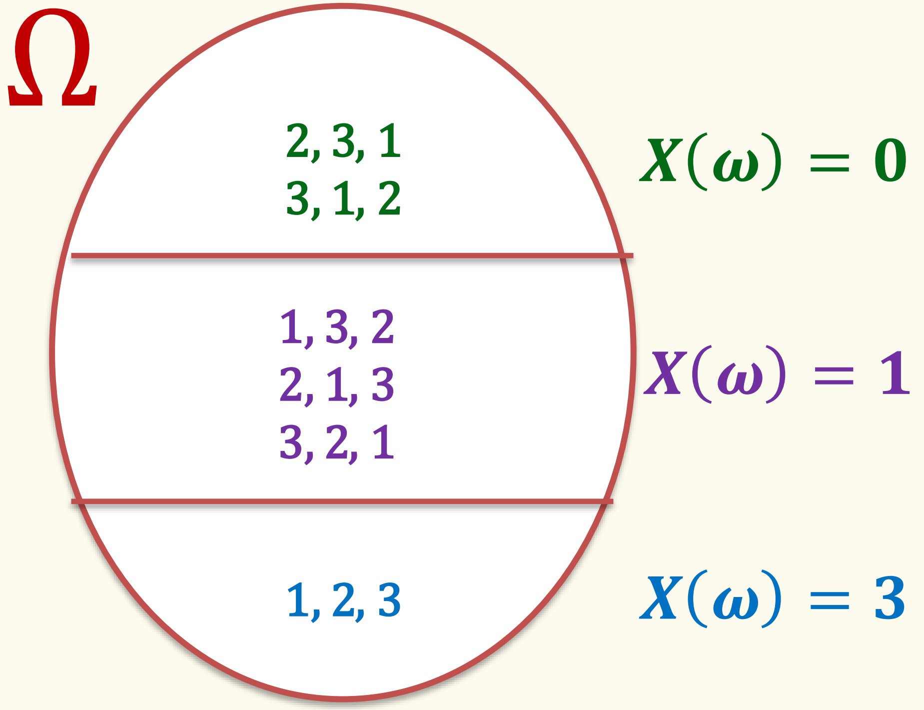
$$\mathrm{p}_X(\mathrm{x}) = \Pr(X = x) = \begin{cases} \frac{1}{4}, & x = 0 \\ \frac{1}{2}, & x = 1 \\ \frac{1}{4}, & x = 2 \\ 0, & o.w. \end{cases}$$

$$F_X(x) = \begin{cases} 0, & x < 0 \\ \frac{1}{4}, & 0 \leq x < 1 \\ \frac{3}{4}, & 1 \leq x < 2 \\ 1, & 2 \leq x \end{cases}$$

Example: Returning Homeworks – Partition of sample space

- Class with 3 students, randomly hand back homeworks. All permutations equally likely.
- Let X be the number of students who get their own HW

$\Pr(\omega)$	ω	$X(\omega)$
1/6	1, 2, 3	3
1/6	1, 3, 2	1
1/6	2, 1, 3	1
1/6	2, 3, 1	0
1/6	3, 1, 2	0
1/6	3, 2, 1	1



Example: Returning Homeworks –pmf and CDF

$\Pr(\omega)$	ω	$X(\omega)$
1/6	1, 2, 3	3
1/6	1, 3, 2	1
1/6	2, 1, 3	1
1/6	2, 3, 1	0
1/6	3, 1, 2	0
1/6	3, 2, 1	1

- Class with 3 students, randomly hand back homeworks.

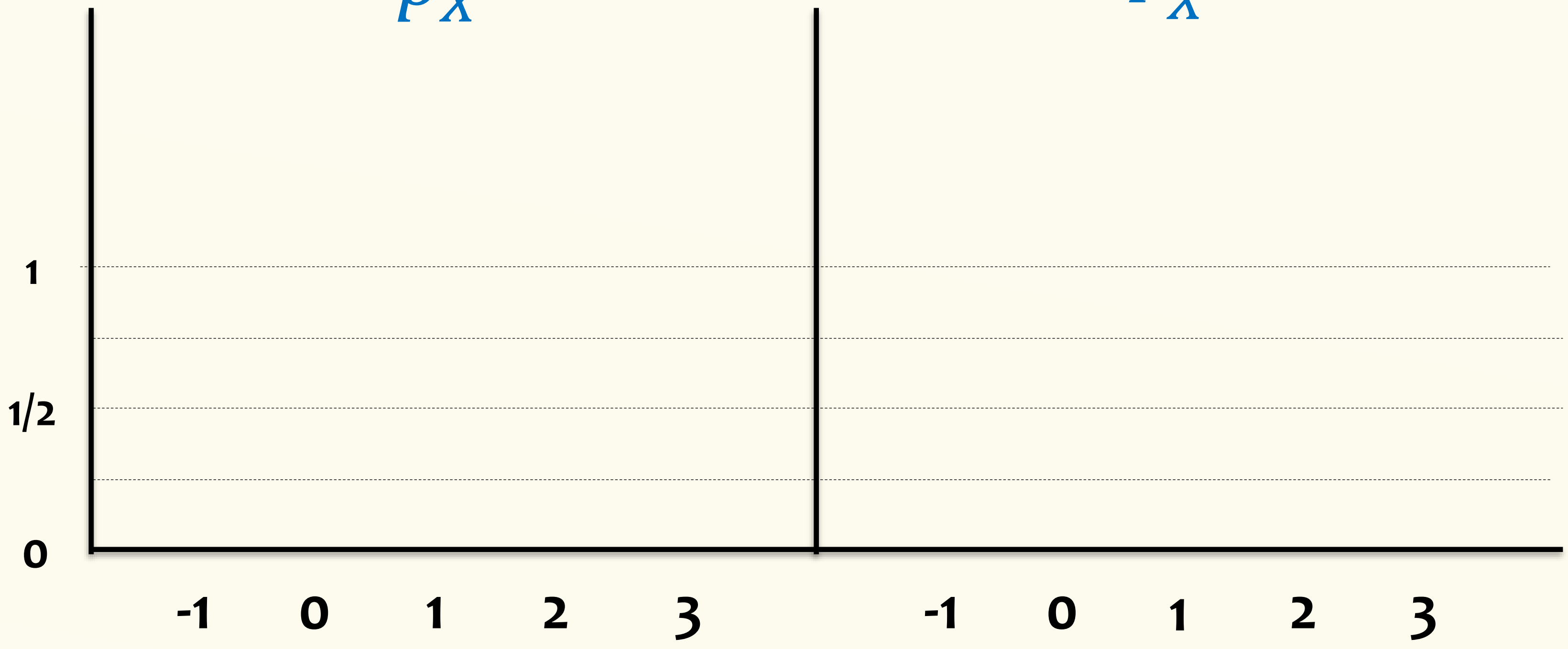
All permutations equally likely.

- **Let X be the number of students who get their own HW**

Probability Mass Fn
PMF p_X

Cumulative Distribution Fn
CDF F_X

$$\mathbf{p_X(0) = P(X = 0) = 1/3}$$
$$\mathbf{p_X(1) = P(X = 1) = 1/2}$$
$$\mathbf{p_X(2) = P(X = 3) = 1/6}$$



Example – Number of Heads

We flip n coins, independently, each heads with probability p

$$\Omega = \{\text{HH}\cdots\text{HH}, \text{HH}\cdots\text{HT}, \text{HH}\cdots\text{TH}, \dots, \text{TT}\cdots\text{TT}\}$$

$X =$ # of heads $\qquad\qquad\qquad \Omega_X =$

$$p_X(k) = P(X = k) =$$

Example – Number of Heads - pmdf

We flip n coins, independently, each heads with probability p

$\Omega = \{\text{HH}\cdots\text{HH}, \text{HH}\cdots\text{HT}, \text{HH}\cdots\text{TH}, \ldots, \text{TT}\cdots\text{TT}\}$

$X =$ # of heads

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

# of sequences with k heads

Prob of sequence w/ k heads

Agenda (4)

- Random Variables
- Probability Mass Function (PMF)
- Cumulative Distribution Function (CDF)
- Expectation

Expectation (Idea)

Example. Toss a coin 20 times independently with probability ¼ of coming up heads on each toss.

$X =$ number of heads

How many heads do you ***expect*** to see?

What if you toss it independently n times and it comes up heads with probability p each time?

Expected Value of a Random Variable

Definition. Given a discrete RV $X: \Omega \to \mathbb{R}$, the **expectation** or **expected value** or **mean** of X is

$$\mathbb{E}[X] = \sum_{\omega \in \Omega} X(\omega) \cdot P(\omega)$$

or equivalently

$$\mathbb{E}[X] = \sum_{x \in \Omega_X} x \cdot P(X = x) \quad = \sum_{x \in \Omega_X} x \cdot p_X(x)$$

Intuition: "Weighted average" of the possible outcomes (weighted by probability)

Expectation

$$\mathbb{E}[X] = \sum_{\omega \in \Omega} X(\omega) \cdot P(\omega)$$

$$\mathbb{E}[X] = \sum_{x \in \Omega_X} x \cdot P(X = x)$$

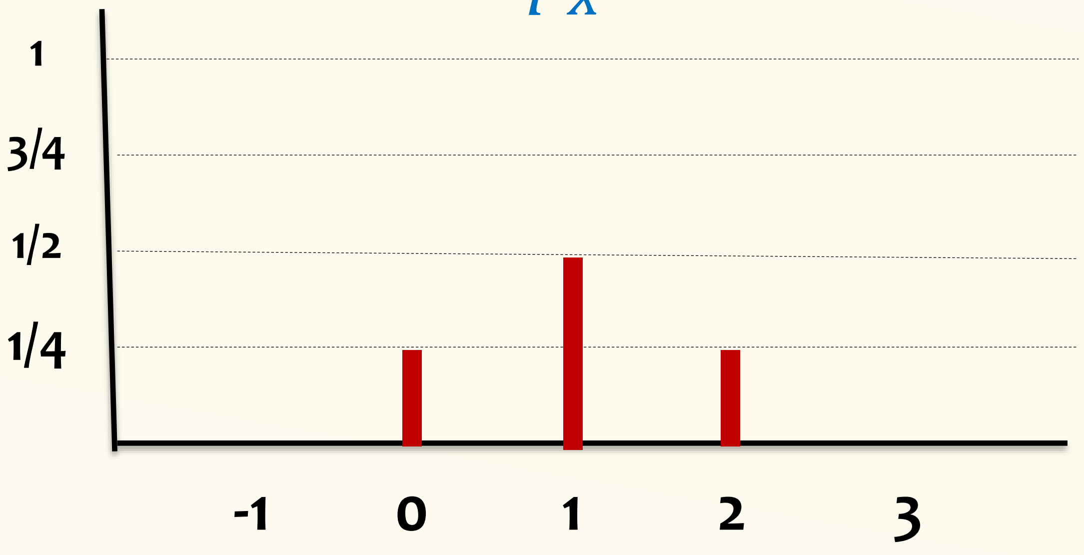
Example. Two fair coin flips

$$\Omega = \{\mathrm{TT}, \mathrm{HT}, \mathrm{TH}, \mathrm{HH}\}$$

$X =$ number of heads

What is $\mathbb{E}[X]$?

p_X



$$\mathbb{E}[X] = X(TT)\,P(TT) + X(HT)\,P(HT) + X(TH)\,P(TH) + X(HH)\,P(HH)$$

$$= 0 \cdot \frac{1}{4} + 1 \cdot \frac{1}{4} + 1 \cdot \frac{1}{4} + 2 \cdot \frac{1}{4} = 1$$

$$\mathbb{E}[X] = 0 \cdot p_X(0) + 1 \cdot p_X(1) + 2 \cdot p_X(2)$$

$$= 0 \cdot \frac{1}{4} + 1 \cdot \frac{1}{2} + 2 \cdot \frac{1}{4} = \frac{1}{2} + \frac{1}{2} = 1$$