CSE 312

Foundations of Computing II

Lecture 9: Variance and Independence of RVs

Recap Linearity of Expectation

Theorem. For any two random variables X and Y *(X, Y do not need to be independent)*

$$\mathbb{E}[X+Y] = \mathbb{E}[X] + \mathbb{E}[Y].$$

Theorem. For any random variables $X_1, \dots, X_n$,

$$\mathbb{E}[X_1 + \cdots + X_n] = \mathbb{E}[X_1] + \cdots + \mathbb{E}[X_n].$$

For any event A, can define the indicator random variable X for A

$$X_A = \begin{cases} 1 & \text{if event } A \text{ occurs} \\ 0 & \text{if event } A \text{ does not occur} \end{cases}$$

$$P(X_A = 1) = P(A)$$
$$P(X_A = 0) = 1 - P(A)$$

$$E[X_A] = 1 \cdot P(A) + 0(1 - P(A))$$
$$= P(A)$$

Example: Returning Homeworks

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

What is $\mathbb{E}[X]$? Use linearity of expectation!

$\mathbf{Pr}(\boldsymbol{\omega})$	$\boldsymbol{\omega}$	$\boldsymbol{X}(\boldsymbol{\omega})$
$1/6$	$1,2,3$	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

Decompose: What is X_i?

$X = \sum_i X$

$X_i = 1$ iff i^{th} student gets own HW back

LOE: $\mathbb{E}[X] = \mathbb{E}[X_1] + \cdots + \mathbb{E}[X_n]$ $= n \cdot \frac{1}{n} = 1$

52 5 10

Conquer: What is $\mathbb{E}[X_i]$? A. $\frac{1}{n}$ B. $\frac{1}{n-1}$ C. $\frac{1}{2}$

Poll: **pollev.com/rachel312**

Pairs with the same birthday

$\binom{m}{2}$

- In a class of m students, on average how many pairs of people have the same birthday (assuming 365 equally likely birthdays)?

$X = \sum_{i \neq j} X_{ij}$

Decompose: Indicator events involve **pairs** of students (i, j) for $i \neq j$

$X_{ij} = 1$ iff students i and j have the same birthday

$\sqrt{365} \sim$ $\sqrt{730} = 27$

LOE: $\binom{m}{2}$ indicator variables X_{ij}

> 1

Conquer: $\mathbb{E}[X_{ij}] = \frac{1}{365}$ so total expectation is $\frac{\binom{m}{2}}{365} = \boxed{\frac{m(m-1)}{730}}$ pairs

$365 \cdot \frac{1}{365} \cdot \frac{1}{365}$

Linearity of Expectation – Even stronger

Theorem. For any random variables $X_1, \dots, X_n$, and real numbers $a_1, \dots, a_n \in \mathbb{R}$,

$$\mathbb{E}[a_1 X_1 + \cdots + a_n X_n] = a_1 \mathbb{E}[X_1] + \cdots + a_n \mathbb{E}[X_n].$$

Very important: In general, we do <u>not</u> have $\mathbb{E}[X \cdot Y] = \mathbb{E}[X] \cdot \mathbb{E}[Y]$

unless independent.

Linearity is special!

$g(X,Y)$

In general $\mathbb{E}[g(X)] \neq g\big(\mathbb{E}(X)\big)$

E.g., $X = \begin{cases} +1 \text{ with prob } 1/2 \\ -1 \text{ with prob } 1/2 \end{cases}$

Then: $\mathbb{E}[X^2] \neq \mathbb{E}[X]^2$

$\quad\ \ \|\qquad\qquad \|$

$\quad\ \ 1 \qquad\qquad 0$

How DO we compute $\mathbb{E}[g(X)]$?

Expected Value of $g(X)$

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

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

or equivalently

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

Agenda

- Variance
- Properties of Variance
- Independent Random Variables
- Properties of Independent Random Variables

Two Games

Game 1: *In every round, you win $2 with probability 1/3, lose $1 with probability 2/3.*

W_1 = payoff in a round of Game 1

$$P(W_1 = 2) = \frac{1}{3}, P(W_1 = -1) = \frac{2}{3}$$

$$\mathbb{E}[W_1] = 0$$

Game 2: *In every round, you win $10 with probability 1/3, lose $5 with probability 2/3.*

W_2 = payoff in a round of Game 2

$$P(W_2 = 10) = \frac{1}{3}, P(W_2 = -5) = \frac{2}{3}$$

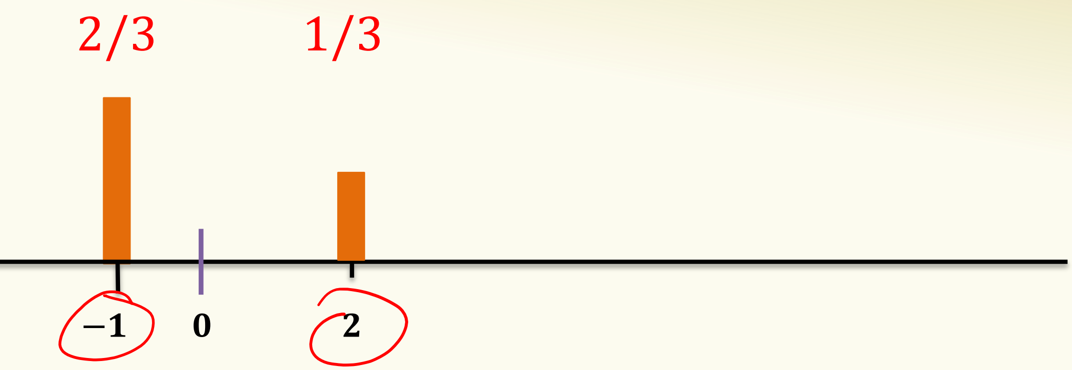
$$\mathbb{E}[W_2] = 0$$

Which game would you rather play?

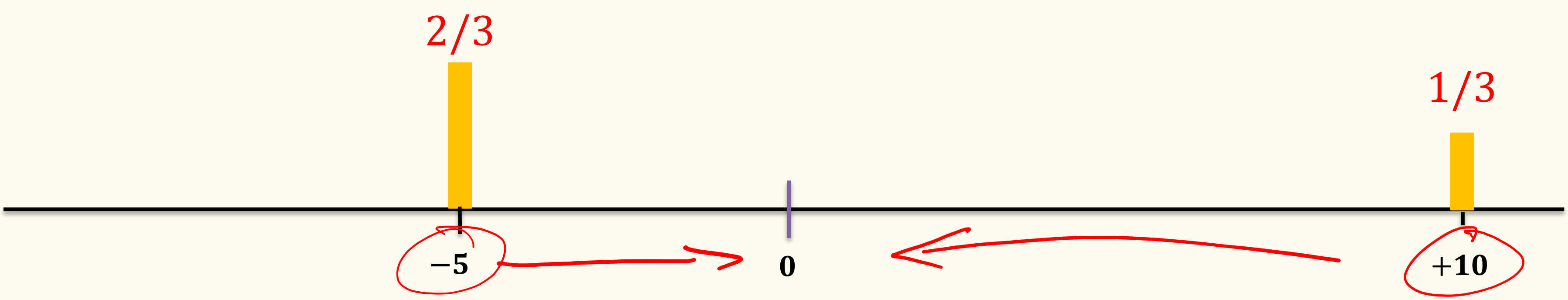
Somehow, Game 2 has higher volatility / exposure!

Two Games

$P(W_1 = 2) = \frac{1}{3}, P(W_1 = -1) = \frac{2}{3}$



$P(W_2 = 10) = \frac{1}{3}, P(W_2 = -5) = \frac{2}{3}$



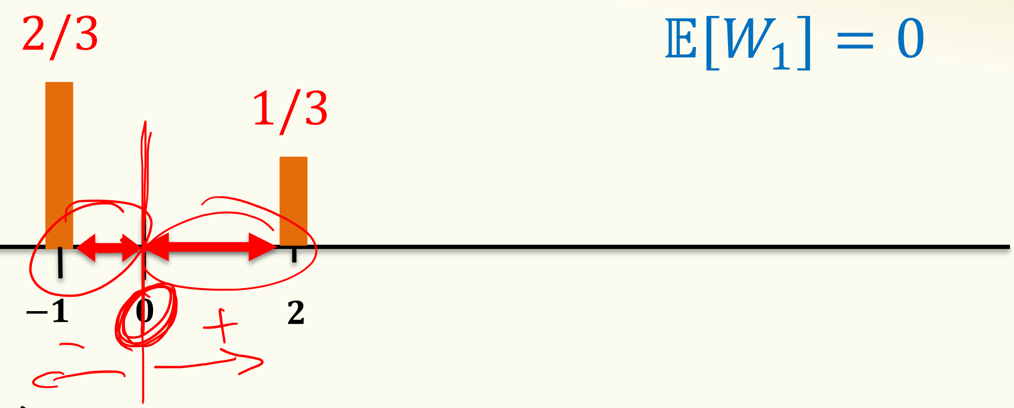
Same expectation, but clearly a very different distribution.

We want to capture the difference – New concept: **Variance**

Variance (Intuition, First Try)

$P(W_1 = 2) = \frac{1}{3}, P(W_1 = -1) = \frac{2}{3}$

$\mathbb{E}[W_1] = 0$



New quantity (random variable): How far from the expectation?

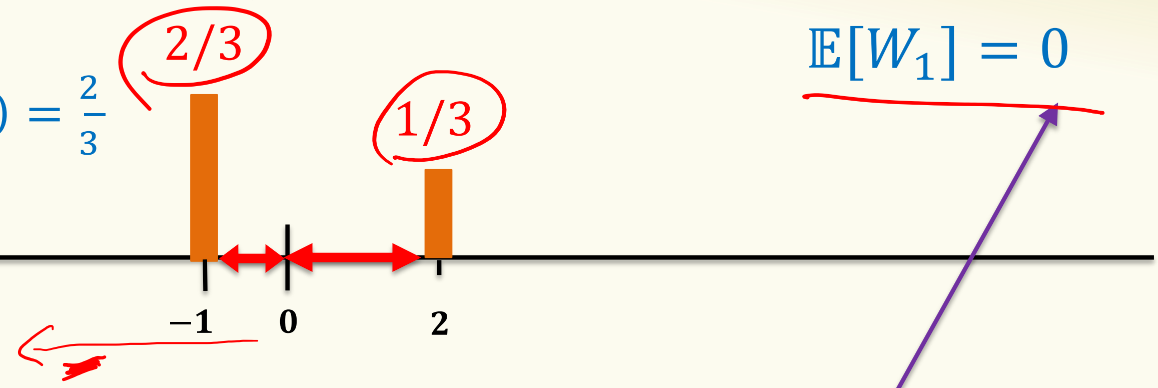
$\Delta(W_1) = W_1 - \mathbb{E}[W_1]$

$$\begin{aligned}\mathbb{E}[\Delta(W_1)] &= \mathbb{E}[W_1 - \mathbb{E}[W_1]] \\ &= \mathbb{E}[W_1] - \mathbb{E}[\mathbb{E}[W_1]] \\ &= \mathbb{E}[W_1] - \mathbb{E}[W_1] \\ &= 0\end{aligned}$$

Variance (Intuition, Better Try)

$P(W_1 = 2) = \frac{1}{3}, P(W_1 = -1) = \frac{2}{3}$

$\mathbb{E}[W_1] = 0$



A better quantity (random variable): How far from the expectation?

$\Delta(W_1) = (W_1 - \mathbb{E}[W_1])^2$

$P(\Delta(W_1) = 1) = \frac{2}{3}$

$P(\Delta(W_1) = 4) = \frac{1}{3}$

$$\mathbb{E}[\Delta(W_1)] = \mathbb{E}[(W_1 - \mathbb{E}[W_1])^2]$$

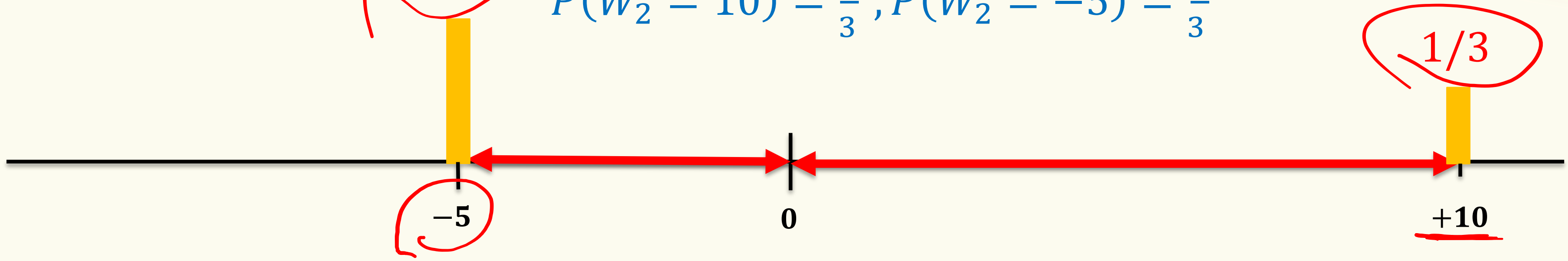
$$= \frac{2}{3} \cdot 1 + \frac{1}{3} \cdot 4$$

$$= 2$$

Variance (Intuition, Better Try)

$\mathbb{E}[W_2] = 0$

$P(W_2 = 10) = \frac{1}{3}$, $P(W_2 = -5) = \frac{2}{3}$



A better quantity (random variable): How far from the expectation?

$$\Delta(W_2) = (W_2 - \mathbb{E}[W_2])^2$$

$$\mathbb{P}(\Delta(W_2) = 25) = \frac{2}{3}$$

$$\mathbb{P}(\Delta(W_2) = 100) = \frac{1}{3}$$

$$\mathbb{E}[\Delta(W_2)] = \mathbb{E}[(W_2 - \mathbb{E}[W_2])^2]$$

$$= \frac{2}{3} \cdot 25 + \frac{1}{3} \cdot 100$$

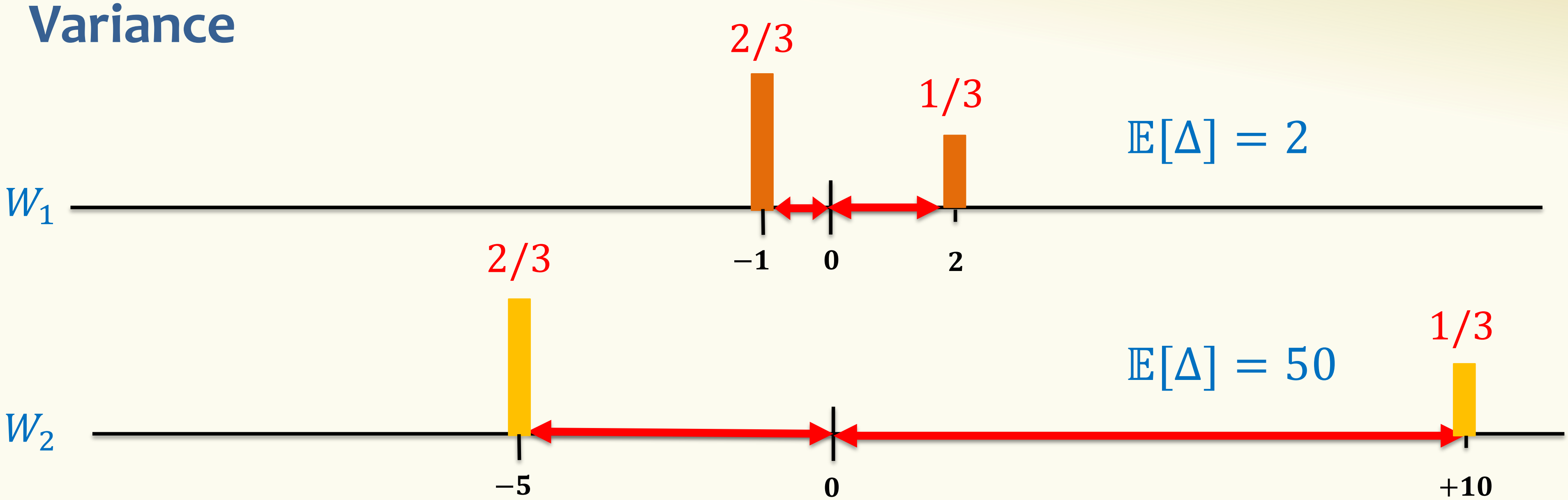
$$= 50$$

Poll:

pollev.com/paulbeame028

A. 0
B. 20/3
C. 50 40
D. 2500

Variance



We say that W_2 has **"higher variance"** than W_1.

Variance

Definition. The **variance** of a (discrete) RV X is

$$\mathrm{Var}(X) = \mathbb{E}[(X - \boxed{\mathbb{E}[X]})^2] = \sum_x p_X(x) \cdot (x - \mathbb{E}[X])^2$$

Recall $\mathbb{E}[X]$ is a **constant**, not a random variable itself.

Standard deviation: $\sigma(X) = \sqrt{\mathrm{Var}(X)}$

Intuition: Variance (or standard deviation) is a quantity that measures, in expectation, how "far" the random variable is from its expectation.

Variance – Example 1

X fair die

- $P(X = 1) = \cdots = P(X = 6) = 1/6$
- $\mathbb{E}[X] = 3.5$

$\mathrm{Var}(X) = ?$ $\left(x - \mathbb{E}(X)\right)^2$

Variance – Example 1

X fair die

- $P(X = 1) = \cdots = P(X = 6) = 1/6$
- $\mathbb{E}[X] = 3.5$

$$\mathrm{Var}(X) = \sum_x P(X = x) \cdot (x - \mathbb{E}[X])^2$$

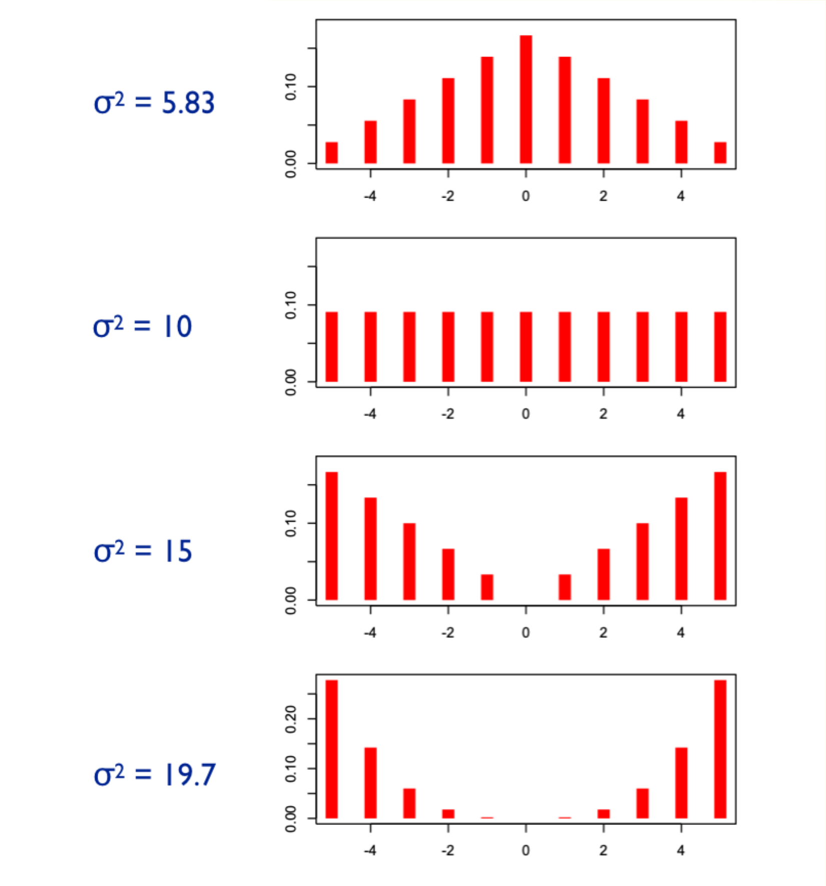
$$= \frac{1}{6}[(1 - 3.5)^2 + (2 - 3.5)^2 + (3 - 3.5)^2 + (4 - 3.5)^2 + (5 - 3.5)^2 + (6 - 3.5)^2]$$

$$= \frac{2}{6}[2.5^2 + 1.5^2 + 0.5^2] = \frac{2}{6}\left[\frac{25}{4} + \frac{9}{4} + \frac{1}{4}\right] = \frac{35}{12} \approx 2.91677 \ldots$$

Variance in Pictures

Captures how much "spread' there is in a pmf

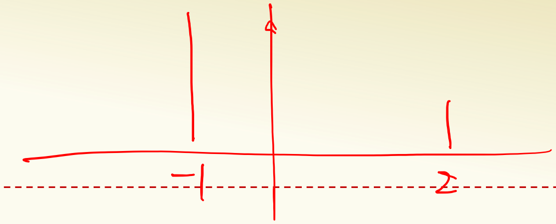
All pmfs have same expectation



Agenda

- Variance
- Properties of Variance
- Independent Random Variables
- Properties of Independent Random Variables

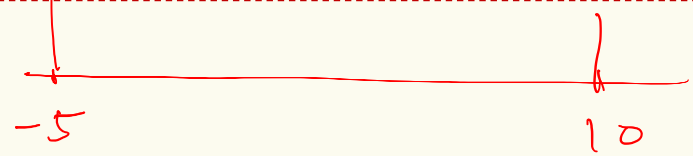
Variance – Properties



Definition. The **variance** of a (discrete) RV X is

$$\mathrm{Var}(X) = \mathbb{E}[(X - \mathbb{E}[X])^2] = \sum_x p_X(x) \cdot (x - \mathbb{E}[X])^2$$

$X_2 = 5X_1$



Theorem. For any $a, b \in \mathbb{R}$, $\mathrm{Var}(a \cdot X + b) = a^2 \cdot \mathrm{Var}(X)$

(Proof: Exercise!)

Theorem. $\mathrm{Var}(X) = \mathbb{E}[X^2] - \mathbb{E}[X]^2$

Variance

Theorem. $\mathrm{Var}(X) = \mathbb{E}[X^2] - \mathbb{E}[X]^2$

Proof: $\mathrm{Var}(X) = \mathbb{E}[(X - \mathbb{E}[X])^2]$

Recall $\mathbb{E}[X]$ is a **constant**

$$= \mathbb{E}[X^2 - 2\mathbb{E}[X] \cdot X + \mathbb{E}[X]^2]$$

$$= \mathbb{E}(X^2) - 2\mathbb{E}[X]\mathbb{E}[X] + \cancel{\mathbb{E}[X]^2}$$

(linearity of expectation!)

$$= \mathbb{E}[X^2] - \mathbb{E}[X]^2$$

$\mathbb{E}[X^2]$ and $\mathbb{E}[X]^2$ are different !

Variance – Example 1

X fair die

- $\mathbb{P}(X = 1) = \cdots = \mathbb{P}(X = 6) = 1/6$
- $\mathbb{E}[X] = \frac{21}{6}$
- $\mathbb{E}[X^2] = \frac{91}{6}$

$$\mathrm{Var}(\mathrm{X}) = \mathbb{E}[X^2] - \mathbb{E}[X]^2 = \frac{91}{6} - \left(\frac{21}{6}\right)^2 = \frac{105}{36} \approx 2.91677$$

Variance of Indicator Random Variables

Suppose that X_A is an indicator RV for event A with $P(A) = p$ so

$$\mathbb{E}[X_A] = P(A) = p \qquad \frac{1}{2}$$

Since X_A only takes on values 0 and 1, we always have $X_A^2 = X_A$ so

$$\mathrm{Var}(X_A) = \mathbb{E}[X_A^2] - \mathbb{E}[X_A]^2 = \mathbb{E}[X_A] - \mathbb{E}[X_A]^2 = p - p^2 = p(1-p)$$

$p = \frac{1}{2}$ $\quad$ var $= \frac{1}{4} = 0.25$

$p = 0.1$ $\quad$ var $= 0.1 \cdot 0.9 = 0.09$

In General, $\mathrm{Var}(X+Y) \neq \mathrm{Var}(X) + \mathrm{Var}(Y)$

$\left(X+Y-E(X+Y)\right)^2$

Proof by counter-example:

- Let X be a r.v. with pmf $P(X=1) = P(X=-1) = 1/2$
  - What is $\mathbb{E}[X]$ and $\mathrm{Var}(X)$?

    $\mathbb{E}[X] = 0$ $\qquad$ $\mathrm{Var}(X) = 1$
- Let $Y = -X$
  - What is $\mathbb{E}[Y]$ and $\mathrm{Var}(Y)$?

    $\mathbb{E}[Y] = 0$ $\qquad$ $\mathrm{Var}(Y) = 1$

What is $\mathrm{Var}(\underbrace{X+Y}_{0})$? $\qquad$ $E[X+\underbrace{Y}_{=-X}] = E[0] = 0$

$= 0$


Brain Break

Agenda

- Variance
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Random Variables and Independence

Comma is shorthand for AND

Definition. Two random variables X, Y are **(mutually) independent** if for all x, y,

$$P(X = x, Y = y) = P(X = x) \cdot P(Y = y)$$

$= P(X=x)\,P(Y=y \mid X=x)$

Intuition: Knowing X doesn't help you guess Y and vice versa

$P(Y=y) = P(Y=y \mid X=x)$

Definition. The random variables $X_1, \dots, X_n$ are **(mutually) independent** if for all $x_1, \dots, x_n$,

$$P(X_1 = x_1, \dots, X_n = x_n) = P(X_1 = x_1) \cdots P(X_n = x_n)$$

Note: No need to check for all subsets, but need to check <u>for all outcomes!</u>

Example

Let X be the number of heads in n *independent* coin flips of the same coin. Let $Y = X \bmod 2$ be the parity (even/odd) of X.

Are X and Y independent?

Poll:

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A. Yes

B. No

Example

Make $2n$ *independent* coin flips of the same coin.

Let X be the number of heads in the first n flips and Y be the number of heads in the last n flips.

Are X and Y independent?

Poll:

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A. Yes
B. No

Agenda

- Variance
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Important Facts about Independent Random Variables

Theorem. If X, Y independent, $\mathbb{E}[X \cdot Y] = \mathbb{E}[X] \cdot \mathbb{E}[Y]$

Theorem. If X, Y independent, $\mathrm{Var}(X + Y) = \mathrm{Var}(X) + \mathrm{Var}(Y)$

Corollary. If $X_1, X_2, \dots, X_n$ mutually independent,

$$\mathrm{Var}\left(\sum_{i=1}^{n} X_i\right) = \sum_{i}^{n} \mathrm{Var}(X_i)$$

(Not covered) Proof of $\mathbb{E}[X \cdot Y] = \mathbb{E}[X] \cdot \mathbb{E}[Y]$

Theorem. If X, Y independent, $\mathbb{E}[X \cdot Y] = \mathbb{E}[X] \cdot \mathbb{E}[Y]$

Proof

Let $x_i, y_i, i = 1, 2, \ldots$ be the possible values of X, Y.

$$\mathbb{E}[X \cdot Y] = \sum_i \sum_j x_i \cdot y_j \cdot P(X = x_i \wedge Y = y_j)$$

independence

$$= \sum_i \sum_j x_i \cdot y_i \cdot P(X = x_i) \cdot P(Y = y_j)$$

$$= \sum_i x_i \cdot P(X = x_i) \cdot \left(\sum_j y_j \cdot P(Y = y_j) \right)$$

$$= \mathbb{E}[X] \cdot \mathbb{E}[Y]$$

Note: *NOT* true in general; see earlier example $\mathbb{E}[X^2] \neq \mathbb{E}[X]^2$

(Not covered) Proof of $\mathrm{Var}(X+Y) = \mathrm{Var}(X) + \mathrm{Var}(Y)$

Theorem. If X, Y independent, $\mathrm{Var}(X+Y) = \mathrm{Var}(X) + \mathrm{Var}(Y)$

Proof

$Var(X+Y)$

$= \mathbb{E}[(X+Y)^2] - (\mathbb{E}[X+Y])^2$

linearity

$= \mathbb{E}[X^2 + 2XY + Y^2] - (\mathbb{E}[X] + \mathbb{E}[Y])^2$

$= \mathbb{E}[X^2] + 2\,\mathbb{E}[XY] + \mathbb{E}[Y^2] - (\mathbb{E}[X]^2 + 2\,\mathbb{E}[X]\,\mathbb{E}[Y] + \mathbb{E}[Y]^2)$

$= \mathbb{E}[X^2] - \mathbb{E}[X]^2 + \mathbb{E}[Y^2] - \mathbb{E}[Y]^2 + 2\,\mathbb{E}[XY] - 2\,\mathbb{E}[X]\,\mathbb{E}[Y]$

$= Var(X) + Var(Y) + 2\,\mathbb{E}[XY] - 2\,\mathbb{E}[X]\,\mathbb{E}[Y]$

$= Var(X) + Var(Y)$

equal by independence

Example – Coin Tosses

We flip n *independent* coins, each one heads with probability p

- $X_i = \begin{cases} 1, & i^{\text{th}} \text{ outcome is heads} \\ 0, & i^{\text{th}} \text{ outcome is tails.} \end{cases}$
- $Z =$ number of heads

Fact. $Z = \sum_{i=1}^{n} X_i$

$P(X_i = 1) = p$
$P(X_i = 0) = 1 - p$

What is $\mathbb{E}[Z]$? What is $\mathrm{Var}(Z)$?

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

Note: $X_1, \dots, X_n$ are mutually independent! [Verify it formally!]

$$\mathrm{Var}(Z) = \sum_{i=1}^{n} \mathrm{Var}(X_i) = n \cdot p(1-p)$$

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