

# Introduction to Probability

Lecture 8: Basic Inequalities and Law of Large Numbers

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# Outline

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Introduction

Markov's Inequality and Chebyshev's Inequality

Weak Law of Large Numbers

# Board Games Involving Dice

- Games with One Die: 



- Games with Two Dice: 

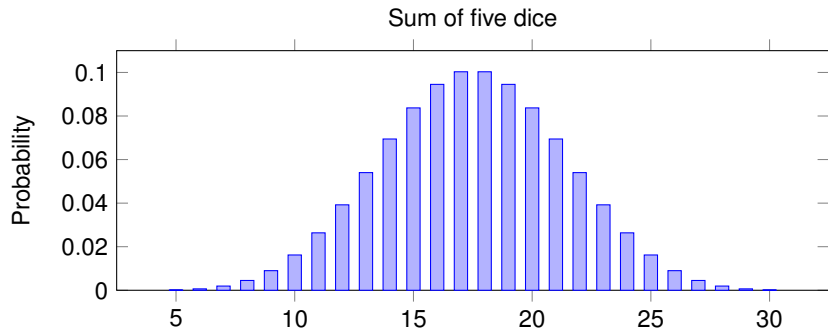
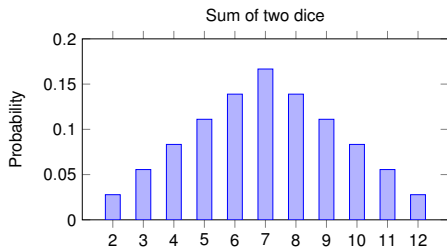
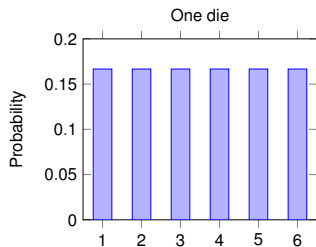


- Games with Five Dice: 



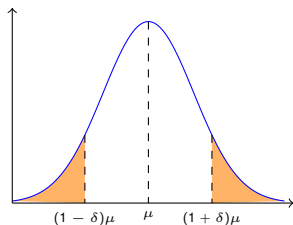
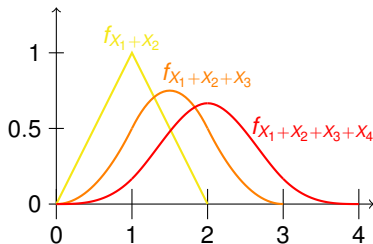
Source: All images from Wikipedia.

# Joint Distributions of Sums



## Motivation

We will study sums of independent and identically distributed variables. How does their distribution look like, and how well do they concentrate around the expectation?



1. Markov's inequality
2. Chebyshev's inequality
3. Law of Large Numbers
4. **Central Limit Theorem**

Re-use concepts from previous lectures:

1. Independence (Random Var.) (Lec. 1, 7)
2. Expectation and Variance (Lec. 2, 3)
3. Normal Distribution (Lec. 5)
4. Sums of Random Variables (Lec. 6)

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Markov's Inequality and Chebyshev's Inequality

Weak Law of Large Numbers

## Markov's Inequality

### Markov's Inequality

For any **non-negative** random variable  $X$  with finite  $\mathbf{E}[X]$ , it holds for any  $a > 0$ ,

$$\mathbf{P}[X \geq a] \leq \frac{\mathbf{E}[X]}{a}.$$

Markov's inequality is a so-called **tail-bound**: it upper bounds the probability that the random variable **exceeds** its mean



A. Markov (1856-1922)

### Comments:

- Markov's inequality can be rewritten as: for any  $\delta > 0$ ,

$$\mathbf{P}[X \geq \delta \cdot \mathbf{E}[X]] \leq 1/\delta.$$

- **Advantage**: Very basic inequality, we only need to know  $\mathbf{E}[X]$
- **Downside**: For many distributions, the tail bound might be quite loose
- Proof is similar to the proof of Chebyshev's inequality (Exercise!)

## Applying Markov's Inequality

### Example 2

Consider throwing an unbiased, six-sided dice 120 times and let  $X$  denote the number of times we obtain a six.

1. Derive an upper bound on  $\mathbf{P}[X \geq 30]$ .
2. Can you also derive an upper bound on  $\mathbf{P}[X \leq 10]$ ?

Answer

1. First compute  $\mathbf{E}[X] = 1/6 \cdot 120 = 20$ . Then by Markov:

$$\mathbf{P}[X \geq 30] \leq \frac{20}{30} = \frac{2}{3}.$$

2. Consider now the second bound.

- Define a new random variable  $Y := 120 - X$ .
- ⇒ This random variable is also non-negative (as  $X \leq 120$ ).
- Applying Markov's inequality (equivalent version) to  $Y$  yields:

$$\begin{aligned}\mathbf{P}[X \leq 10] &= \mathbf{P}[Y \geq 110] = \mathbf{P}\left[Y \geq \frac{110}{100} \cdot \mathbf{E}[Y]\right] \\ &\leq \frac{100}{110} = \frac{10}{11}.\end{aligned}$$

## Chebyshev's Inequality

### Chebyshev's Inequality

For **any** random variable  $X$  with finite  $\mathbf{E}[X]$  and  $\mathbf{V}[X]$ , for any  $a > 0$ ,

$$\mathbf{P}[|X - \mathbf{E}[X]| \geq a] \leq \mathbf{V}[X]/a^2.$$



P. Chebyshev (1821-1894)

### Comments:

- can be rewritten as:

The " $\mu \pm$  a few  $\sigma$ " rule. Most of the probability mass is within a few standard deviations from  $\mu$ .

$$\mathbf{P}[|X - \mathbf{E}[X]| \geq \sqrt{\delta \cdot \mathbf{V}[X]}] \leq 1/\delta.$$

- Unlike Markov, Chebyshev's inequality is two-sided and also holds for random variables with **negative** values
- In most cases, Chebyshev's inequality yields much **stronger bounds** than Markov (however, it requires knowledge not only of  $\mathbf{E}[X]$  but also  $\mathbf{V}[X]$ !)
- Chebyshev's inequality is also known as **Second Moment Method**

## Derivation of Chebychev's inequality

### Proof

- We will give a **self-contained** proof for a continuous random variable  $X$  (the case for discrete  $X$  is analogous).
- Write down the definition of  $\mathbf{V}[X]$  and then lower bound:

$$\begin{aligned}\mathbf{V}[X] &= \mathbf{E}[(X - \mu)^2] = \int_{-\infty}^{\infty} (x - \mu)^2 \cdot f_X(x) dx \\ &\geq \int_{|x - \mu| \geq a} (x - \mu)^2 \cdot f_X(x) dx \\ &\geq \int_{|x - \mu| \geq a} a^2 \cdot f_X(x) dx \\ &= a^2 \cdot \int_{|x - \mu| \geq a} f_X(x) dx \\ &= a^2 \cdot \mathbf{P}[|X - \mu| \geq a].\end{aligned}$$

- Dividing both sides by  $a^2$  yields the result.

**Exercise:** Can you find a proof that uses Markov's inequality?

## Example: Chebychev is (usually) much stronger than Markov

### Example 3

Throw an unbiased coin  $n$  times and let  $X$  be the total number of heads. In an experiment, with  $n$  large, we would usually expect a number of heads that is close to the expectation. Can we justify that?

Answer

$X \sim \text{Bin}(n, 1/2)$  so  $\mathbf{E}[X] = n \cdot \frac{1}{2}$ .

- **Markov's inequality:** For any  $\delta > 0$ ,

$$\mathbf{P}[X \geq (1 + \delta) \cdot \mathbf{E}[X]] \leq \frac{1}{1 + \delta}$$

- **Chebychev's inequality:**

$\Rightarrow$  We have  $\mathbf{V}[X] = np(1 - p) = n \cdot 1/2 \cdot 1/2$ . For any  $\delta > 0$ ,

$$\begin{aligned} \mathbf{P}[X \geq (1 + \delta) \cdot \mathbf{E}[X]] &= \mathbf{P}[X - \mathbf{E}[X] \geq \delta \cdot \mathbf{E}[X]] \\ &\leq \mathbf{P}[|X - n/2| \geq \delta \cdot (n/2)] \\ &\leq \frac{n \cdot 1/4}{\delta^2 (n/2)^2} = \frac{1}{\delta^2 n} \end{aligned}$$

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Markov's Inequality and Chebyshev's Inequality

**Weak Law of Large Numbers**

## Law of Large Numbers

= independent and identically distributed

### The Weak Law of Large Numbers

Let  $\bar{X}_n := 1/n \cdot \sum_{i=1}^n X_i$ , where the  $X_i$ 's are **i.i.d.** with finite expectation  $\mu$  and finite variance  $\sigma^2$ . Then, for any  $\epsilon > 0$ ,

$$\lim_{n \rightarrow \infty} \mathbf{P} \left[ |\bar{X}_n - \mu| > \epsilon \right] = 0$$

$$\forall \epsilon > 0: \forall \delta > 0: \exists N > 0: \forall n \geq N: \mathbf{P} \left[ |\bar{X}_n - \mu| > \epsilon \right] \leq \delta$$

- “Power of Averaging”: repeated samples allow us to estimate  $\mu$
- A similar statement holds even if the  $X_i$ 's are not identically distributed
- There is also a **strong law of large numbers**:

$$\mathbf{P} \left[ \lim_{n \rightarrow \infty} \bar{X}_n = \mu \right] = 1.$$

*“For even the most stupid of men, by some instinct of nature, by himself and without any instruction (which is a remarkable thing), is convinced that the more observations have been made, the less danger there is of wandering from one’s goal.”*



J. Bernoulli (1655-1705)

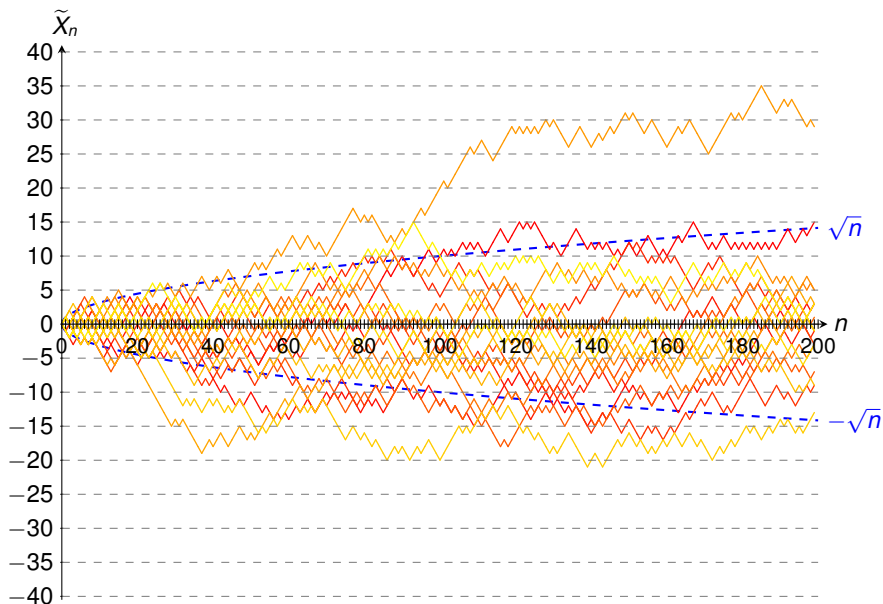
## Illustration of Weak Law of Large Numbers (1/4)

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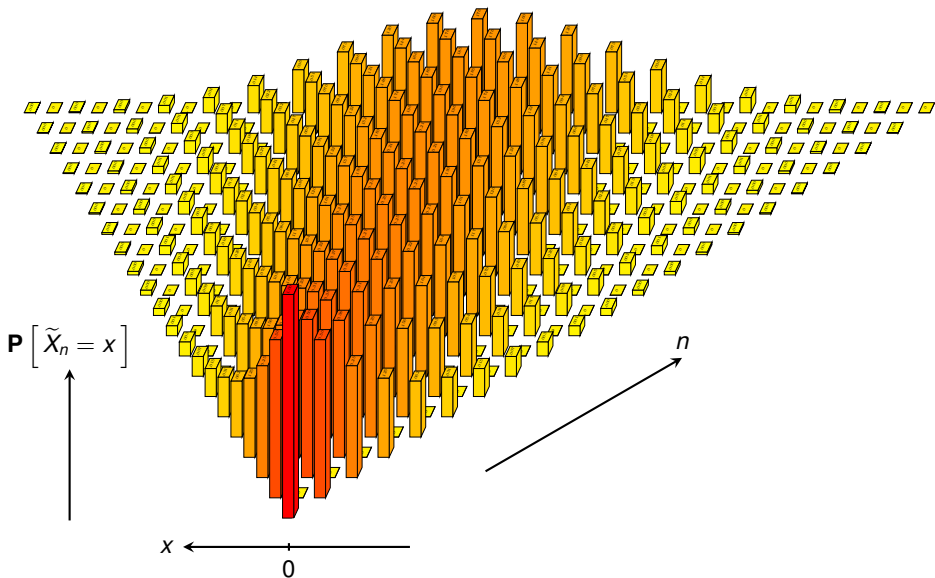
- Let  $X_i$  be independent random variables taking values  $\in \{-1, +1\}$  with probability  $1/2$  each
- Consider  $\tilde{X}_n := \sum_{i=1}^n X_i$  for any  $n = 0, 1, \dots, 200$

How does a “typical” realisation look like?

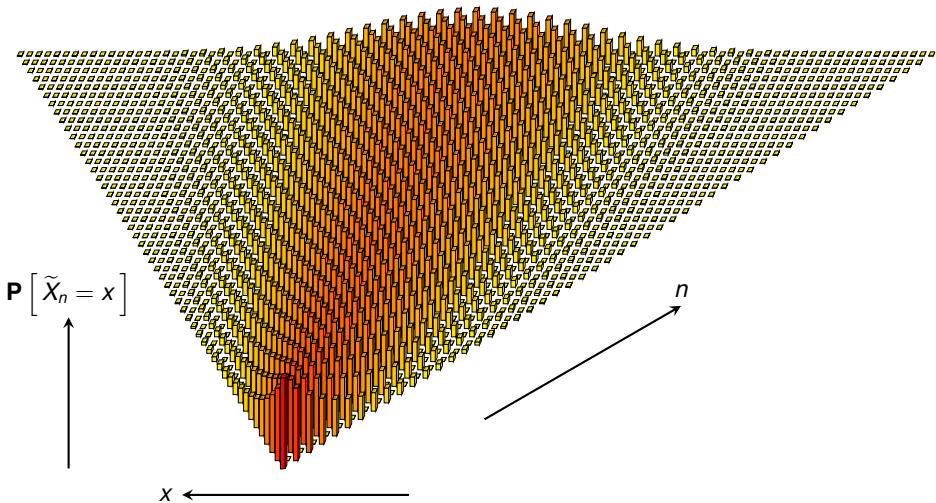
## Illustration of Weak Law of Large Numbers (2/4)



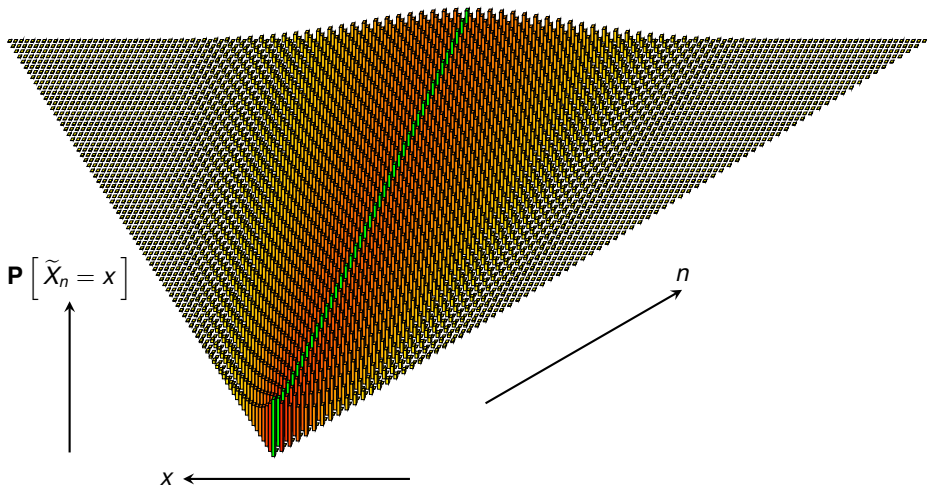
## Plot of the Distributions for $n = 0, 1, \dots, 20$



# Plot of the Distributions for $n = 0, 1, \dots, 50$



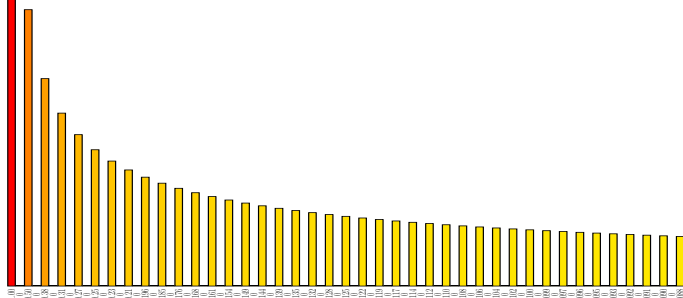
# Plot of the Distributions for $n = 0, 1, \dots, 80$



## Interlude: Approximation of $\mathbf{P}[\tilde{X}_n = 0]$

### Exercise

Try to find an expression for  $\mathbf{P}[\tilde{X}_n = 0]$ . Using Stirling's approximation for  $n!$ , conclude that  $\mathbf{P}[\tilde{X}_n = 0] = \Theta(1/\sqrt{n})$  for even integers  $n$ .



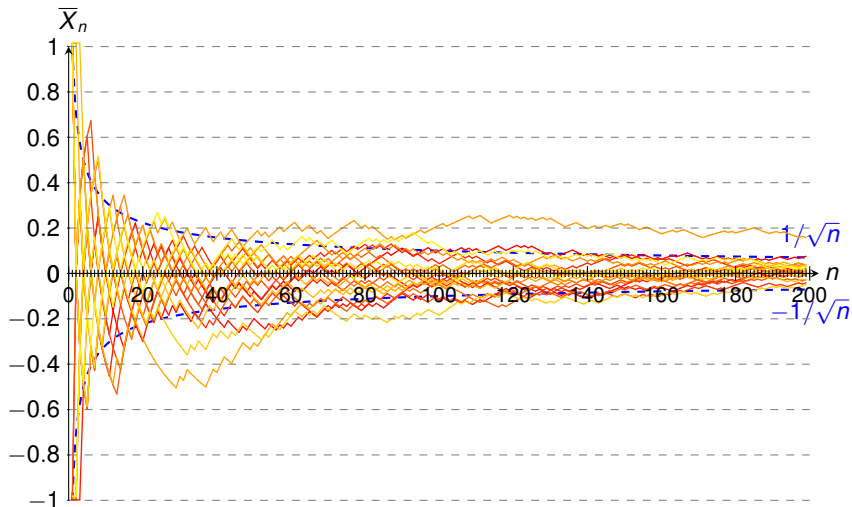
## Illustration of Weak Law of Large Numbers (3/4)

- Let  $X_i$  be independent random variables taking values  $\in \{-1, +1\}$  with probability  $1/2$  each
- Consider  $\tilde{X}_n := \sum_{i=1}^n X_i$  for any for any  $n = 0, 1, \dots, 200$

This does **not** converge!

Consider now the **average (sample mean)**:  $\bar{X}_n := 1/n \cdot \sum_{i=1}^n X_i$ .

## Illustration of Weak Law of Large Numbers (4/4)



## Proof of the Weak Law of Large Numbers

### The Weak Law of Large Numbers

Let  $\bar{X}_n := 1/n \cdot \sum_{i=1}^n X_i$ , where the  $X_i$ 's are **i.i.d.** with finite expectation  $\mu$  and finite variance  $\sigma^2$ . Then, for any  $\epsilon > 0$ ,

$$\lim_{n \rightarrow \infty} \mathbf{P} \left[ |\bar{X}_n - \mu| > \epsilon \right] = 0$$

#### Proof

- Let  $\bar{X}_n := 1/n \cdot \sum_{i=1}^n X_i$
- Then  $\mathbf{E} \left[ \bar{X}_n \right] = \mu$  and  
 $\mathbf{V} \left[ \bar{X}_n \right] = 1/n^2 \cdot \mathbf{V} \left[ \sum_{i=1}^n X_i \right] = 1/n^2 \cdot \sum_{i=1}^n \mathbf{V} \left[ X_i \right] = 1/n \cdot \sigma^2$ .
- Applying **Chebyshev's inequality** yields:

$$\mathbf{P} \left[ \left| \bar{X}_n - \mathbf{E} \left[ \bar{X}_n \right] \right| > \epsilon \right] \leq \frac{1}{\epsilon^2} \cdot \mathbf{V} \left[ \bar{X}_n \right] = \frac{\sigma^2}{n\epsilon^2}.$$

- For any (fixed)  $\epsilon > 0$ , the right hand side vanishes as  $n \rightarrow \infty$ .  
(Let  $\epsilon > 0, \delta > 0$ . Pick  $N = \frac{\sigma^2}{\epsilon^2 \cdot \delta}$ . Then for any  $n \geq N$ , the probability above is smaller than  $\delta$ .)

## Inferring Probabilities of an Event

### Example 4

Suppose that, instead of the expectation  $\mu$ , we want to estimate the probability of an **event**, e.g.,

$$p := \mathbf{P}[X \in (a, b)], \text{ where } a < b.$$

How can we use the **Law of Large Numbers**?

Answer

- Let  $X_1, X_2, \dots, X_n \sim X$ . For each  $1 \leq i \leq n$ , define:

$$Y_i = \begin{cases} 1 & \text{if } X_i \in (a, b), \\ 0 & \text{otherwise.} \end{cases}$$

- We have:

$$\mathbf{E}[Y_i] = \mathbf{P}[X_i \in (a, b)] \cdot 1 + \mathbf{P}[X_i \notin (a, b)] \cdot 0 = p.$$

- Similarly,  $\mathbf{V}[Y_i] = p(1 - p)$
- The random variables  $Y_1, Y_2, \dots, Y_n$  are i.i.d., so we can apply the Law of Large Numbers to  $\bar{Y}_n$ .