12: Independent RVs

Lisa Yan and Jerry Cain
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Quick slide reference

Independent Discrete RVs

Independent discrete RVs

Recall the definition of independent events E and F:

$$P(EF) = P(E)P(F)$$

Two discrete random variables X and Y are **independent** if:

for all x, y:

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

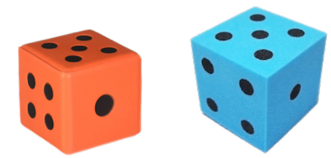
Different notation, same idea:

$$p_{X,Y}(x, y) = p_X(x)p_Y(y)$$

- Intuitively: knowing value of X tells us nothing about the distribution of Y (and vice versa)
- If two variables are not independent, they are called **dependent**.

Dice (after all this time, still our friends)

Let: D_1 and D_2 be the outcomes of two rolls
$S = D_1 + D_2$, the sum of two rolls



- Each roll of a 6-sided die is an independent trial.
- Random variables D_1 and D_2 are independent.

1. Are events $(D_1 = 1)$ and $(S = 7)$ independent?
2. Are events $(D_1 = 1)$ and $(S = 5)$ independent?
3. Are random variables D_1 and S independent?

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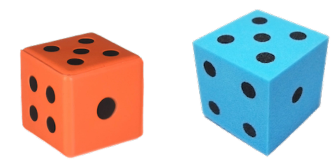


- Each roll of a 6-sided die is an independent trial.
- Random variables D_1 and D_2 are independent.

1. Are events $(D_1 = 1)$ and $(S = 7)$ independent? ✅
2. Are events $(D_1 = 1)$ and $(S = 5)$ independent? ❌
3. Are random variables D_1 and S independent? ❌

All events $(X = x, Y = y)$ must be independent for X, Y to be independent RVs.

What about continuous random variables?

Continuous random variables can also be independent! We'll see this later.

Today's goal:

How can we model sums of discrete random variables?

Big motivation: Model total successes observed over multiple experiments

Sums of independent Binomial RVs

Sum of independent Binomials

$X \sim \text{Bin}(n_1, p)$
$Y \sim \text{Bin}(n_2, p)$
X, Y independent

$$X + Y \sim \text{Bin}(n_1 + n_2, p)$$

Intuition:

- Each trial in X and Y is independent and has same success probability p
- Define $Z =$# successes in $n_1 + n_2$ independent trials, each with success probability p. $Z \sim \text{Bin}(n_1 + n_2, p)$, and also $Z = X + Y$

Holds in general case:

$X_i \sim \text{Bin}(n_i, p)$
X_i independent for $i = 1, \ldots, n$

$$\sum_{i=1}^{n} X_i \sim \text{Bin}\left(\sum_{i=1}^{n} n_i, p\right)$$

If only it were always so simple...

Convolution: Sum of independent Poisson RVs

Convolution: Sum of independent random variables

For any discrete random variables X and Y:

$$P(X+Y=n)=\sum_k P(X=k,Y=n-k)$$

In particular, for independent discrete random variables X and Y:

$$P(X+Y=n)=\underbrace{\sum_k P(X=k)P(Y=n-k)}_{\text{the convolution of } p_X \text{ and } p_Y}$$

Insight into convolution

For independent discrete random variables X and Y:

$$P(X+Y=n)=\sum_k P(X=k)P(Y=n-k)$$

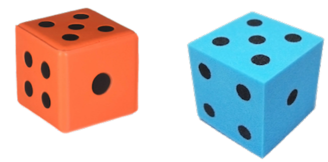
the convolution of p_X and p_Y

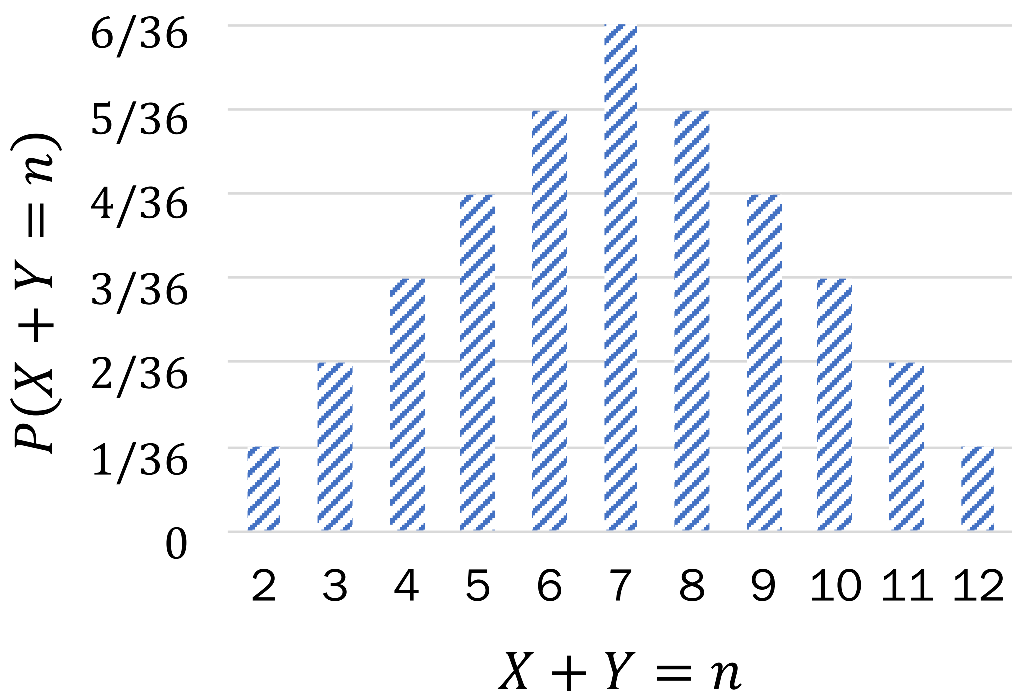
Suppose X and Y are independent, both with support $\{0, 1, \dots, n, \dots\}$:

		X						
		0	1	2	…	n	$n+1$	…
Y	0					✓		
	…				…			
	$n-2$			✓				
	$n-1$		✓					
	n	✓						
	$n+1$							
	…							

- ✓: event where $X+Y=n$
- Each event has probability:
  $P(X=k, Y=n-k)$
  $= P(X=k)P(Y=n-k)$
  (because X, Y are independent)
- $P(X+Y=n)$ = sum of mutually exclusive events

Sum of 2 dice rolls



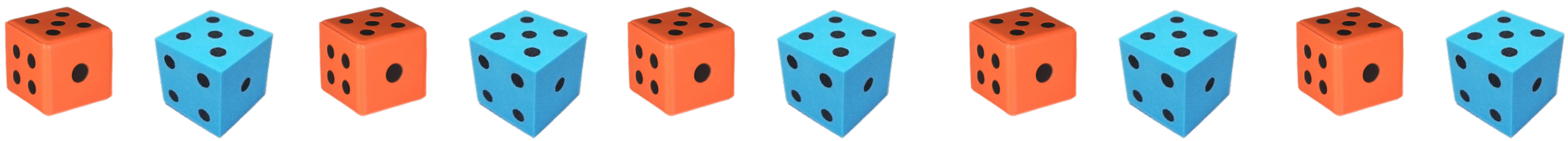


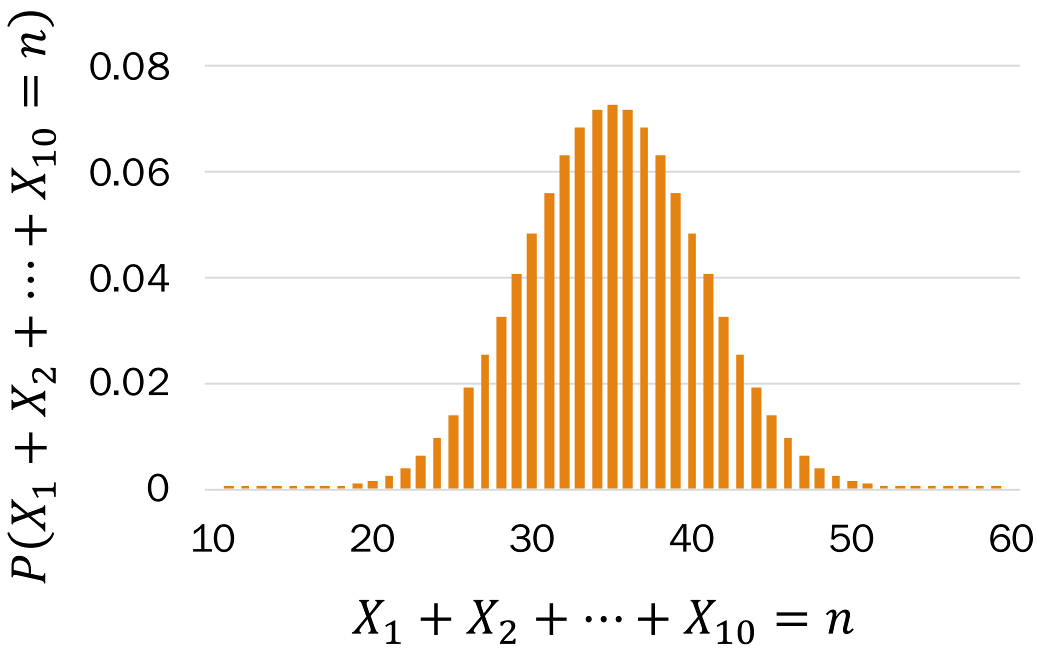
The distribution of a sum of 2 dice rolls is a convolution of 2 PMFs.

Example:

$$P(X+Y=4) = P(X=1)P(Y=3) + P(X=2)P(Y=2) + P(X=3)P(Y=1)$$

Sum of 10 dice rolls (fun preview)





The distribution of a sum of <u>10</u> dice rolls is a convolution <u>10</u> PMFs.

Looks kinda Normal...???
(more on this in Week 7)

Sum of independent Poissons

$X \sim \text{Poi}(\lambda_1), Y \sim \text{Poi}(\lambda_2)$
X, Y independent

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

Proof (just for reference):

$$P(X+Y=n) = \sum_k P(X=k)P(Y=n-k)$$

X and Y independent, convolution

$$= \sum_{k=0}^{n} e^{-\lambda_1} \frac{\lambda_1^k}{k!} e^{-\lambda_2} \frac{\lambda_2^{n-k}}{(n-k)!} = e^{-(\lambda_1+\lambda_2)} \sum_{k=0}^{n} \frac{\lambda_1^k \lambda_2^{n-k}}{k!\,(n-k)!}$$

PMF of Poisson RVs

$$= \frac{e^{-(\lambda_1+\lambda_2)}}{n!} \sum_{k=0}^{n} \frac{n!}{k!\,(n-k)!} \lambda_1^k \lambda_2^{n-k} = \underbrace{\frac{e^{-(\lambda_1+\lambda_2)}}{n!}(\lambda_1+\lambda_2)^n}_{\text{Poi}(\lambda_1+\lambda_2)}$$

Binomial Theorem:

$$(a+b)^n = \sum_{k=0}^{n} \binom{n}{k} a^k b^{n-k}$$

General sum of independent Poissons

Holds in general case:

$$X_i \sim \text{Poi}(\lambda_i)$$
$$X_i \text{ independent for } i = 1, \dots, n$$

$$\Rightarrow \quad \sum_{i=1}^{n} X_i \sim \text{Poi}\left(\sum_{i=1}^{n} \lambda_i\right)$$

(live)
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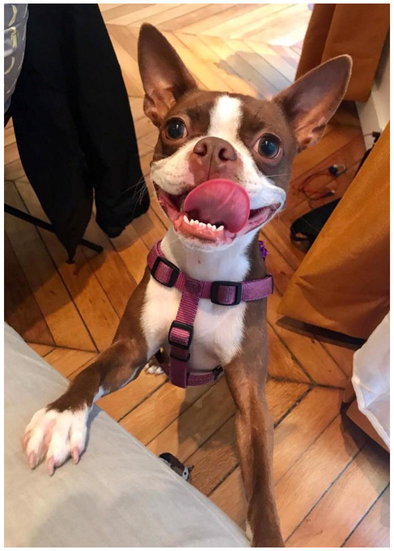
Quiz #1 is D-O-N-E done!



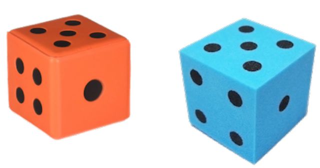
Independent discrete RVs

Two discrete random variables X and Y are independent if:

for all x, y:

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

$$p_{X,Y}(x, y) = p_X(x)p_Y(y)$$



The sum of 2 dice and the outcome of 1st die are **dependent RVs.**

Important: Joint PMF must decompose into product of marginal PMFs for ALL values of X and Y for X, Y to be independent RVs.

Think

Slide 21 has a question to go over by yourself.

Post any clarifications here!

https://us.edstem.org/courses/2678/discussion/141413

Think by yourself: 2 min

(by yourself)

Coin flips

Flip a coin with probability p of "heads" a total of $n + m$ times.

Let X = number of heads in first n flips. $X \sim \text{Bin}(n, p)$
Y = number of heads in next m flips. $Y \sim \text{Bin}(m, p)$
Z = total number of heads in $n + m$ flips.

1. Are X and Z independent?
2. Are X and Y independent?

🤔 (by yourself)

Coin flips

Flip a coin with probability p of "heads" a total of $n + m$ times.

Let X = number of heads in first n flips. $X \sim \text{Bin}(n, p)$
Y = number of heads in next m flips. $Y \sim \text{Bin}(m, p)$
Z = total number of heads in $n + m$ flips.

1. Are X and Z independent? ❌ Counterexample: What if $Z = 0$?
2. Are X and Y independent? ✅

$$P(X = x, Y = y) = P\left(\begin{array}{c}\text{first } n \text{ flips have } x \text{ heads} \\ \text{and next } m \text{ flips have } y \text{ heads}\end{array}\right)$$

# of mutually exclusive outcomes in event : $\binom{n}{x}\binom{m}{y}$

P(each outcome) $= p^x(1-p)^{n-x}p^y(1-p)^{m-y}$

$$= \binom{n}{x} p^x (1-p)^{n-x} \binom{m}{y} p^y (1-p)^{m-y}$$

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

This probability (found through counting) is the product of the marginal PMFs.

Sum of independent Poissons

$X \sim \text{Poi}(\lambda_1), Y \sim \text{Poi}(\lambda_2)$
X, Y independent

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

- n servers with independent number of requests/minute
- Server i's requests each minute can be modeled as $X_i \sim \text{Poi}(\lambda_i)$

What is the probability that the total number of web requests received at all servers in the next minute exceeds 10?

Breakout Rooms

Slide 25 has two questions to go over in groups.

ODD breakout rooms: Try question 1

EVEN breakout rooms: Try question 2

Post any clarifications here!

https://us.edstem.org/courses/2678/discussion/141413

Breakout rooms: 5 min. Introduce yourself!

🤔

Independent questions

1. Let $X \sim \text{Bin}(30, 0.01)$ and $Y \sim \text{Bin}(50, 0.02)$ be independent RVs.
   - How do we compute $P(X + Y = 2)$ using a Poisson approximation?
   - How do we compute $P(X + Y = 2)$ exactly?

2. Let $N =$ # of requests to a web server per day. Suppose $N \sim \text{Poi}(\lambda)$.
   - Each request independently comes from a human (prob. p), or bot $(1 - p)$.
   - Let X be # of human requests/day, and Y be # of bot requests/day.

Are X and Y independent? What are their marginal PMFs?

1. Approximating the sum of independent Binomial RVs

Let $X \sim \text{Bin}(30, 0.01)$ and $Y \sim \text{Bin}(50, 0.02)$ be independent RVs.

- How do we compute $P(X + Y = 2)$ using a Poisson approximation?

- How do we compute $P(X + Y = 2)$ exactly?

$$P(X + Y = 2) = \sum_{k=0}^{2} P(X = k)P(Y = 2 - k)$$

$$= \sum_{k=0}^{2} \binom{30}{k} 0.01^k (0.99)^{30-k} \binom{50}{2-k} 0.02^{2-k} 0.98^{50-(2-k)} \approx 0.2327$$

2. Web server requests

Let N = # of requests to a web server per day. Suppose $N \sim \text{Poi}(\lambda)$.

- Each request independently comes from a human (prob. p), or bot ($1-p$).
- Let X be # of human requests/day, and Y be # of bot requests/day.

Are X and Y independent? What are their marginal PMFs?

$$P(X=n, Y=m) = P(X=n, Y=m \mid N=n+m)P(N=n+m) + P(X=n, Y=m \mid N \neq n+m)P(N \neq n+m)$$

Law of Total Probability

$$= P(X=n \mid N=n+m)P(Y=m \mid X=n, N=n+m)P(N=n+m)$$

Chain Rule

$$= \binom{n+m}{n} p^n (1-p)^m \cdot 1 \cdot e^{-\lambda}\frac{\lambda^{n+m}}{(n+m)!}$$

Given $N=n+m$ indep. trials, $X|N=n+m \sim \text{Bin}(n+m, p)$

$$= \frac{(n+m)!}{n!\,m!} e^{-\lambda} \frac{(\lambda p)^n \big(\lambda(1-p)\big)^m}{(n+m)!} = e^{-\lambda p}\frac{(\lambda p)^n}{n!} \cdot e^{-\lambda(1-p)}\frac{\big(\lambda(1-p)\big)^m}{m!}$$

$$= P(X=n)P(Y=m)$$

where $X \sim \text{Poi}(\lambda p)$, $Y \sim \text{Poi}\big(\lambda(1-p)\big)$

Yes, X and Y are independent!

Interlude for announcements

Announcements

Quiz #1

Grades/solutions: Next week

Problem Set 3

Due: Monday 10/16 1pm
Covers: Up to and including Lecture 11

CS109 Contest

Make up any part(s) of your grade
Details Next week

Interesting probability news

Column: Did Astros beat the Dodgers by cheating? The numbers say no

”…new analyses of the Astros’ 2017 season by baseball’s corps of unofficial statisticians — "sabermetricians," to the sport — indicate that the Astros didn’t gain anything from their cheating; in fact, it may have hurt them.”

https://www.latimes.com/business/story/2020-02-27/astros-cheating-analysis

https://www.theguardian.com/sport/2020/jan/17/houston-astros-sign-stealing-cheating-scandal

Independence of multiple random variables

Recall independence of n events $E_1, E_2, \ldots, E_n$:

for $r = 1, \ldots, n$:
for every subset $E_1, E_2, \ldots, E_r$:
$P(E_1, E_2, \ldots, E_r) = P(E_1)P(E_2) \cdots P(E_r)$

We have independence of n discrete random variables $X_1, X_2, \ldots, X_n$ if for all $x_1, x_2, \ldots, x_n$:

$$P(X_1 = x_1, X_2 = x_2, \ldots, X_n = x_n) = \prod_{i=1}^{n} P(X_i = x_i)$$

Independence is symmetric

If X and Y are independent random variables, then
X is independent of Y, and Y is independent of X

Let N be the number of times you roll 2 dice repeatedly until a 4 is rolled (the player wins), or a 7 is rolled (the player loses).

Let X be the value (4 or 7) of the final throw.

- Is N independent of X?
  $P(N = n|X = 7) = P(N = n)$?
  $P(N = n|X = 4) = P(N = n)$?
- Is X independent of N?
  $$\left.\begin{array}{l} P(X = 4|N = n) = P(X = 4)? \\ P(X = 7|N = n) = P(X = 7)? \end{array}\right\}$$
  (yes, easier to intuit)

Redux: Independence is not always intuitive, but it is **always** symmetric.

LIVE

Statistics on Two RVs

Expectation and Covariance

In real life, we often have many RVs interacting at once.

- We've seen some simpler cases (e.g., sum of independent Poissons).
- Computing joint PMFs in general is hard!
- But often you don't need to model joint RVs completely.

Instead, we'll focus next on reporting ***statistics*** of multiple RVs:

- Expectation: sum of RV expectations == expectation of RV sums
- Covariance: measure of how two RVs vary with each other (coming soon)

Properties of Expectation, extended to two RVs

1. Linearity:

$$E[aX + bY + c] = aE[X] + bE[Y] + c$$

2. Expectation of a sum = sum of expectation:

$$E[X + Y] = E[X] + E[Y]$$

(we've seen this; we'll prove this next)

3. Unconscious statistician:

$$E[g(X, Y)] = \sum_x \sum_y g(x, y) p_{X,Y}(x, y)$$

True for both independent and dependent random variables!

Proof of expectation of a sum of RVs

$E[X+Y] = E[X] + E[Y]$

$$E[X+Y] = \sum_x \sum_y (x+y) p_{X,Y}(x,y)$$

LOTUS,
$g(X,Y) = X + Y$

$$= \sum_x \sum_y x p_{X,Y}(x,y) + \sum_x \sum_y y p_{X,Y}(x,y)$$

$$= \sum_x x \sum_y p_{X,Y}(x,y) + \sum_y y \sum_x p_{X,Y}(x,y)$$

Linearity of summations
(cont. case: linearity of integrals)

$$= \sum_x x p_X(x) + \sum_y y p_Y(y)$$

Marginal PMFs for X and Y

$$= E[X] + E[Y]$$

Expectations of common RVs: Binomial

Review

$X \sim \text{Bin}(n, p) \quad E[X] = np$

# of successes in n independent trials with probability of success p

Recall: $\text{Bin}(1, p) = \text{Ber}(p)$

$$X = \sum_{i=1}^{n} X_i$$

Let $X_i = i$th trial is heads

$X_i \sim \text{Ber}(p), E[X_i] = p$

$$E[X] = E\left[\sum_{i=1}^{n} X_i\right] = \sum_{i=1}^{n} E[X_i] = \sum_{i=1}^{n} p = np$$