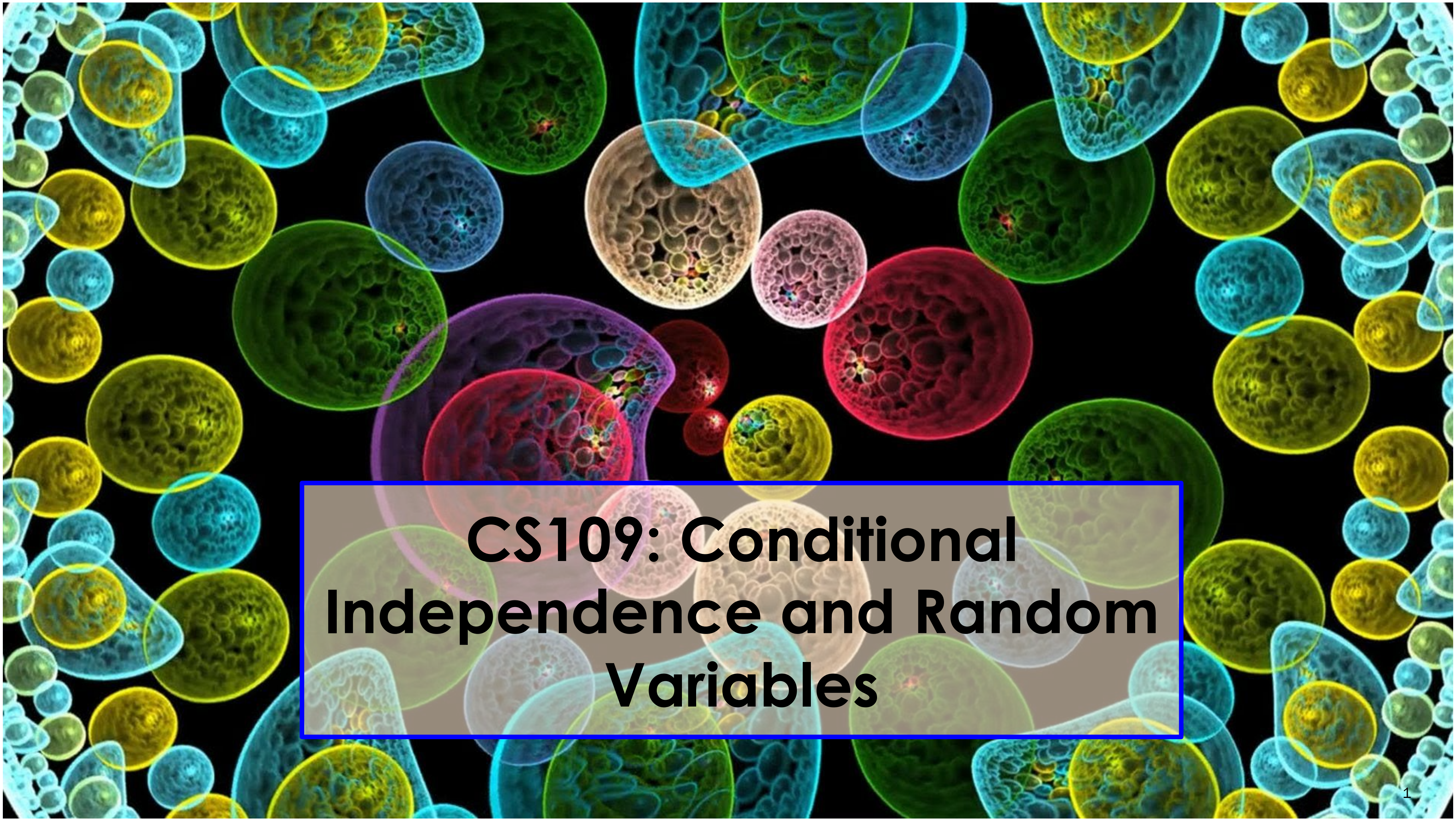


CS109: Conditional Independence and Random Variables

Conditional Independence

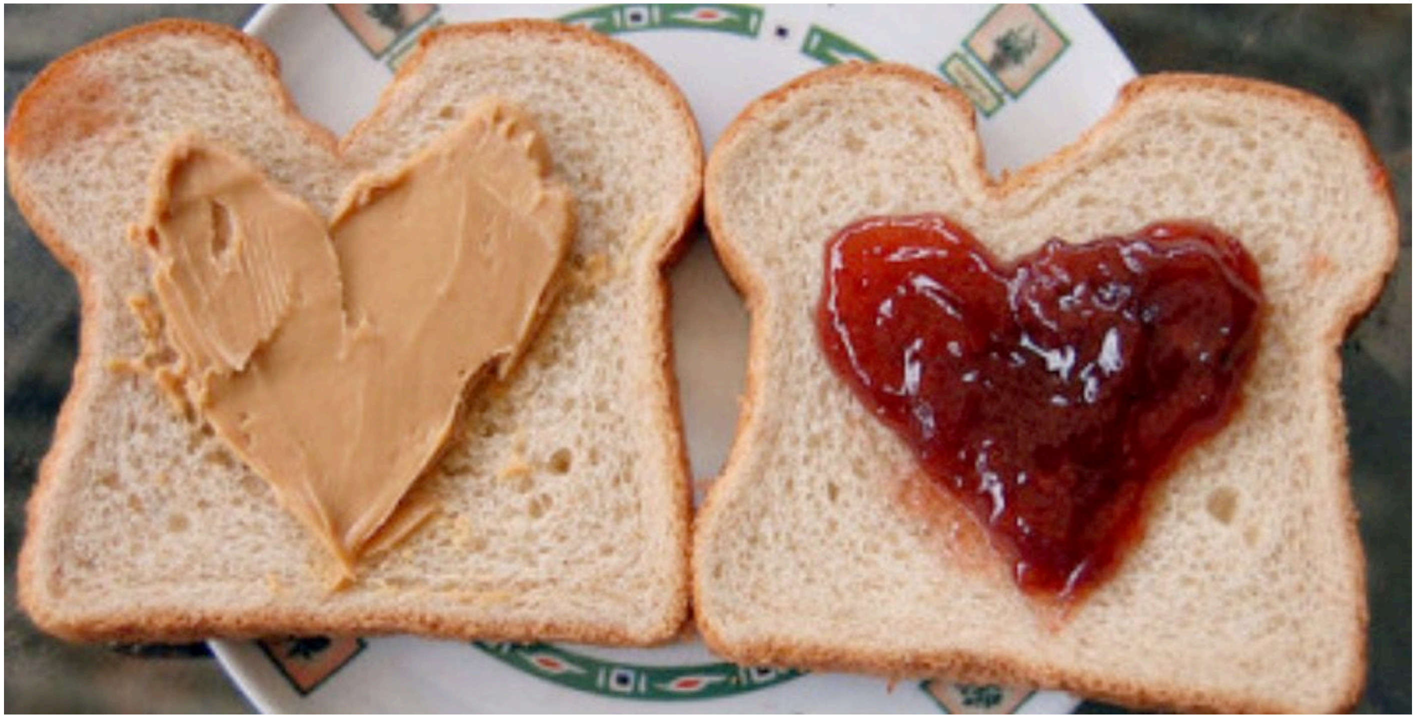
Conditional Paradigm

For any events A, B, and E, you can condition consistently on E, and all formulas still hold:

Axiom 1	$0 \leq P(A\|E) \leq 1$
Corollary 1 (complement)	$P(A\|E) = 1 - P(A^C\|E)$
Commutativity	$P(AB\|E) = P(BA\|E)$
Chain Rule	$P(AB\|E) = P(B\|E)P(A\|BE)$
Bayes' Theorem	$P(A\|BE) = \frac{P(B\|AE)P(A\|E)}{P(B\|E)}$

BAE ‘s theorem?

Conditional Independence



Conditional Probability Independence

Conditional Independence

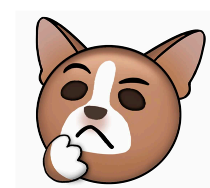
Independent events E and F $\Leftrightarrow$ $P(EF) = P(E)P(F)$
$P(E|F) = P(E)$

Two events A and B are defined as conditionally independent given E if:

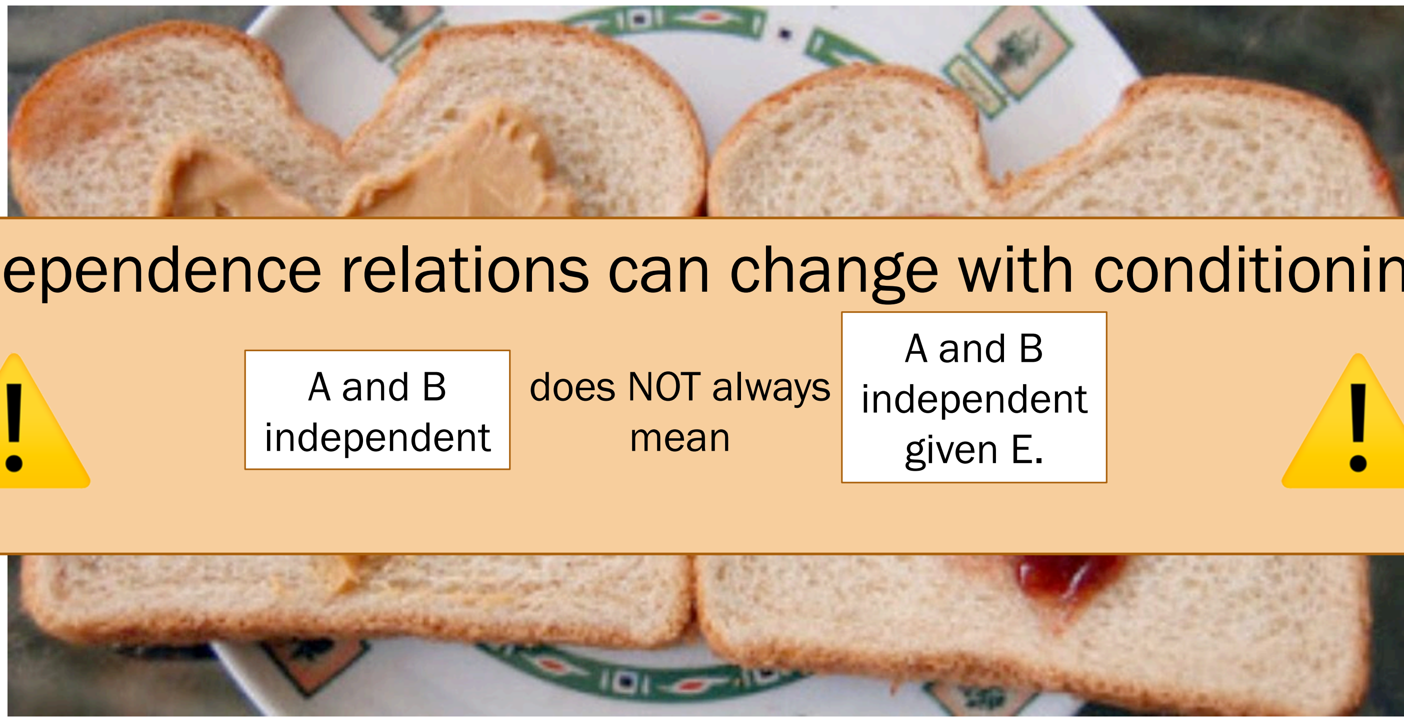
$$P(AB|E) = P(A|E)P(B|E)$$

Which one of the three statements below is an equivalent definition?

A. $P(A|B) = P(A)$
B. $P(A|BE) = P(A)$
C. $P(A|BE) = P(A|E)$



Conditional Independence



Independence relations can change with conditioning.

A and B independent	does NOT always mean	A and B independent given E.

Conditional Probability

Independence

Netflix and Condition

Let E = a user watches Life is Beautiful.

Let F = a user watches Amelie.

What is $P(E)$?

$$P(E) \approx \frac{\text{\# people who have watched movie}}{\text{\# people on Netflix}} = \frac{10{,}234{,}231}{50{,}923{,}123} \approx 0.20$$

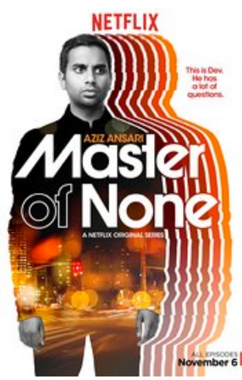
What is the probability that a user watches Life is Beautiful, given they watched Amelie?

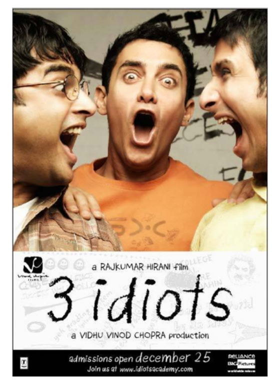
$$P(E|F) = \frac{P(EF)}{P(F)} = \frac{\text{\# people who have watched both}}{\text{\# people who have watched Amelie}} \approx 0.42$$

Netflix and Condition

Review

Let E be the event that a user watches the given movie.
Let F be the event that the same user watches Amelie.





$P(E) = 0.19$	$P(E) = 0.32$	$P(E) = 0.20$	$P(E) = 0.09$	$P(E) = 0.20$
$P(E\|F) = 0.14$	$P(E\|F) = 0.35$	$P(E\|F) = 0.20$	$P(E\|F) = 0.72$	$P(E\|F) = 0.42$

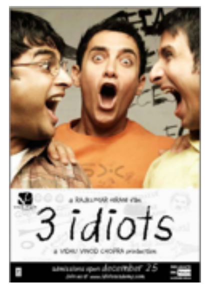
Independent!

Netflix and Condition (on many movies)

Watched:

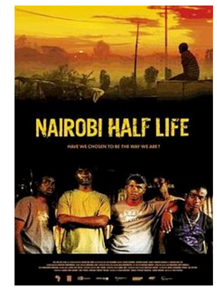
E_1

E_2



E_3

Will they watch?



E_4

What if $E_1 E_2 E_3 E_4$ are not independent? (e.g., all international emotional comedies)

$$P(E_4 | E_1 E_2 E_3) = \frac{P(E_1 E_2 E_3 E_4)}{P(E_1 E_2 E_3)} = \frac{\text{\# people who have watched all 4}}{\text{\# people who have watched those 3}}$$

We need to keep track of an exponential number of movie-watching statistics

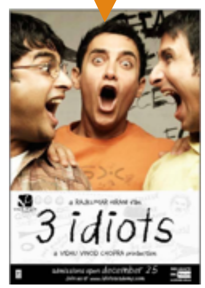
Netflix and Condition (on many movies)

K: likes international emotional comedies

Watched:

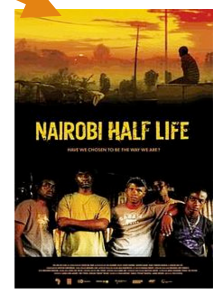
E_1

E_2



E_3

Will they watch?



E_4

Assume: $E_1 E_2 E_3 E_4$ are *conditionally independent given* K

$$P(E_4|E_1E_2E_3) = \frac{P(E_1E_2E_3E_4)}{P(E_1E_2E_3)}$$

$$P(E_4|E_1E_2E_3K) = P(E_4|K)$$

An easier probability to store and compute!

Conditional independence is a Big Deal

Conditional independence is a practical, real-world way of decomposing hard probability questions.

"Exploiting conditional independence to generate fast probabilistic computations is one of the main contributions CS has made to probability theory."

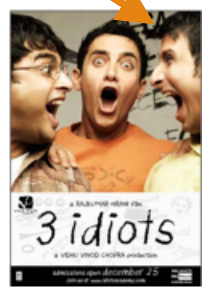
–Judea Pearl wins 2011 Turing Award,
"For fundamental contributions to artificial intelligence through the development of a calculus for probabilistic and causal reasoning"

Netflix and Condition

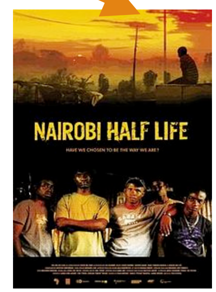
K: likes international emotional comedies

E_1

E_2



E_3



E_4

Challenge: How do we determine K? Stay tuned in 6 weeks' time!

$E_1 E_2 E_3 E_4$ are dependent

$E_1 E_2 E_3 E_4$ are conditionally independent given K

Dependent events can become conditionally independent.
And vice versa: Independent events can become conditionally dependent.

Random Variables

Random variables are like typed variables

type name value

```
int a = 5;

double b = 4.2;

bit c = 1;
```

CS variables

A is the number of Pokemon we bring to our *future* battle.

$$A \in \{1, 2, \ldots, 6\}$$

B is the amount of money we get *after* we win a battle.

$$B \in \mathbb{R}^+$$

C is 1 *if* we successfully beat the Elite Four. 0 otherwise.

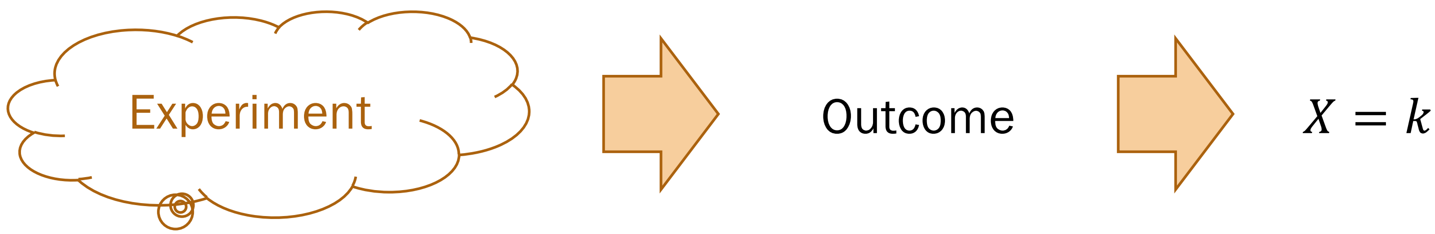
$$C \in \{0,1\}$$

Random variables

Random variables are like typed variables (but with uncertainty)

Random Variable

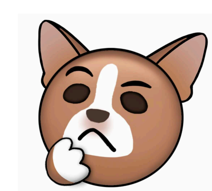
A random variable is a real-valued function defined on a sample space.



Example:

3 coins are flipped.
Let X = # of heads.
X is a random variable.

1. What is the value of X for the outcomes:
   - (T,T,T)?
   - (H,H,T)?
2. What is the event (set of outcomes) where $X = 2$?
3. What is $P(X = 2)$?



Random Variable

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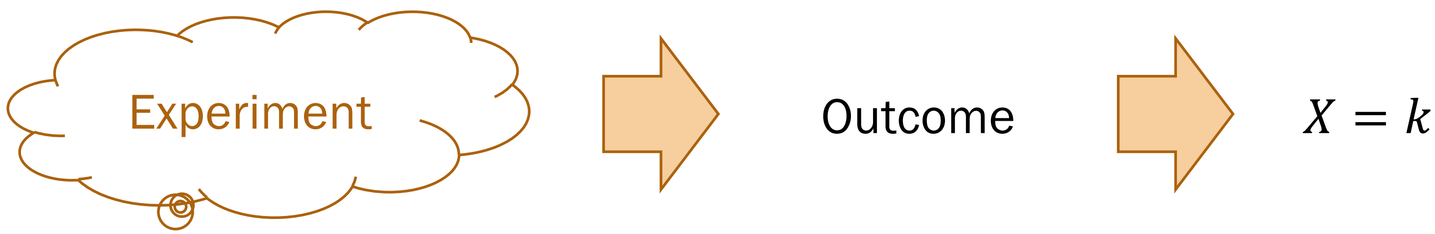

Example:

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   - (T,T,T)?
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3. What is $P(X = 2)$?

Random variables are not events!

It is confusing that random variables and events use the same notation.

- **Random variables $\neq$ events.**
- We can define an event to be a particular assignment of a random variable.

Example:

3 coins are flipped.
Let X = # of heads.
X is a random variable.

$$X = 2$$

event

$$P(X = 2)$$

probability
(number b/t 0 and 1)

Random variables are not events!

It is confusing that random variables and events use the same notation.

- **Random variables ≠ events.**
- We can define an event to be a particular assignment of a random variable.

Example:

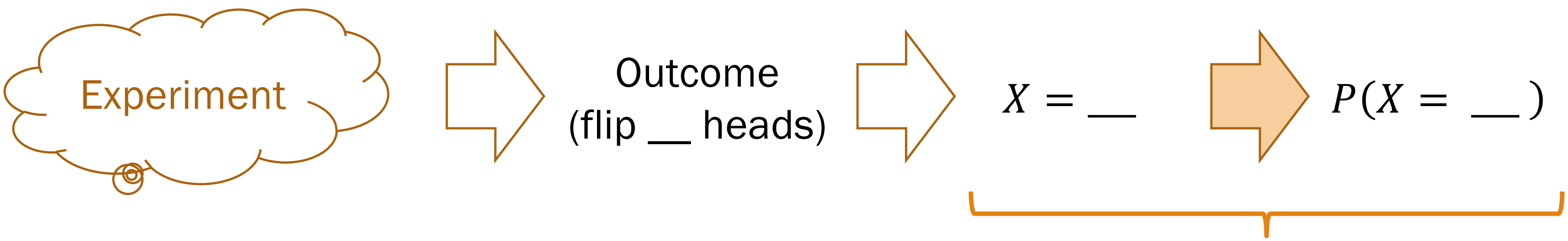
3 coins are flipped.
Let X = # of heads.
X is a random variable.

$X = x$	Set of outcomes	$P(X = k)$
$X = \mathbf{0}$	{(T, T, T)}	1/8
$X = \mathbf{1}$	{(H, T, T), (T, H, T), (T, T, H)}	3/8
$X = \mathbf{2}$	{(H, H, T), (H, T, H), (T, H, H)}	3/8
$X = \mathbf{3}$	{(H, H, H)}	1/8
$X \geq 4$	{ }	0

PMFs and CDFs

So far

3 coins are flipped. Let X = # of heads. X is a random variable.



$X = x$	$P(X = k)$	Set of outcomes
$X = \mathbf{0}$	1/8	{(T, T, T)}
$X = \mathbf{1}$	3/8	{(H, T, T), (T, H, T), (T, T, H)}
$X = \mathbf{2}$	3/8	{(H, H, T), (H, T, H), (T, H, H)}
$X = \mathbf{3}$	1/8	{(H, H, H)}
$X \geq 4$	0	{ }

Can we get a "shorthand" for this last step?
Seems like it might be useful!

Probability Mass Function

3 coins are flipped. Let X = # of heads. X is a random variable.

A function on k
with range [0,1]

parameter/input k

$$P(X = k)$$

return value/output
number between
0 and 1

What would be a *useful* function to define?

The probability of the event that a random variable X takes on the value k!

For discrete random variables, this is a probability mass function, or PMF.

Probability Mass Function

3 coins are flipped. Let X = # of heads. X is a random variable.

A function on k
with range [0,1]

2

parameter/input k:
a value of X

$$P(X = k) \Rightarrow 0.375$$

return value/output:
probability of the event
$X = k$

```
def prob_event_y_equals(n, k, p):
  n_ways = scipy.special.binom(n, k)
  p_way = np.power(p, k) * np.power(1-p, n-k)
  return n_ways * p_way

print(prob_event_y_equals(3, 2, 0.5))
```

probability mass function

Discrete RVs and Probability Mass Functions

A random variable X is discrete if it can take on countably many values.

- $X = x$, where $x \in \{x_1, x_2, x_3, \dots\}$

The probability mass function of a discrete random variable is

$$P(X = x) = \underbrace{p(x)}_{} = \underbrace{p_X(x)}_{}$$

shorthand notation

- Probabilities must sum to 1: $\displaystyle\sum_{i=1}^{\infty} p(x_i) = 1$

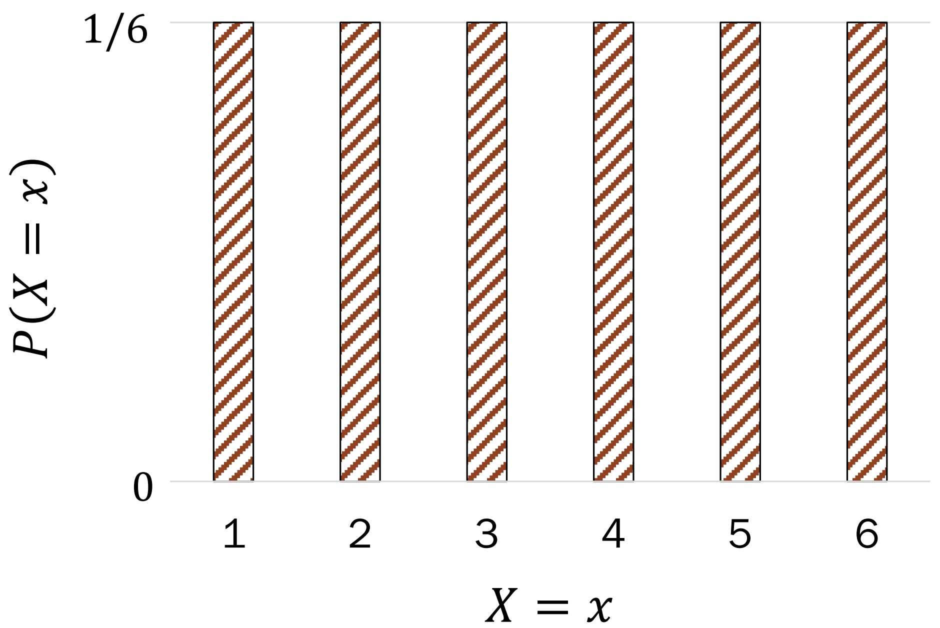
This last point is a good way to verify any PMF you create.

PMF for a single 6-sided die

Let X be a random variable that represents the result of a single dice roll.

- Support of X : $\{1, 2, 3, 4, 5, 6\}$
- Therefore X is a discrete random variable.
- PMF of X:

$$p(x) = \begin{cases} 1/6 & x \in \{1, \dots, 6\} \\ 0 & \text{otherwise} \end{cases}$$



Cumulative Distribution Functions

For a random variable X, the cumulative distribution function (CDF) is defined as

$$F(a) = F_X(a) = P(X \leq a), \text{where } -\infty < a < \infty$$

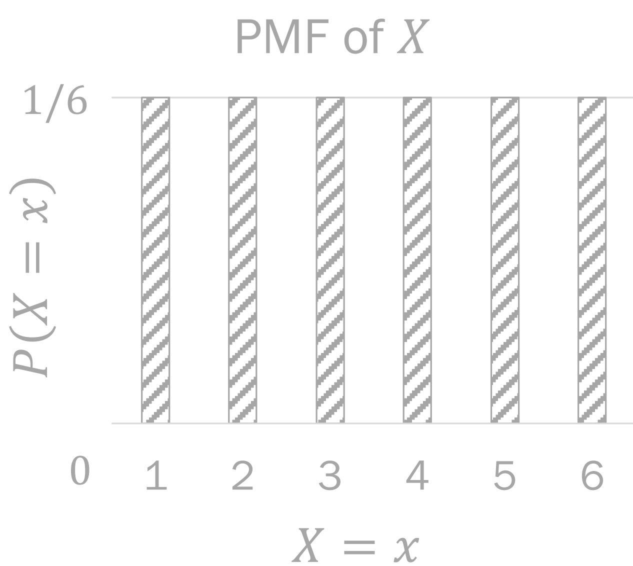
For a discrete RV X, the CDF is:

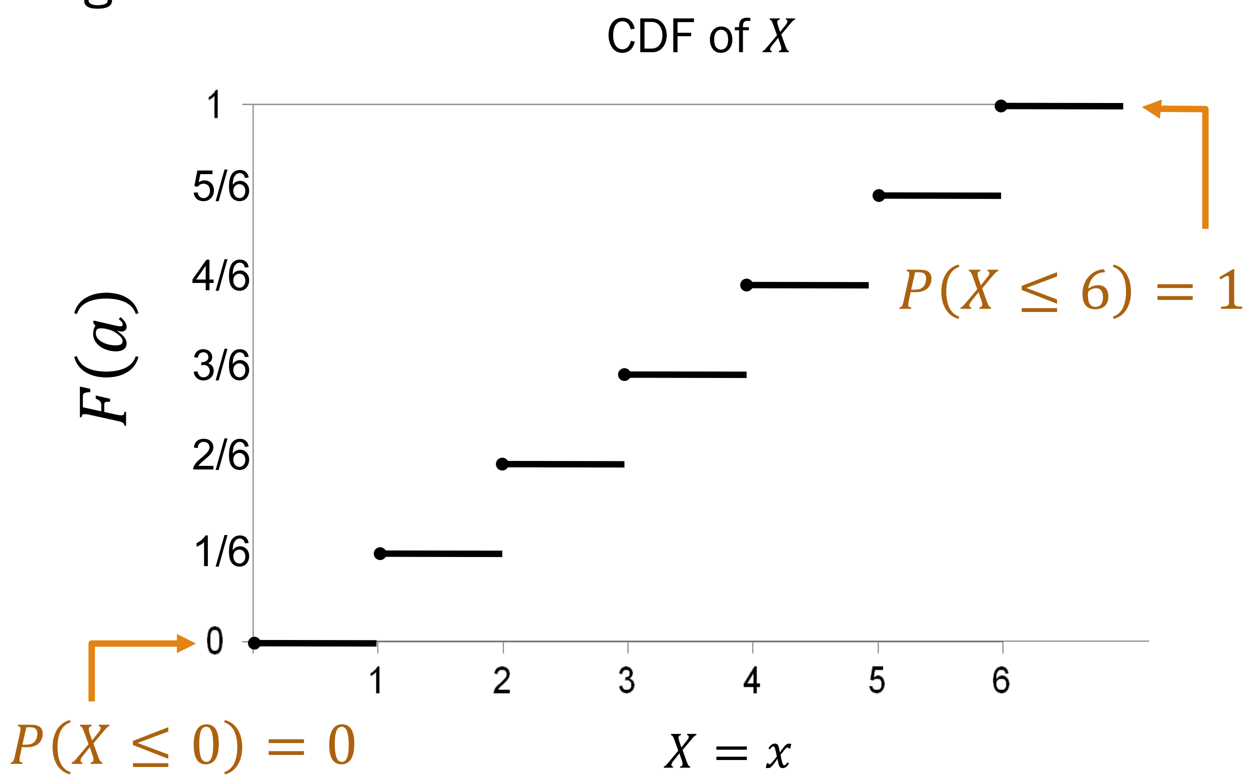
$$F(a) = P(X \leq a) = \sum_{\text{all } x \leq a} p(x)$$

CDFs as graphs

CDF (cumulative distribution function) $F(a) = P(X \le a)$

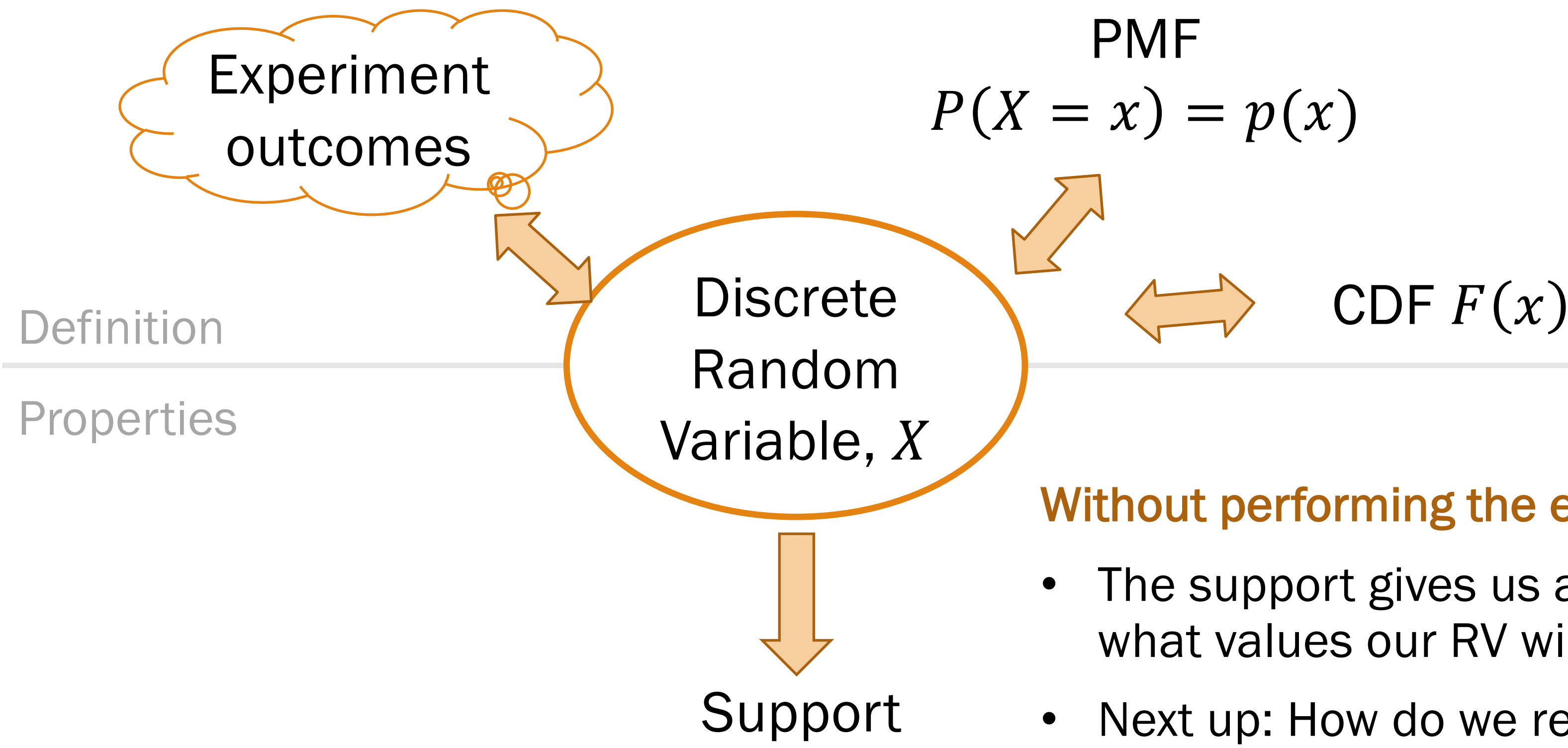
Let X be a random variable that represents the result of a single dice roll.





Expectation

Discrete random variables



Without performing the experiment:

- The support gives us a ballpark of what values our RV will take on
- Next up: How do we report an "average" value?

Expectation

The expectation of a discrete random variable X is defined as:

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

- Note: sum over all values of $X = x$ that have non-zero probability.
- Other names: **mean**, expected value, **weighted average**, center of mass, first moment

Expectation of a die roll

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

What is the expected value of a 6-sided die roll?

1. Define random variables

X = RV for value of roll

$$P(X = x) = \begin{cases} 1/6 & x \in \{1, \dots, 6\} \\ 0 & \text{otherwise} \end{cases}$$

2. Solve

$$E[X] = 1\left(\frac{1}{6}\right) + 2\left(\frac{1}{6}\right) + 3\left(\frac{1}{6}\right) + 4\left(\frac{1}{6}\right) + 5\left(\frac{1}{6}\right) + 6\left(\frac{1}{6}\right) = \frac{7}{2}$$

Important properties of expectation

1. Linearity:

$$E[aX + b] = aE[X] + b$$

- Let X = 6-sided dice roll, $Y = 2X - 1$.
- $E[X] = 3.5$
- $E[Y] = 6$

2. Expectation of a sum = sum of expectation:

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

Sum of two dice rolls:

- Let X = roll of die 1
  Y = roll of die 2
- $E[X + Y] = 3.5 + 3.5 = 7$

3. Unconscious statistician:

$$E[g(X)] = \sum_x g(x)p(x)$$

These properties let you avoid defining difficult PMFs.

Important properties of expectation

1. Linearity:

$$E[aX + b] = aE[X] + b$$

2. Expectation of a sum = sum of expectation:

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

3. Unconscious statistician:

$$E[g(X)] = \sum_x g(x)p(x)$$

Linearity of Expectation: Proof

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

$$E[aX + b] = aE[X] + b$$

Proof:

$$E[aX + b] = \sum_x (ax + b)p(x) = \sum_x axp(x) + bp(x)$$

$$= a \sum_x xp(x) + b \sum_x p(x)$$

$$= a\, E[X] + b \cdot 1$$

Expectation of Sum: Intuition

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

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

(we'll prove this in two weeks)

Intuition for now:

X	Y	$X+Y$
3	6	9
2	4	6
6	12	18
10	20	30
-1	-2	-3
0	0	0
8	16	24

Average:

$$\frac{1}{n}\sum_{i=1}^{n} x_i \quad + \quad \frac{1}{n}\sum_{i=1}^{n} y_i \quad = \quad \frac{1}{n}\sum_{i=1}^{n}(x_i + y_i)$$

$$\frac{1}{7}(28) \quad + \quad \frac{1}{7}(56) \quad = \quad \frac{1}{7}(84)$$

LOTUS: Proof

$E[g(X)] = \sum_x g(x)p(x)$ Expectation of $g(X)$

Let $Y = g(X)$, where g is some real-valued function.

$$E[g(X)] = E[Y] = \sum_j y_j p(y_j)$$

$$= \sum_j y_j \sum_{i:g(x_i)=y_j} p(x_i)$$

$$= \sum_j \sum_{i:g(x_i)=y_j} y_j \, p(x_i)$$

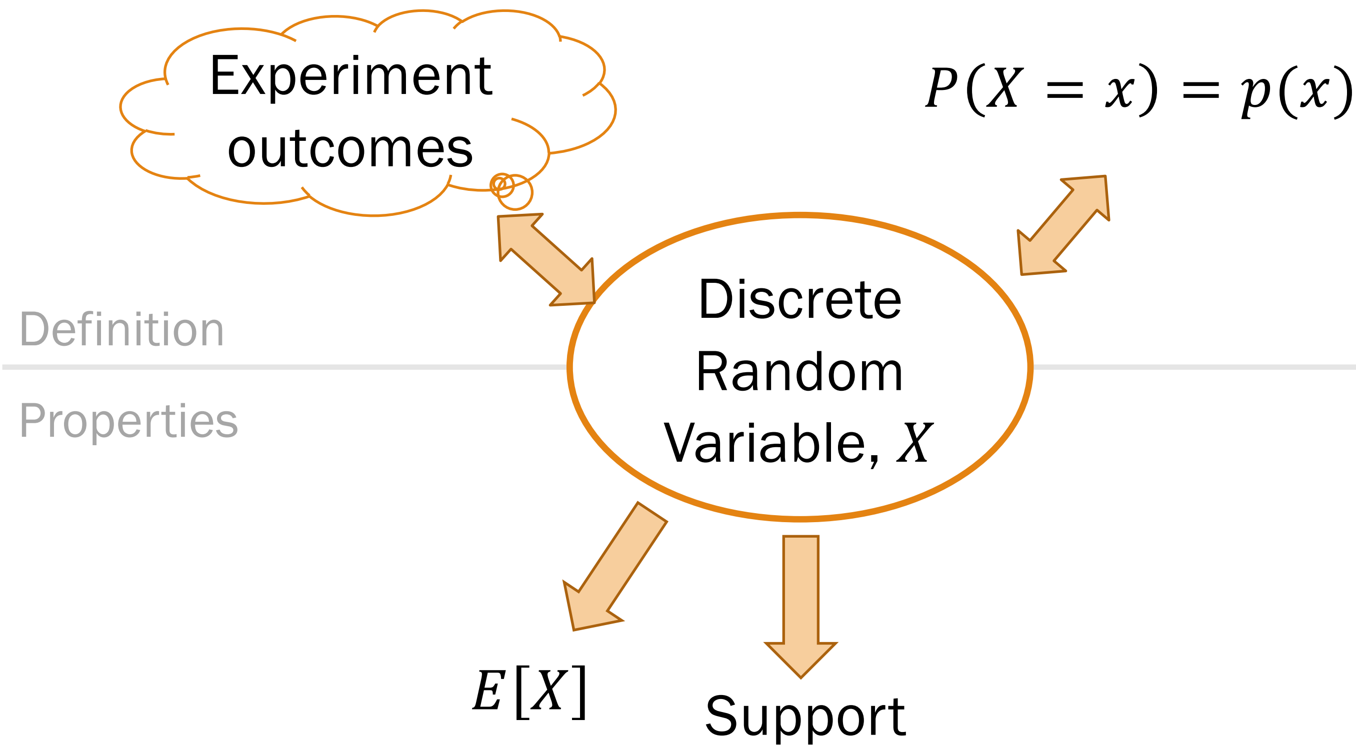
$$= \sum_j \sum_{i:g(x_i)=y_j} g(x_i) \, p(x_i)$$

$$= \sum_i g(x_i) \, p(x_i)$$

For you to review so that you can sleep at night

Discrete random variables

Review



Note: Random Variables also called distributions

A Whole New World with Random Variables

Event-driven probability

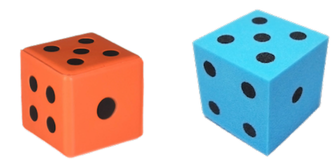
- Relate only binary events
  - Either happens (E)
  - or doesn't happen (E^C)
- Can only report probability
- Lots of combinatorics

Random Variables

- Link multiple but similar events together ($X = 1,\ X = 2, \dots, X = 6$)
- Can compute statistics: e,g. report the expectation
- Once we have the PMF (for discrete RVs), we can employ traditional math

PMF for the sum of two dice

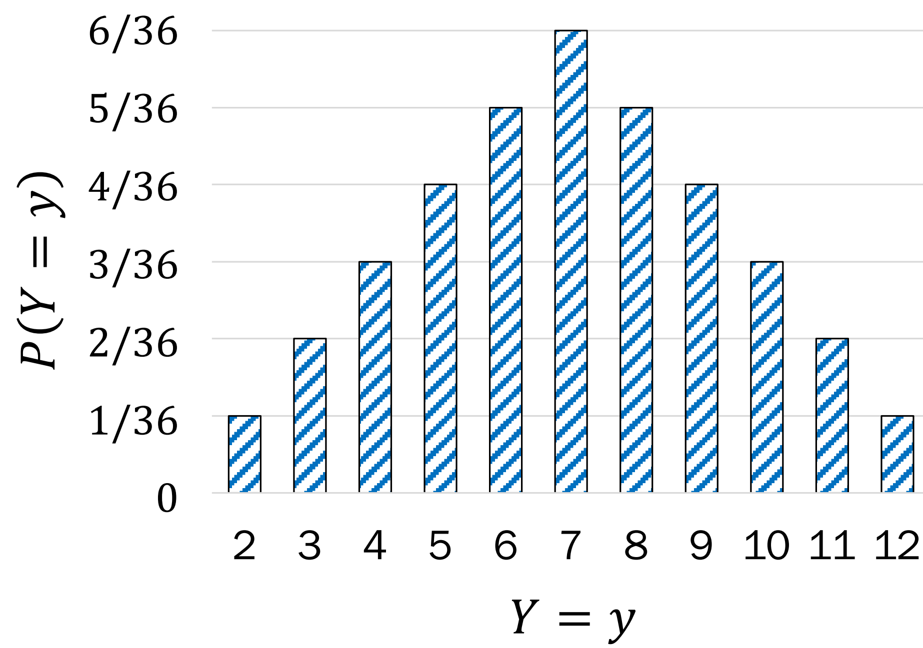
Let Y be a random variable that represents the sum of two independent dice rolls.



Support of Y: $\{2, 3, \dots, 11, 12\}$

$$p(y) = \begin{cases} \frac{y-1}{36} & y \in \mathbb{Z}, 2 \le y \le 6 \\ \frac{13-y}{36} & y \in \mathbb{Z}, 7 \le y \le 12 \\ 0 & \text{otherwise} \end{cases}$$

Sanity check: $$\sum_{y=2}^{12} p(y) = 1$$



Ponder

Let’s take a one-minute breather.

Slide 40 has three questions to think over by yourself while you do that breathing. We’ll go over it together afterwards.

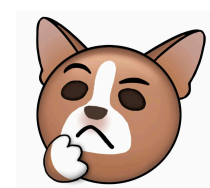
Example random variable

Consider 5 flips of a coin which comes up heads with probability p.
Each coin flip is an independent trial. **Let Y = # of heads on 5 flips.**

1. What is the support of Y? In other words, what are the values that Y can take on with non-zero probability?

2. Define the event $Y = 2$. What is $P(Y = 2)$?

3. What is the PMF of Y? In other words, what is $P(Y = k)$, for k in the support of Y?



Example random variable

Consider 5 flips of a coin which comes up heads with probability p.
Each coin flip is an independent trial. **Let Y = # of heads on 5 flips.**

1. What is the support of Y? In other words, what are the values that Y can take on with non-zero probability?

   $\{0, 1, 2, 3, 4, 5\}$

2. Define the event $Y = 2$. What is $P(Y = 2)$? $P(Y = k) = \binom{5}{2} p^2 (1-p)^3$

3. What is the PMF of Y? In other words, what is $P(Y = k)$, for k in the support of Y?

   $P(Y = k) = \binom{5}{k} p^k (1-p)^{5-k}$

Expectation

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

Expectation: The average value of a random variable

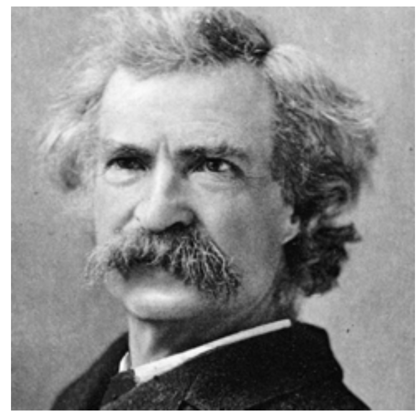
Remember that the expectation of a die roll is 3.5.

X = RV for value of roll

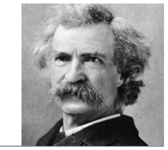
$$E[X] = 1\left(\frac{1}{6}\right) + 2\left(\frac{1}{6}\right) + 3\left(\frac{1}{6}\right) + 4\left(\frac{1}{6}\right) + 5\left(\frac{1}{6}\right) + 6\left(\frac{1}{6}\right) = \frac{7}{2}$$

Lying with statistics

“There are three kinds of lies:
lies, damned lies, and statistics”
–popularized by Mark Twain, 1906



Lying with statistics



A school has 3 classes with 5, 10, and 150 students.

What is the average class size?

1. Interpretation #1

- Randomly choose a <u>class</u> with equal probability.
- X = size of chosen class

$$E[X] = 5\left(\frac{1}{3}\right) + 10\left(\frac{1}{3}\right) + 150\left(\frac{1}{3}\right)$$

$$= \frac{165}{3} = 55$$

What universities usually report

2. Interpretation #2

- Randomly choose a <u>student</u> with equal probability.
- Y = size of chosen class

$$E[Y] = 5\left(\frac{5}{165}\right) + 10\left(\frac{10}{165}\right) + 150\left(\frac{150}{165}\right)$$

$$= \frac{22635}{165} \approx 137$$

Average student perception of class size

Important properties of expectation

1. Linearity:

$$E[aX + b] = aE[X] + b$$

Roll a die, outcome is X. You win $\$2X - 1$. What are your expected winnings?

Let X = 6-sided dice roll.

$E[2X - 1] = 2(3.5) - 1 = 6$

2. Expectation of a sum = sum of expectation:

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

3. Unconscious statistician:

$$E[g(X)] = \sum_x g(x)p(x)$$

Important properties of expectation

1. Linearity:

$$E[aX + b] = aE[X] + b$$

Roll a die, outcome is X. You win \$$2X - 1$.
What are your expected winnings?

Let X = 6-sided dice roll.
$E[2X - 1] = 2(3.5) - 1 = 6$

2. Expectation of a sum = sum of expectation:

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

What is the expectation of the sum of two dice rolls?

Let X = roll of die 1, Y = roll of die 2.
$E[X + Y] = 3.5 + 3.5 = 7$

3. Unconscious statistician:

$$E[g(X)] = \sum_x g(x)p(x)$$

Important properties of expectation

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(next up)

Being a statistician unconsciously

$E[g(X)] = \sum_x g(x)p(x)$ Expectation of $g(X)$

Let X be a discrete random variable.

- $P(X = x) = \frac{1}{3}$ for $x \in \{-1, 0, 1\}$

Let $Y = |X|$. What is $E[Y]$?

A. $\frac{1}{3} \cdot 1 + \frac{1}{3} \cdot 0 + \frac{1}{3} \cdot -1 \quad = 0$

B. $E[Y] = E[0] \quad = 0$

C. $\frac{1}{3} \cdot 0 + \frac{2}{3} \cdot 1 \quad = \frac{2}{3}$

D. $\frac{1}{3} \cdot |-1| + \frac{1}{3} \cdot |0| + \frac{1}{3} |1| = \frac{2}{3}$

E. C and D

Being a statistician unconsciously

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C. $\frac{1}{3} \cdot 0 + \frac{2}{3} \cdot 1 \quad = \frac{2}{3}$

1. Find PMF of Y: $p_Y(0) = \frac{1}{3}, p_Y(1) = \frac{2}{3}$
2. Compute $E[Y]$

D. $\frac{1}{3} \cdot |-1| + \frac{1}{3} \cdot |0| + \frac{1}{3}|1| = \frac{2}{3}$

Use LOTUS by using PMF of X:

1. $P(X = x) \cdot |x|$
2. Sum up

E. C and D

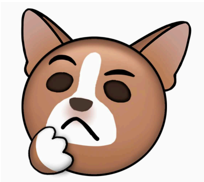
I want to play a game

$$E[g(x)] = \sum_x g(x)p(x)$$ Expectation of $g(X)$

Ponder

Let’s take another break, this time for two minutes.

Slide 52 has three questions to think over by yourself while you do take that break.



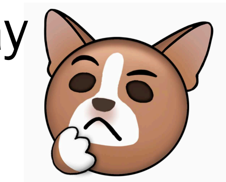
St. Petersburg Paradox

$E[g(x)] = \sum_{x} g(x)p(x)$ Expectation of $g(X)$

- A fair coin (comes up "heads" with $p = 0.5$)
- Define Y = number of coin flips ("heads") before first "tails"
- You win $\$2^Y$

How much would you pay to play? (How much you expect to win?)

A. \$10000
B. \$∞
C. \$1
D. \$0.50
E. \$0 but let's play
F. I will not play



St. Petersburg Paradox

$E[g(x)] = \sum_x g(x)p(x)$ Expectation of $g(X)$

- A fair coin (comes up "heads" with $p = 0.5$)
- Define Y = number of coin flips ("heads") before first "tails"
- You win $\$2^Y$

How much would you pay to play? (How much you expect to win?)

1. Define random variables

For $i \geq 0$: $P(Y = i) = \left(\frac{1}{2}\right)^{i+1}$

Let W = your winnings, 2^Y.

2. Solve

$$E[W] = E[2^Y] = \left(\frac{1}{2}\right)^1 2^0 + \left(\frac{1}{2}\right)^2 2^1 + \left(\frac{1}{2}\right)^3 2^2 + \cdots$$

$$= \sum_{i=0}^{\infty} \left(\frac{1}{2}\right)^{i+1} 2^i = \sum_{i=0}^{\infty} \left(\frac{1}{2}\right) = \infty$$

St. Petersburg + Reality

$E[g(x)] = \sum_x g(x)p(x)$ Expectation of $g(X)$

What if the house has only $65,536?

- Same game
  - Define Y = # heads before first tails
  - You win $W = \$2^Y$

- If you win over $65,536, you break the house and pay 2020 -21 tuition

1. Define random variables

   For $i \geq 0$: $P(Y = i) = \left(\frac{1}{2}\right)^{i+1}$

   Let W = your winnings, 2^Y.

2. Solve

   $$E[W] = \left(\frac{1}{2}\right)^1 2^0 + \left(\frac{1}{2}\right)^2 2^1 + \left(\frac{1}{2}\right)^3 2^2 + \cdots$$

   $k = \log_2(65{,}536)$
   $= 16$

   $$= \sum_{i=0}^{k} \left(\frac{1}{2}\right)^{i+1} 2^i = \sum_{i=0}^{16} \left(\frac{1}{2}\right) = 8.5$$