CS 440/ECE 448 Lecture 2: Random Variables

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Outline

- Probability
- Random Variables
- Jointly random variables
- Conditional Probability
- Independence
- MP01

Notation: Probability

If an experiment is run in an infinite number of parallel universes, the probability of event A is the fraction of those universes in which event A occurs.

Axiom 1: every event A has a non-negative probability.

$$\mathrm{P}(A) \geq 0$$

Axiom 2: If an event Ω always occurs, we say it has probability 1.

$$\mathrm{P}(\Omega) = 1$$

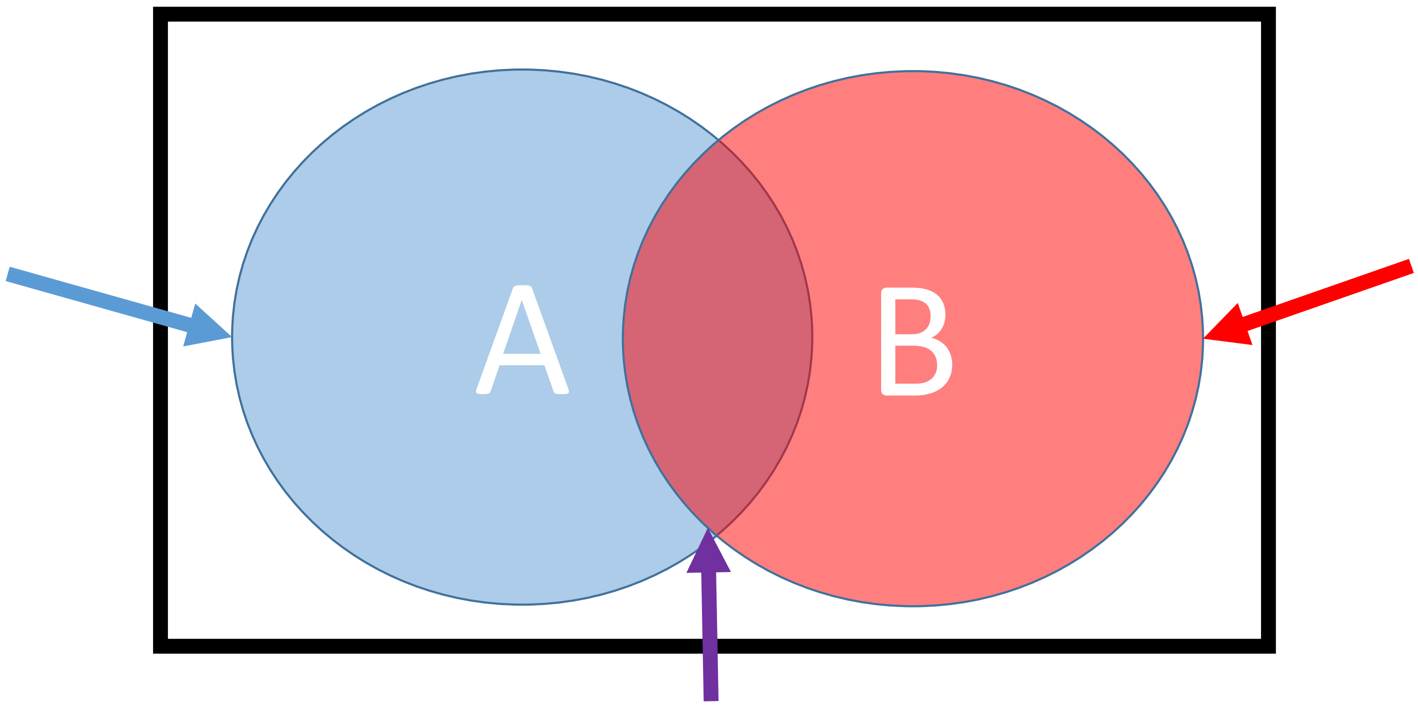
Axiom 3: probability measures behave like set measures.

$$\mathrm{P}(A \vee B) = \mathrm{P}(A) + \mathrm{P}(B) - \mathrm{P}(A \wedge B)$$

Axiom 3: probability measures behave like set measures.

Area of the whole rectangle is $P(\Omega) = 1$.

Area of this circle is $P(A)$.



Area of this circle is $P(B)$.

Area of their intersection is $P(A \wedge B)$.

Area of their union is $P(A \vee B) = P(A) + P(B) - P(A \wedge B)$

The Dutch Book

- A "Dutch Book," sometimes called a "money pump," is a sequence of bets that is guaranteed to lose money

Simple example of a Dutch book:

BET #1: I pay \$1; if it rains tomorrow, I win \$1.50

BET #2: I pay \$1; if it does not rain tomorrow, I win \$1.50

RESULT: I am guaranteed to lose \$0.50

- An agent making decisions using any system other than correctly normalized probabilities can be tricked into accepting a Dutch book.
- Never trust an AI unless it uses correctly normalized probabilities.

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Notation: Random Variables

A **random variable** is a function that summarizes the output of an experiment. We use **capital letters** to denote random variables.

- Example: every Friday, Maria brings a cake to her daughter's pre-school. X is the number of children who eat the cake.

We use a **small letter** to denote a particular **outcome** of the experiment.

- Example: for the last three weeks, each week, 5 children had cake, but this week, only 4 children had cake. Estimate $P(X = x)$ for all possible values of x.

Notation: $P(X = x)$ is a number, but $P(X)$ is a distribution

- $P(X = 4)$ is the probability of the outcome "$X = 4$." For example:

$$P(X = 4) = \frac{1}{4}$$

- $P(X)$ is the complete **distribution**, specifying $P(X = x)$ for all possible values of x. For example:

$P(X) =$

x	**4**	**5**
$P(x)$	$\frac{1}{4}$	$\frac{3}{4}$

Domain and Cardinality

- $\mathcal{X}$ is the domain of X, i.e., the set of its possible values.

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

- $|\mathcal{X}|$ is the cardinality of X, i.e., the number of possible values. For example, if $\mathcal{X} = \{4,5\}$, then $|\mathcal{X}| = 2$.
- The probability of an “average” outcome is $P(X = x) = \frac{1}{|\mathcal{X}|}$

Expectation

The expected value of a function is its probability-weighted average.

$$E[f(X)] = \sum_{x \in \mathcal{X}} f(x) P(X = x)$$

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Jointly Random Variables

- Two or three random variables are “jointly random” if they are both outcomes of the same experiment.
- For example, here are the temperature (x, in °C), and precipitation (y, symbolic) for six days in Urbana:

	X=Temperature (°C)	Y=Precipitation
January 11	4	cloud
January 12	1	cloud
January 13	-2	snow
January 14	-3	cloud
January 15	-3	clear
January 16	4	rain

Joint Distribution

Based on the data on previous slide, here is an estimate of the joint distribution of these two random variables:

$P(X = x, Y = y)$		y			
		snow	rain	cloud	clear
x	-3	0	0	1/6	1/6
	-2	1/6	0	0	0
	1	0	0	1/6	0
	4	0	1/6	1/6	0

Marginal Distribution

Suppose we know the joint distribution $P(X, Y)$. The **marginal distribution** is $P(X)$:

$$P(X = x) = \sum_{y} P(X = x, Y = y)$$

Marginal Distributions

Here are the marginal distributions of the two weather variables:

$P(X,Y)$	**snow**	**rain**	**cloud**	**clear**
-3	0	0	1/6	1/6
-2	1/6	0	0	0
1	0	0	1/6	0
4	0	1/6	1/6	0

$P(X)$
1/3
1/6
0
1/3

$P(Y)$	1/6	1/6	1/2	1/6

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Joint and Conditional distributions

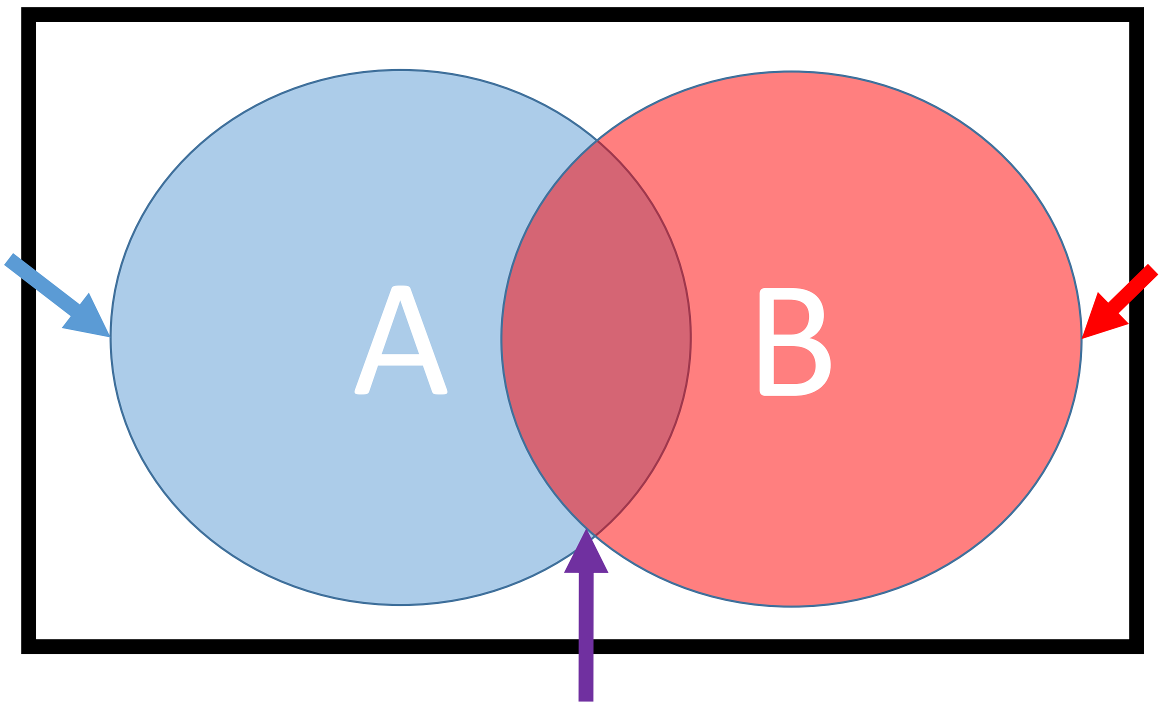
- **Joint distribution** $P(X = x, Y = y)$ is the probability that $X = x$ and $Y = y$.

- **Conditional distribution** $P(Y = y|X = x)$ is the probability that $Y = y$ given that $X = x$.

Joint probabilities are usually given in the problem statement

Area of the whole rectangle is $\Pr(\Omega) = 1$.

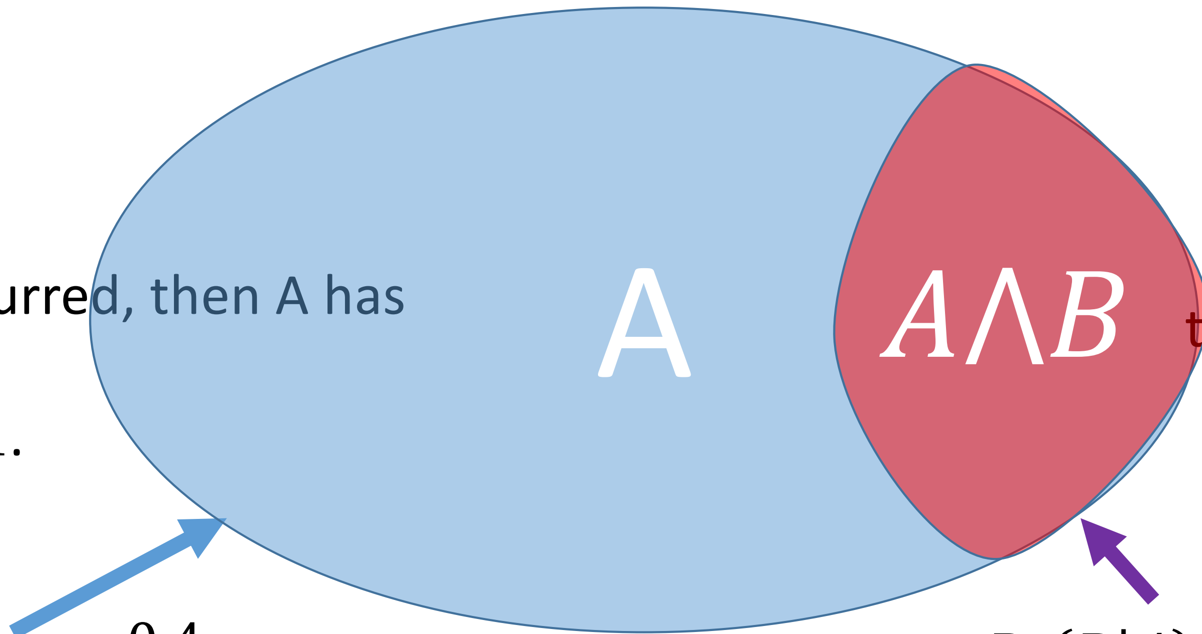
Suppose $\Pr(A) = 0.4$



Suppose $\Pr(B) = 0.2$

Suppose $\Pr(A \land B) = 0.1$

Conditioning events change our knowledge!
For example, given that A is true…



If A has occurred, then A has occurred.
$P(A|A) = 1.$
We can say that

$$\mathrm{P}(A|A) = \frac{0.4}{0.4} = 1$$

If A has occurred, then the only way for B to occur is if both A and B occur:

$$\Pr(B|A) = \frac{\Pr(A \wedge B)}{\Pr(A)} = \frac{0.1}{0.4}$$

Joint and Conditional distributions

- **<u>Joint distribution</u>** $P(X = x, Y = y)$ is the probability that $X = x$ and $Y = y$.

- **<u>Conditional distribution</u>** $P(Y = y|X = x)$ is the probability that $Y = y$ given that $X = x$.

- **<u>Definition of conditional probability</u>**:

$$P(Y = y|X = x) = \frac{P(X = x, Y = y)}{P(X = x)}$$

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Independent Random Variables

Two random variables are said to be independent if:

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

In other words, knowing the value of Y tells you nothing about the value of X.

… and a more useful definition of independence…

Plugging the definition of independence:

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

…into the definition of conditional probability:

$$P(Y = y|X = x) = \frac{P(X = x, Y = y)}{P(X = x)}$$

…gives us a more useful definition of independence.

Definition of Independence: Two random variables, X and Y, are independent if and only if

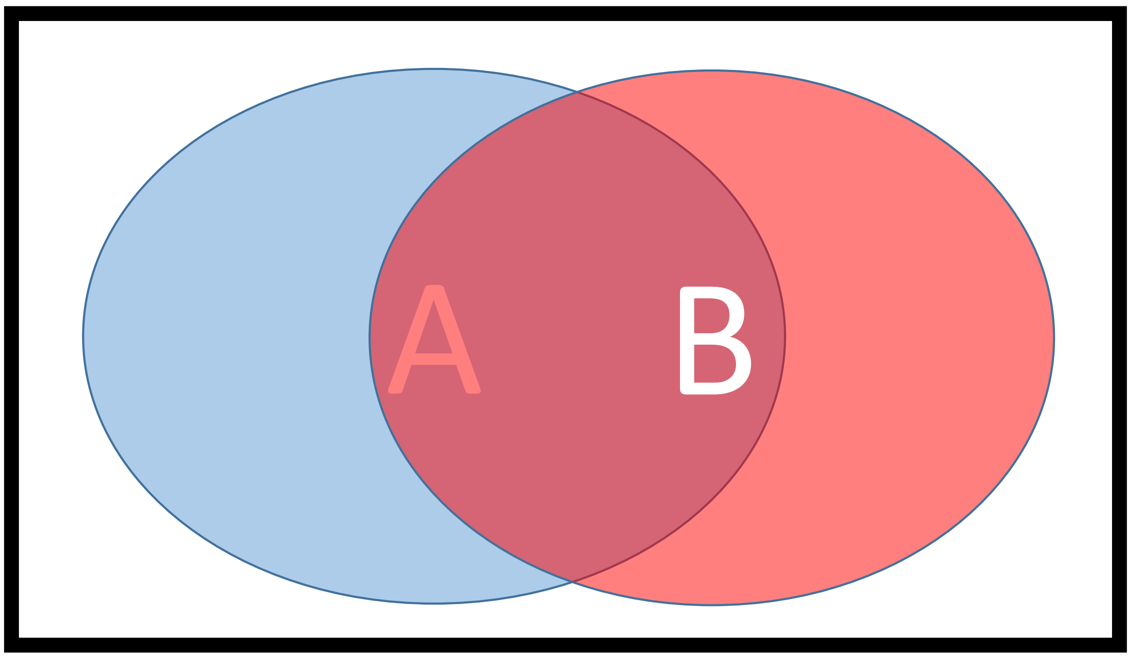
$$P(X = x, Y = y) = P(X = x)P(Y = y)$$

Independent events

Independent events occur with equal probability, regardless of whether the other event has occurred:

$$\Pr(A|B) = \Pr(A)$$

$$\Pr(A \wedge B) = \Pr(A)\Pr(B)$$



Quiz question

Go to PrairieLearn,

Take the quiz called “23-Jan”

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MP01: Random Variables

- MP01 is now available to you!
- Go to the course web page to find instructions and a ZIP file
- Go to Gradescope to submit
- Submit as often as you like, before the deadline (next Friday night); only your best score will be retained
- Office hours will start this weekend (Sunday January 25, 2026)
  - Weekends: 11am-1pm, online, at the URL on the course web page
  - Weekdays: 11am-1pm every day, in person, in ECEB 5034

Summary

- Axioms of probability:

$$\mathrm{P}(A) \geq 0$$

$$\mathrm{P}(\Omega) = 1$$

$$\mathrm{P}(A \vee B) = \mathrm{P}(A) + \mathrm{P}(B) - \mathrm{P}(A \wedge B)$$

- Domain of a random variable:

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

- Conditional probability:

$$P(Y = y | X = x) = \frac{P(X = x, Y = y)}{P(X = x)}$$

- Independence:

$$P(X|Y) = P(X) \Leftrightarrow P(X, Y) = P(X)P(Y)$$

- Expectation:

$$E[f(X)] = \sum_{x \in \mathcal{X}} f(x)P(X = x)$$