

# Quick review of probability theory

## 9.S918

### Spring 2024

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MIT Course 9 (Brain & Cognitive Sciences)

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# Core introductory concepts in probability theory

- ▶ Foundations of probability theory
- ▶ Joint, marginal, and conditional probability
- ▶ Bayes' Rule
- ▶ Conditional Independence
- ▶ Discrete and continuous random variables
- ▶ Mean, variance, covariance, and correlation

# Probability spaces

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A **probability space**  $P$  on a sample space  $\Omega$  is a function from events  $E$  in  $\Omega$  to real numbers such that the following three axioms hold:

1.  $P(E) \geq 0$  for all  $E \subseteq \Omega$  (non-negativity).
2. If  $E_1$  and  $E_2$  are disjoint, then  $P(E_1 \cup E_2) = P(E_1) + P(E_2)$  (disjoint union).
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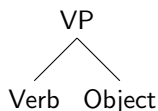
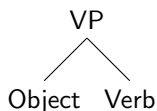
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Note that the set-theoretic characterization of events can also be translated into fundamental operations in Boolean logic:

	Sets	Boolean logic
Subset	$A \subseteq B$	$A \rightarrow B$
Disjointness	$E_1 \cap E_2 = \emptyset$	$\neg(E_1 \wedge E_2)$
Union	$E_1 \cup E_2$	$E_1 \vee E_2$

## A simple example

In historical English, object NPs could be *preverbal* or *postverbal*.



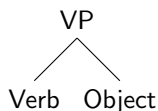
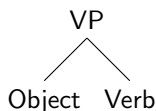
There is a broad cross-linguistic tendency for *pronominal* objects to occur earlier on average than *non-pronominal* objects.

So, hypothetical probabilities from historical English:

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		Pronoun	Not Pronoun
X:	Object <b>Preverbal</b>	0.224	0.655
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We will sometimes call this the **joint distribution**  $P(X, Y)$  over two **random variables**—here, verb-object word order  $X$  and object pronominality  $Y$ .

# Checking the axioms of probability

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$$\Omega = \{\text{Preverbal+Pronoun, Preverbal+Not Pronoun, Postverbal+Pronoun, Postverbal+Not Pronoun}\}$$



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- If we define  $E_1 = \{\text{Preverbal+Pronoun, Postverbal+Not Pronoun}\}$ , then  $P(E_1) = 0.224 + 0.107 = 0.331$ .

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then  $P(E_1) = 0.224 + 0.107 = 0.331$ .

- Check for properness:

$$P(\Omega) = 0.224 + 0.655 + 0.014 + 0.107 = 1$$

# Marginal probability

- ▶ Sometimes we have a joint distribution  $P(X, Y)$  over random variables  $X$  and  $Y$ , but we're interested in the distribution implied over one of them (here, without loss of generality,  $X$ )

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- ▶ This is sometimes known as the **law of total probability**.

## Marginal probability: an example

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Finding the marginal distribution on  $X$ :

$$\begin{aligned}P(X = \mathbf{Preverbal}) &= P(X = \mathbf{Preverbal}, Y = \mathbf{Pronoun}) \\&\quad + P(X = \mathbf{Preverbal}, Y = \mathbf{Not Pronoun}) \\&= 0.224 + 0.655 \\&= 0.879\end{aligned}$$

$$\begin{aligned}P(X = \mathbf{Postverbal}) &= P(X = \mathbf{Postverbal}, Y = \mathbf{Pronoun}) \\&\quad + P(X = \mathbf{Postverbal}, Y = \mathbf{Not Pronoun}) \\&= 0.014 + 0.107 \\&= 0.121\end{aligned}$$

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So, the marginal distribution on  $X$  is

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Likewise, the marginal distribution on  $Y$  is

	$P(Y)$
<b>Pronoun</b>	0.238
<b>Not Pronoun</b>	0.762



# Conditional probability

The conditional probability of event  $B$  given that  $A$  has occurred/is known is defined as follows:

$$P(B|A) \equiv \frac{P(A, B)}{P(A)}$$

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How do we calculate the following?

$$\begin{aligned}P(Y = \text{Pronoun} | X = \text{Postverbal}) &= \frac{P(X = \text{Postverbal}, Y = \text{Pronoun})}{P(X = \text{Postverbal})} \\&= \frac{0.014}{0.121} = 0.116\end{aligned}$$

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Breaking a joint probability down into the product of a marginal probability and several conditional probabilities this way is called **chain rule decomposition**.

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## Bayes' Rule, more closely inspected

$$\overbrace{P(A|B)}^{\text{Posterior}} = \frac{\overbrace{P(B|A)}^{\text{Likelihood}} \overbrace{P(A)}^{\text{Prior}}}{\underbrace{P(B)}_{\text{Normalizing constant}}}$$

# Bayes' Rule in action

Let me give you the same information you had before:

$$P(Y = \mathbf{Pronoun}) = 0.238$$

$$P(X = \mathbf{Preverbal} | Y = \mathbf{Pronoun}) = 0.941$$

$$P(X = \mathbf{Preverbal} | Y = \mathbf{Not Pronoun}) = 0.860$$

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<sup>1</sup>A “transitive” verb is one that requires an object.

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Imagine you're an incremental sentence processor. You encounter a transitive verb<sup>1</sup> but haven't encountered the object yet. **Inference under uncertainty:** How likely is it that the object is a pronoun?

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$$P(Y = \text{Pron} | X = \text{PostV}) = \frac{P(X = \text{PostV} | Y = \text{Pron})P(Y = \text{Pron})}{P(X = \text{PostV})}$$

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# Bayes Rule in Action

$$P(Y = \text{Pronoun}) = 0.238$$

$$P(X = \text{Preverbal} | Y = \text{Pronoun}) = 0.941$$

$$P(X = \text{Preverbal} | Y = \text{Not Pronoun}) = 0.860$$

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## Other ways of writing Bayes' Rule

$$P(A|B) = \frac{\overbrace{P(B|A)}^{\text{Likelihood}} \overbrace{P(A)}^{\text{Prior}}}{\underbrace{P(B)}_{\text{Normalizing constant}}}$$

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2. Ignoring the partition function:

$$P(A|B) \propto P(B|A)P(A)$$

## (Conditional) Independence

Events  $A$  and  $B$  are said to be Conditionally Independent given information  $C$  if

$$P(A, B|C) = P(A|C)P(B|C)$$

Conditional independence of  $A$  and  $B$  given  $C$  is often expressed as

$$A \perp B|C$$

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  - ▶ Remember that probability densities have units (the inverse of the unit of the continuum), and the densities can exceed 1 per unit!

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- ▶ (We are presently eliding over cases where a random variable can have both mass and density on different sets of values)
  - ▶ Unless I mention otherwise, things I say will hold for both discrete and continuous random variables, and I will freely use sums or integrals with the implicit understanding that what I say applies to both cases

# Mean and variance

- ▶ (Population) **mean**, or **expected value**:

$$E[X] = \sum_x x P(X = x) \quad (\text{discrete})$$

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- ▶ (Population) **variance**:

$$\text{Var}[X] = \sum_x (x - E[X])^2 P(X = x) \quad (\text{discrete})$$

$$\text{Var}[X] = \int_x (x - E[X])^2 p(X = x) dx \quad (\text{continuous})$$



# Covariance and correlation

- ▶ The **covariance** between two random variables is how much they vary together:

$$\text{Cov}(X, Y) = \int_{x,y} (x - E[X])(y - E[Y])dx dy$$