Probability: What is it good for?

- Language to express uncertainty
In AI/ML Context

• Quantify predictions

\[ p(\text{lion}), p(\text{tiger}) = [0.98, 0.02] \]

\[ p(\text{lion}), p(\text{tiger}) = [0.01, 0.99] \]

\[ p(\text{lion}), p(\text{tiger}) = [0.43, 0.57] \]
Model Data Generation

• Model complex distributions

StyleGAN2 (Kerras et al ’20)
Outline

• Basics: definitions, axioms, RVs, joint distributions

• Independence, conditional probability, chain rule

• Bayes’ Rule and Inference
Basics: Outcomes & Events

• Outcomes: possible results of an experiment
• Events: subsets of outcomes we’re interested in

Ex: \( \Omega = \{1, 2, 3, 4, 5, 6\} \)
\[ \mathcal{F} = \{\emptyset, \{1\}, \{2\}, \ldots, \{1, 2\}, \ldots, \Omega\} \]
Basics: Outcomes & Events

- Event space can be smaller:

\[ \mathcal{F} = \{\emptyset, \{1, 3, 5\}, \{2, 4, 6\}, \Omega\} \]

- Two components always in it!

\[ \emptyset, \Omega \]
Basics: Probability Distribution

- We have outcomes and events.
- Now assign probabilities \( \text{For } E \in \mathcal{F}, \ P(E) \in [0, 1] \)

Back to our example:

\[ \mathcal{F} = \{\emptyset, \{1, 3, 5\}, \{2, 4, 6\}, \Omega \} \]

\[ P(\{1, 3, 5\}) = 0.2, \ P(\{2, 4, 6\}) = 0.8 \]
Axiom 1: for all event $E \in \mathcal{F}$, $P(E) \geq 0$

$P(E) \geq 0$
Probability Axioms

• **Axiom 2**: Always, $P(\emptyset) = 0$, $P(\Omega) = 1$
• Axiom 3: for disjoint events, \( P(E_1 \cup E_2) = P(E_1) + P(E_2) \)
Other Probability Laws

• Ex: non-disjoint events

\[ P(E_1 \cup E_2) = P(E_1) + P(E_2) - P(E_1 \cap E_2) \]
Break & Quiz

• **Q 1.1:** We toss a biased coin. If $P(\text{heads}) = 0.7$, then $P(\text{tails}) = ?$

  • A. 0.4
  • B. 0.3
  • C. 0.6
  • D. 0.5
• Q 1.1: We toss a biased coin. If $P(\text{heads}) = 0.7$, then $P(\text{tails}) = ?$
• A. 0.4
• B. 0.3
• C. 0.6
• D. 0.5
Break & Quiz

• **Q 1.2:** There are exactly 3 candidates, A, B and C, for a presidential election. We know A has a 30% chance of winning, B has a 35% chance. What’s the probability that C wins?
  
  • A. 0.35
  • B. 0.23
  • C. 0.333
  • D. 0.8
Break & Quiz

• **Q 1.2**: There are exactly 3 candidates, A, B and C, for a presidential election. We know A has a 30% chance of winning, B has a 35% chance. What’s the probability that C wins?
  
  • **A. 0.35**
  • B. 0.23
  • C. 0.333
  • D. 0.8
Break & Quiz

• **Q 1.3**: What’s the probability of selecting a black card or a number 6 from a standard deck of 52 cards?
  • A. 26/52
  • B. 4/52
  • C. 30/52
  • D. 28/52
• **Q 1.3**: What’s the probability of selecting a black card or a number 6 from a standard deck of 52 cards?

• A. 26/52
• B. 4/52
• C. 30/52
• D. 28/52
Basics: Random Variables

• Really, functions
• Map outcomes to real values \( X : \Omega \rightarrow \mathbb{R} \)

• Why?
  – Sets are hard to work with
  – Real values are more convenient
Basics: **CDF & PDF**

- Can still work with probabilities:
  \[ P(X = 3) := P(\{\omega : X(\omega) = 3\}) \]

- Cumulative Distribution Func. (CDF)
  \[ F_X(x) := P(X \leq x) \]

- Density / mass function \( p_X(x) \)
Basics: **Expectation & Variance**

- Another advantage of RVs are "summaries"
- **Expectation:** \[ E[X] = \sum_{a} a \times P(x = a) \]
  
  - The "average"
- **Variance:** \[ Var[X] = E[(X - E[X])^2] \]
  
  - A measure of "spread"
- Higher moments
Basics: Joint Distributions

• Move from one variable to several
• Joint distribution: $P(X = a, Y = b)$
  – Allow us to work with **multiple** types of uncertainty
Basics: **Marginal Probability**

- Given a joint distribution $P(X = a, Y = b)$
  - Get the distribution in just one variable:
    $$P(X = a) = \sum_b P(X = a, Y = b)$$
  - This is called the **marginal** distribution.
Basics: Marginal Probability

\[ P(X = a) = \sum_b P(X = a, Y = b) \]

<table>
<thead>
<tr>
<th></th>
<th>Sunny</th>
<th>Cloudy</th>
<th>Rainy</th>
</tr>
</thead>
<tbody>
<tr>
<td>hot</td>
<td>150/365</td>
<td>40/365</td>
<td>5/365</td>
</tr>
<tr>
<td>cold</td>
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\[ [P(\text{hot}), P(\text{cold})] = \left[ \frac{195}{365}, \frac{170}{365} \right] \]
Probability Tables

• Write our distributions as tables

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• # of entries? 6.
  – If we have $n$ variables with $k$ values, we get $k^n$ entries
  – **Big!** For a 1080p screen, 12 bit color, size of table: $10^{7490589}$
  – No way of writing down all terms
Independence

• Independence between RVs:

\[ P(X, Y) = P(X)P(Y) \]

• Why useful? Go from \( k^n \) entries in a table to \( \sim kn \)

• Reduces joint distribution into product of marginal distributions
Conditional Probability

- For when we know something,

\[ P(X = a | Y = b) = \frac{P(X = a, Y = b)}{P(Y = b)} \]

- Leads to **conditional independence**

\[ P(X, Y | Z) = P(X | Z)P(Y | Z) \]

Credit: Devin Soni
Chain Rule

• Apply repeatedly,

\[ P(A_1, A_2, \ldots, A_n) = P(A_1)P(A_2|A_1)P(A_3|A_2, A_1) \ldots P(A_n|A_{n-1}, \ldots, A_1) \]

• Note: still big!
  – If some \textbf{conditional independence}, can factor!
  – Leads to \textbf{probabilistic graphical models}
Break & Quiz

Q 2.1: Back to our joint distribution table:

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What is the probability the temperature is hot given the weather is cloudy?
A. 40/365
B. 2/5
C. 3/5
D. 195/365
Break & Quiz

**Q 2.1:** Back to our joint distribution table:

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A. 40/365  
B. 2/5  
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D. 195/365
Q 2.2: Of a company’s employees, 30% have CS degrees and 6% have CS Ph.D. degrees. Suppose an employee is selected at random. If the employee selected has a CS degree, what is the probability that the employee has a Ph.D. degree?

A. 0.3
B. 0.06
C. 0.24
D. 0.2
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Evaluating probabilities:

– Wake up with a sore throat ($S$).
– Do I have the flu ($F$)?

One approach: $S \rightarrow F$

– Too strong.

**Inference:** compute probability given evidence $P(F|S)$

– Can be much more complex!
Using Bayes’ Rule

• Want: \( P(F|S) \)

• **Bayes’ Rule:** \( P(F|S) = \frac{P(F,S)}{P(S)} = \frac{P(S|F)P(F)}{P(S)} \)

• **Parts:**
  
  – \( P(S) = 0.1 \) Sore throat rate
  
  – \( P(F) = 0.01 \) Flu rate
  
  – \( P(S|F) = 0.9 \) Sore throat rate among flu sufferers

So: \( P(F|S) = 0.09 \)
Using Bayes’ Rule

• Interpretation $P(F|S) = 0.09$
  – Much higher chance of flu than normal rate (0.01).
  – Very different from $P(S|F) = 0.9$
    • 90% of folks with flu have a sore throat
    • But, only 9% of folks with a sore throat have flu

• Idea: **update** probabilities from evidence
Bayesian Inference

- Fancy name for what we just did. Terminology:

\[ P(H|E) = \frac{P(E|H)P(H)}{P(E)} \]

- \( H \) is the hypothesis
- \( E \) is the evidence
Bayesian Inference

• Terminology:

\[ P(H|E) = \frac{P(E|H)P(H)}{P(E)} \]

• Prior: estimate of the probability \textbf{without} evidence
Bayesian Inference

• Terminology:

\[ P(H|E) = \frac{P(E|H)P(H)}{P(E)} \]

• Likelihood: probability of evidence given a hypothesis.
Bayesian Inference

• Terminology:

\[ P(H|E) = \frac{P(E|H)P(H)}{P(E)} \]

\[ \uparrow \]

Posterior

• Posterior: probability of hypothesis *given* evidence.
Two Envelopes Problem

• We have two envelopes:
  – $E_1$ has two black balls, $E_2$ has one black, one red
  – The red one is worth $100. Others, zero
  – Open an envelope, see one ball. Then, can switch (or not).
  – You see a black ball. **Switch?**
Two Envelopes Solution

• Let’s solve it.

\[ P(E_1 |\text{Black ball}) = \frac{P(\text{Black ball} | E_1) P(E_1)}{P(\text{Black ball})} \]

• Now plug in:

\[ P(E_1 |\text{Black ball}) = \frac{1 \times \frac{1}{2}}{P(\text{Black ball})} \]
\[ P(E_2 |\text{Black ball}) = \frac{\frac{1}{2} \times \frac{1}{2}}{P(\text{Black ball})} \]

So switch!
Q 3.1: 50% of emails are spam. Software has been applied to filter spam. A certain brand of software claims that it can detect 99% of spam emails, and the probability for a false positive (a non-spam email detected as spam) is 5%. Now if an email is detected as spam, then what is the probability that it is in fact a non-spam email?

A. 5/104  
B. 95/100  
C. 1/100  
D. 1/2
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A. 5/104  
B. 95/100  
C. 1/100  
D. 1/2
Q 3.2: A fair coin is tossed three times. Find the probability of getting 2 heads and a tail

A. 1/8
B. 2/8
C. 3/8
D. 5/8
**Break & Quiz**

**Q 3.2:** A fair coin is tossed three times. Find the probability of getting 2 heads and a tail

A. $\frac{1}{8}$
B. $\frac{2}{8}$
C. $\frac{3}{8}$
D. $\frac{5}{8}$