Lecture 1. General concepts, formalism, coin-flipping

Introduction to Bayesian Statistical Learning

24.03.2025 Instructors: Alina Bazarova, Jose Robledo

General concepts

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- Does one have to pick a side (Classical or Bayesian)? No! But we will talk about it later…

Typical use-cases of Bayesian statistics

- Situations when new evidence (data) may significantly influence model parameters and thereby require immediate actions.

- Situations where one is interested in the degree of uncertainty of the results (which you get automatically when using Bayesian approach)

Example:

COVID-19 pandemic. Non-pharmaceutical interventions: lockdowns of various degrees, increased testing - all lead to changes in model parameters such as **reproduction number**, **infection rate** etc. Same as vaccine and drug development which came in significantly later.

Such model would be **data-driven** and have **immediate implications** for public health.

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$$posterior = \frac{prior \times likelihood}{evidence}$$ Reformulated in Bayesian language

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continuous Bayes rule

Possible issues with $\dfrac{p_Y(y)p_{X|Y}(x\,|\,y)}{\int_{\mathbb{R}} p_Y(y)p_{X|Y}(x\,|\,y)dy}$

- Likelihood $p(x\,|\,y)$ might be very complicated
- The integral in the denominator is often intractable, hence computational methods (MCMC, Variational Bayes etc.)

<u>Note:</u>

- $p(x\,|\,y)$ is our model of the data: data-generating distribution
- $p(y)$ is what we think about the parameters of the model $a\ priori$ (prior)

Example: Bayesian vs Frequentist murder trial

Assume you are (hopefully falsely) accused of a murder and have to face a jury in a misfortunate country where the guilt presumed over innocence (null hypothesis is that one is guilty).

The CCTV footage indicates that you were in the same house as the victim on the night of a murder. There are two types of trial:

1. **Frequentist trial.** The jurors specify a model based on the previous trials: if you commit the murder, 30% of the time you would have been seen by the CCTV. Since the probability $P(security\ camera\ footage \,|\, guilt) > 0.05$, you are declared guilty.

2. **Bayesian trial.** The jury first are looking at the evidence, such as absence of previous violent conduct etc. and based on that assign a prior probability of $\frac{1}{1000}$. They compute probability according to Bayes rule

$$P(guilt \,|\, security\ camera\ footage) = \frac{P(security\ camera\ footage \,|\, guilt)P(guilt)}{P(security\ camera\ footage)} = \frac{0.3 \cdot 0.001}{0.3 \cdot 0.001 + 0.3 \cdot 0.999} = 0.001 < 0.05$$

And therefore you are declared innocent.

Note: here the Bayesians also assumed that the probability of you being seen by the camera is 30% whether you were guilty or not

Coin-flipping example

Suppose, that you are unsure about the probability of heads in a coin flip (spoiler alert: usually it's 50%).

You believe there is some true underlying ratio, call it p , but have no prior opinion on what p might be.

We begin to flip a coin, and record the observations: either H or T. This is our observed data.

Question to ask: how will our inference change as we observe more and more data?

$P(H = s) = \binom{n}{s} p^s (1-p)^{n-s}$**,** prior is uniform (constant density function $= 1$), s and n are our data, p is the parameter

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Jupyter notebook Lecture_1_examples: coin flipping example

Some implications I

If $p \,|\, s, n \sim Beta(s+1, n-s+1)$, which is $Ep = \dfrac{s+1}{n+2} \approx \dfrac{s}{n}$ for large n, similarly

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Punchline: if sample is large enough there is no difference whether to use Bayesian or frequentist approach!

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This is very useful both for numerical and analytical methods.

A comprehensive list of **pairs likelihood - conjugate prior** https://en.wikipedia.org/wiki/Conjugate_prior

Jupyter notebook 1 - play around with a prior in a coin-flipping example, look how posterior changes

Continuous distributions

A typical (and somewhat simplified) question: what is the parameter of the distribution based on the data?

Example: exponential distribution with pdf $p_X(x \mid \lambda) = \lambda e^{-\lambda x}$, where X is our r.v.

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Bayesian inference: rather than guessing λ exactly we try assigning a probability distribution to it, hence our **inference provides confidence intervals automatically**.

Jupyter notebook Lecture_1_examples: example with text message data