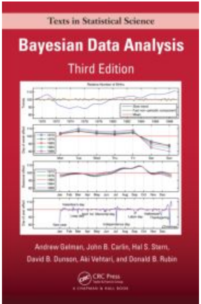
Bayesian data analysis (Aalto fall 2023)

Don't leave empty seats in the middle, as the lecture hall will be almost full today!

- Book: Gelman, Carlin, Stern, Dunson, Vehtari & Rubin: Bayesian Data Analysis, Third Edition. (online pdf available)
- The course website has more detailed information
  https://avehtari.github.io/BDA_course_Aalto/Aalto2023.html
- Timetable: see the course website
- TAs: David Kohns, Noa Kallioinen, Andrew Johnson, Leevi Lindgren, Anna Riha, Niko Siccha, Maksim Sinelnikov, Teemu Säilynoja



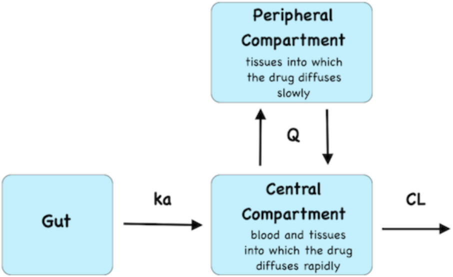
Uncertainty and decision making

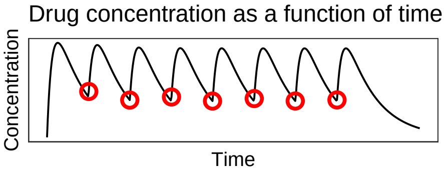
- Predicting concrete quality

$\rightarrow$

Uncertainty and decision making[1]

- Everolimus is immunosuppressant to prevent rejection of organ transplants
- Pharmacokinetic model of drug and body, optimal dosage depends on weight





[1] with E. Siivola, Aalto and S. Weber, Novartis Pharma

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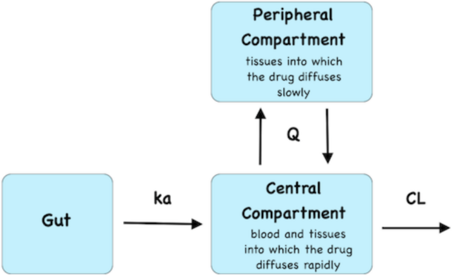

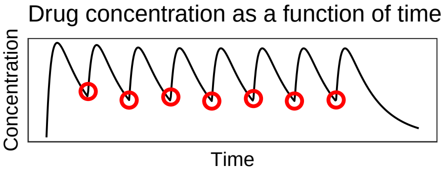

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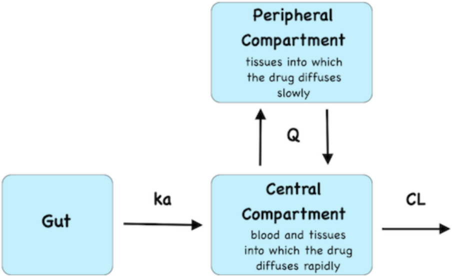
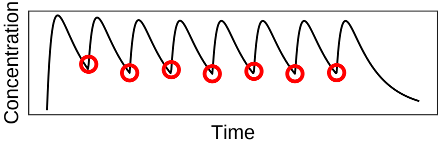


Drug concentration as a function of time



- Model fitted with 500 adults, extrapolation to children?
- Maturation effect, 17 observations from children

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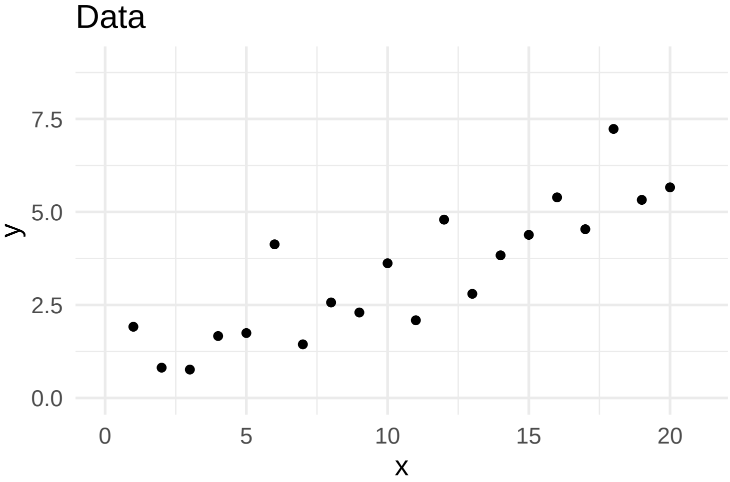
Uncertainty in modeling



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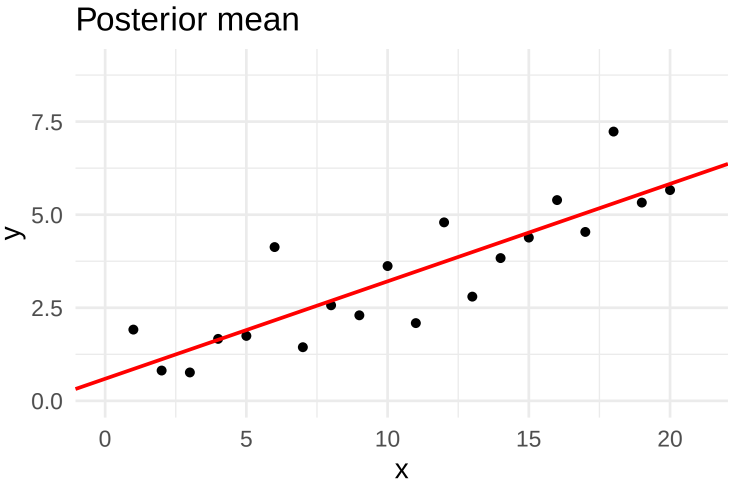

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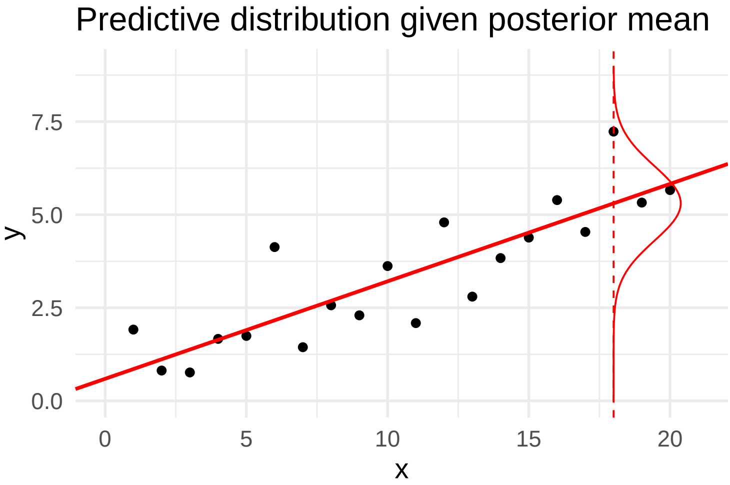

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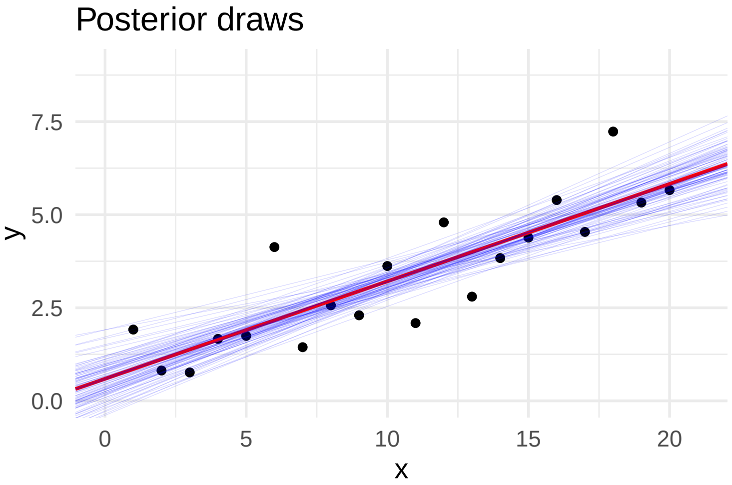

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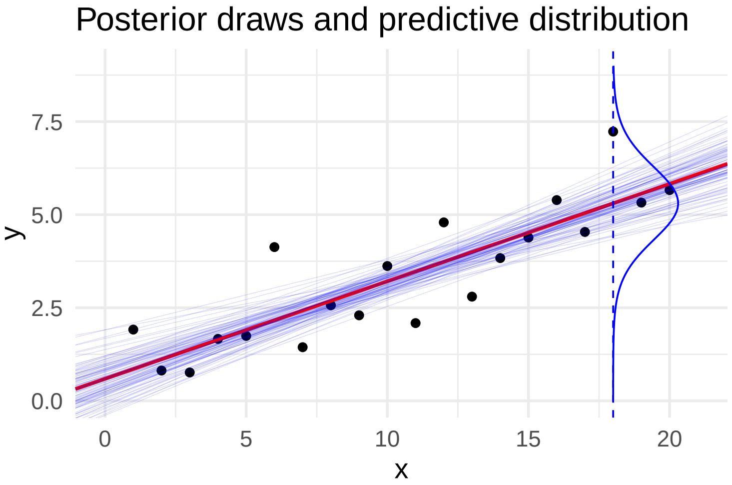

Bayesian probability theory

expert information

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expert information

$\searrow$

mathematical model

$+$

uncertainty with probabilities

Bayesian probability theory

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Bayesian probability theory

expert information $\searrow$ mathematical model + uncertainty with probabilities

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mathematical model + uncertainty with probabilities + Bayesian probability theory

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updated uncertainty

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understandable trusted models

Bayesian inference with computers

mathematical model to computer

probabilistic programming

computation, automatic inference algorithms

limitations of computers

Yes, but did it work?

computation + inference diagnostics

model diagnostics

limitations of mathematical models

improve and iterate

Probabilistic programming and Stan

Stan is a probabilistic programming framework and ecosystem
40+ developers, 100+ contributors, 100K+ users

mc-stan.org

Bayesian Data Analysis course

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  - need to understand the math part (prereq.)
  - continuous vs discrete (prereq.)
  - observation model, likelihood, prior
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  - grid, importance sampling, Monte Carlo, Markov chain Monte Carlo

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- Workflow
  - steps of model building, inference, and diagnostics

Impact on society

Better modelling and quantification of uncertainty

$\rightarrow$ better science

$\rightarrow$ better informed decision making
in companies, government, and NGOs

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- A nice book about history: Sharon Bertsch McGrayne, *The Theory That Would Not Die*, 2012.

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- The probabilistic programming revolution started in early 1990's

Uncertainty and probabilistic modeling

- Two types of uncertainty: aleatoric and epistemic
- Representing uncertainty with probabilities
- Updating uncertainty

Two types of uncertainty

- Aleatoric uncertainty due to randomness

- Epistemic uncertainty due to lack of knowledge

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- Epistemic uncertainty due to lack of knowledge
  - we are able to obtain observations which can reduce this uncertainty
  - two observers may have different epistemic uncertainty

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- $p(\theta|\text{y} = \#\text{red}, \#\text{yellow}, \#\text{red}, \#\text{red}, \ldots) = ?$

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- $p(\theta|\text{y} = \#\text{red}, \#\text{yellow}, \#\text{red}, \#\text{red}, \ldots) = ?$
- Bayes rule $p(\theta|y) = \frac{p(y|\theta)p(\theta)}{\int p(y|\theta)p(\theta)d\theta}$

Model vs. likelihood

- Bayes rule $p(\theta|y) \propto p(y|\theta)p(\theta)$
- Model: $p(\mathbf{y}|\theta)$ as a function of $\mathbf{y}$ given fixed θ describes the aleatoric uncertainty
- Likelihood: $p(y|\boldsymbol{\theta})$ as a function of $\boldsymbol{\theta}$ given fixed y provides information about epistemic uncertainty, but is not a probability distribution

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- Bayes rule combines the likelihood with prior uncertainty $p(\theta)$ and transforms them to updated posterior uncertainty

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- Other parts of the art of probabilistic modeling are, for example,
  - model checking: is data in conflict with our prior knowledge?
  - presentation: presenting the model and the results to the application experts

Modeling nature

- Drop a ball from different heights and measure time

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  - air resistance, air pressure, shape and surface structure of the ball
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  - air resistance, air pressure, shape and surface structure of the ball
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- Taking into account the accuracy of the measurements, how accurate model is needed?
  - often simple models are adequate and useful
  - *All models are wrong, but some of them are useful*, George P. Box

Reminder: Uncertainty and probabilistic modeling

- Two types of uncertainty: aleatoric and epistemic
- Representing uncertainty with probabilities
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Chapter 1

Reading instructions

- 1.1-1.3 important terms
- 1.4 a useful example
- 1.5 foundations
- 1.6 & 1.7 examples (can be skipped, but may be useful to read)
- 1.8 & 1.9 background material, good to read before doing the exercises
- 1.10 a point of view for using Bayesian inference

Part of the assignment 1

Refresh your memory on these concepts!

- probability
- probability density
- probability mass
- probability density function (pdf)
- probability mass function (pmf)
- probability distribution
- discrete probability distribution
- continuous probability distribution
- cumulative distribution function (cdf)
- likelihood

Ambiguous notation in statistics

Find this in the Chapter 1 reading instructions on the course web page!

In $p(y \mid \theta)$

- y can be variable or value
  - we could clarify by using $p(Y \mid \theta)$ or $p(y \mid \theta)$
- θ can be variable or value
  - we could clarify by using $p(y \mid \Theta)$ or $p(y \mid \theta)$
- p can be a discrete or continuous function of y or θ
  - we could clarify by using P_Y, P_Θ, p_Y or p_Θ
- $P_Y(Y \mid \Theta = \theta)$ is a probability mass function, sampling distribution, observation model
- $P(Y = y \mid \Theta = \theta)$ is a probability
- $P_\Theta(Y = y \mid \Theta)$ is a likelihood function (can be discrete or continuous)
- $p_Y(Y \mid \Theta = \theta)$ is a probability density function, sampling distrbution, observation model
- $p(Y = y \mid \Theta = \theta)$ is a density
- $p_\Theta(Y = y \mid \Theta)$ is a likelihood function (can be discrete or continuous)
- y and θ can also be mix of continuous and discrete
- due to the sloppines sometimes likelihood is used to refer $P_{Y,\theta}(Y \mid \Theta)$, $p_{Y,\theta}(Y \mid \Theta)$

Questions

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  - is the number of fingers raised random (by you or by others)?
- If we build a robot with very fast vision which can observe the rotating coin accurately, is the throw random for the robot?
- What is your own example with both aleatoric and epistemic uncertainty?