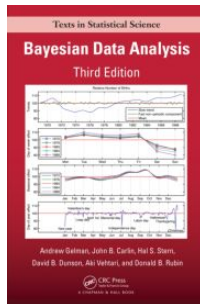


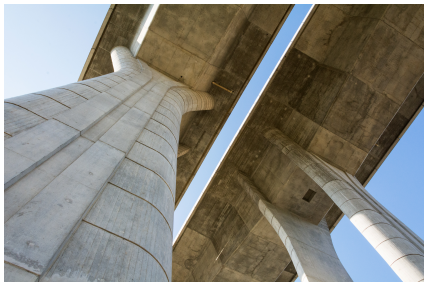
Bayesian data analysis (Aalto fall 2024)

- 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/Aalto2024.html
- Timetable: see the course website
- TAs: David Kohns, Mélanie Guhl, Noa Kallioinen, Anna Riha, Varun Shanmugam, Maksim Sinelnikov, Teemu Säilynoja



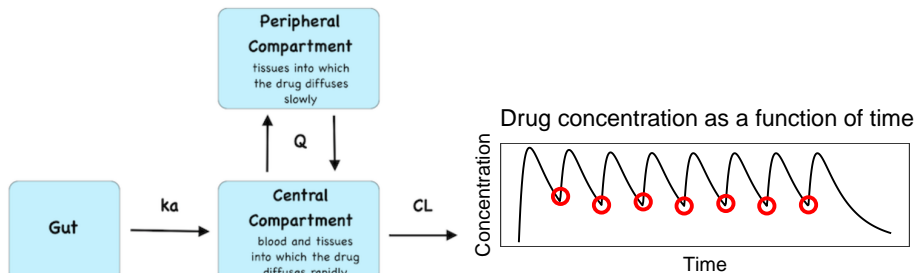
Uncertainty and decision making

- Predicting concrete quality



Uncertainty and decision making¹

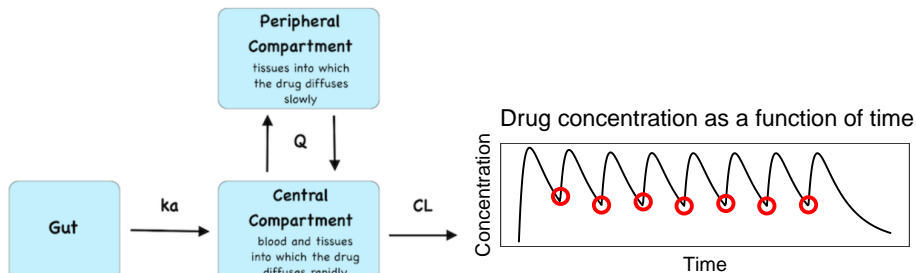
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- Pharmacokinetic model of drug and body, optimal dosage depends on weight



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

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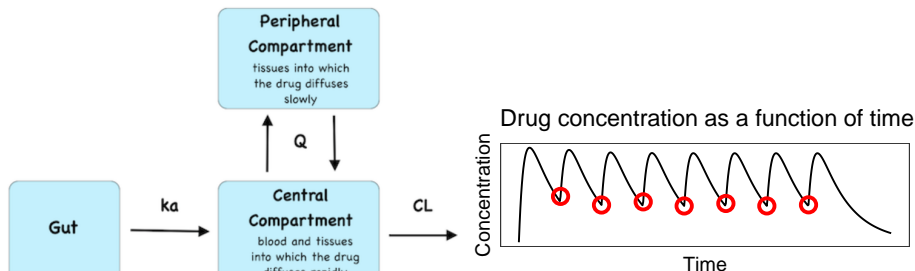


- Model fitted with 500 adults, extrapolation to children?

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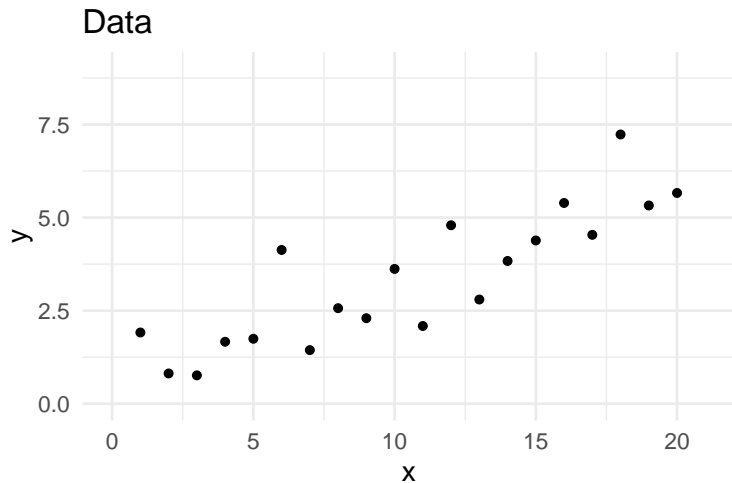
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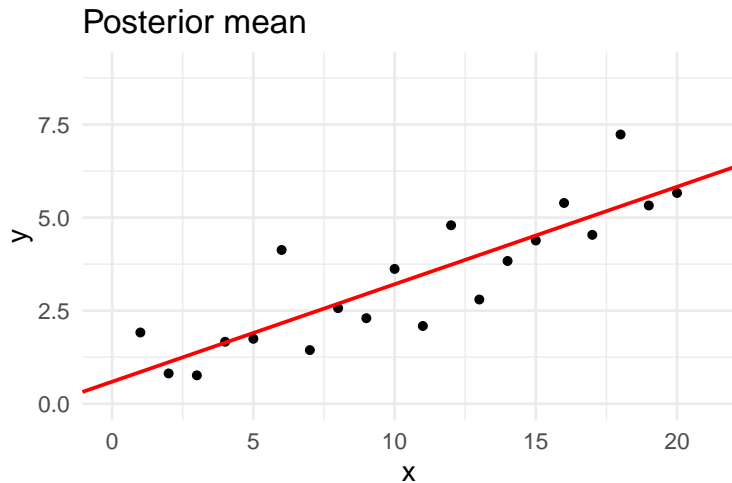
- Model fitted with 500 adults, extrapolation to children?
- Maturation effect, 17 observations from children

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Uncertainty in modeling

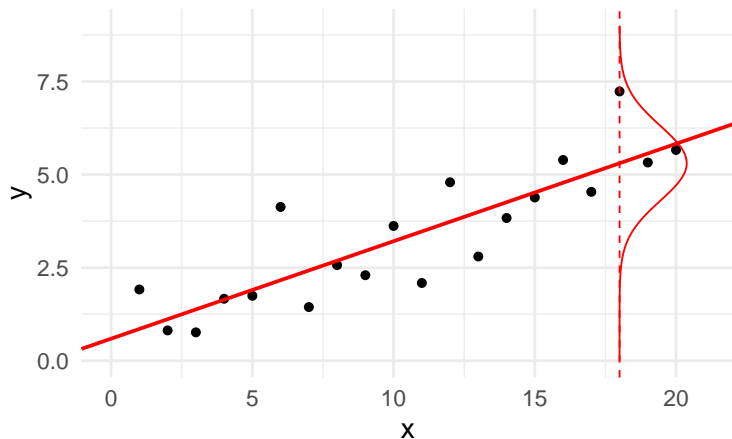


Uncertainty in modeling



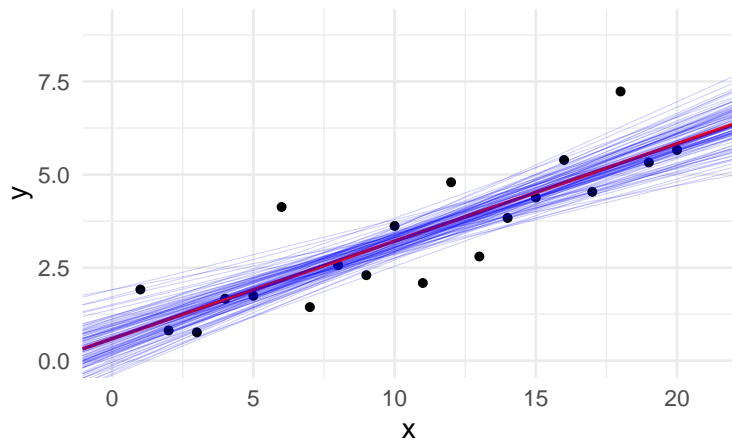
Uncertainty in modeling

Predictive distribution given posterior mean



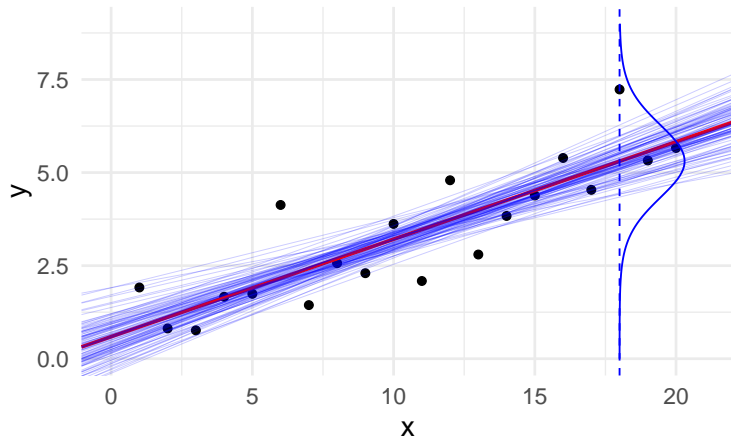
Uncertainty in modeling

Posterior draws



Uncertainty in modeling

Posterior draws and predictive distribution



Bayesian probability theory

expert information

Bayesian probability theory

expert information



mathematical model

+

uncertainty with probabilities

Bayesian probability theory

expert information



mathematical model

+

uncertainty with probabilities

data

Bayesian probability theory

expert information



mathematical model

+

uncertainty with probabilities

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Bayesian probability theory

data



$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)}$$

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Bayesian probability theory

expert information



mathematical model

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updated uncertainty

Bayesian probability theory

expert information



mathematical model

+

uncertainty with probabilities

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Bayesian probability theory

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updated uncertainty

+

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

Bayesian Workflow

All the pieces put together

Probabilistic programming and Stan

Stan is a probabilistic programming framework and ecosystem
40+ developers, 100+ contributors, 200K+ users



mc-stan.org

Bayesian Data Analysis course

- Probability distributions as model building blocks
 - need to understand the math part (prereq.)
 - continuous vs discrete (prereq.)
 - observation model, likelihood, prior
 - constructing bigger models

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 - grid, importance sampling, Monte Carlo, Markov chain Monte Carlo
- Workflow
 - steps of model building, inference, and diagnostics

Impact on society

Better modelling and quantification of uncertainty

→ better science

→ better informed decision making
in companies, government, and NGOs

Bayesian probability theory

- Based on Bayesian probability theory
 - uncertainty is presented with probabilities
 - probabilities are updated based on new information
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 - English nonconformist, Presbyterian minister, mathematician
 - considered the problem of *inverse probability*
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- A nice book about history: Sharon Bertsch McGrayne, *The Theory That Would Not Die*, 2012.

Term Bayesian used first time in mid 20th century

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 - concept of the probability was not strictly defined, although it was close to modern Bayesian interpretation
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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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Two types of uncertainty

- Aleatoric uncertainty due to randomness
 - we are not able to obtain observations which could reduce this uncertainty
- 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

Updating uncertainty

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

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- $p(\theta|y = \text{\#red}, \text{\#yellow}, \text{\#red}, \text{\#red}, \dots) = ?$
- 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: $p(y|\theta)$ as a function of θ given fixed y provides information about epistemic uncertainty, but is not a probability distribution

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- Likelihood: $p(y|\theta)$ as a function of θ given fixed y provides information about epistemic uncertainty, but is not a probability distribution
- Bayes rule combines the likelihood with prior uncertainty $p(\theta)$ and transforms them to updated posterior uncertainty

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 - computational challenges

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- The art of probabilistic modeling is to describe in a mathematical form (model and prior distributions) what we already know and what we don't know
- “Easy” part is to use Bayes rule to update the uncertainties
 - computational challenges
- 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

Modeling nature

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 - Newton
 - air resistance, air pressure, shape and surface structure of the ball
 - relativity

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Modeling nature

- Drop a ball from different heights and measure time
 - Newton
 - air resistance, air pressure, shape and surface structure of the ball
 - relativity
- 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
- Updating uncertainty

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
- Bayes rule

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 distribution, 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 sloppiness sometimes likelihood is used to refer $P_{Y,\theta}(Y \mid \Theta), p_{Y,\theta}(Y \mid \Theta)$

Questions

- Pick a number between 1–5

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 - raise as many fingers

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- Pick a number between 1–5
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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?