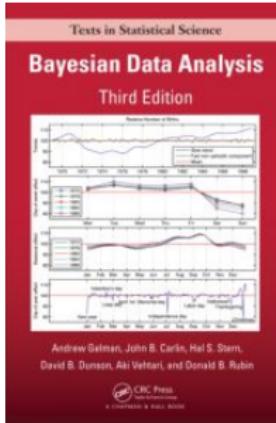


# Bayesian data analysis (Aalto fall 2025)

- 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/Aalto2025.html](https://avehtari.github.io/BDA_course_Aalto/Aalto2025.html)
- Timetable: see the course website
- TAs: David Kohns, Osvaldo Martin, Wanxian Chen, Ningyi Peng, Maksim Sinelnikov, Reza Soumi, Herman Tesso, Quan Tran, Aristomenis Tsopelakos, Behram Ulukir



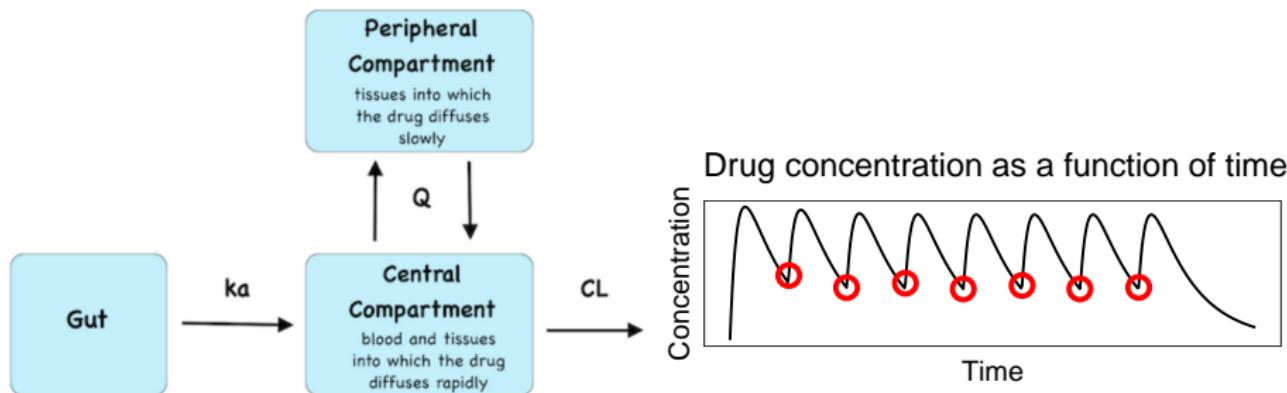
# Uncertainty and decision making

- Predicting concrete quality



# Uncertainty and decision making<sup>1</sup>

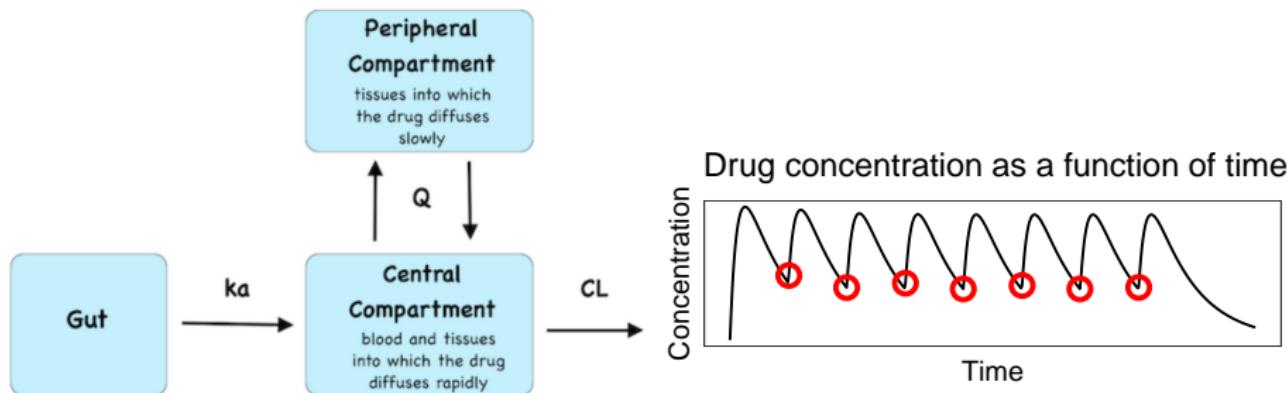
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- Pharmacokinetic model of drug and body, optimal dosage depends on weight



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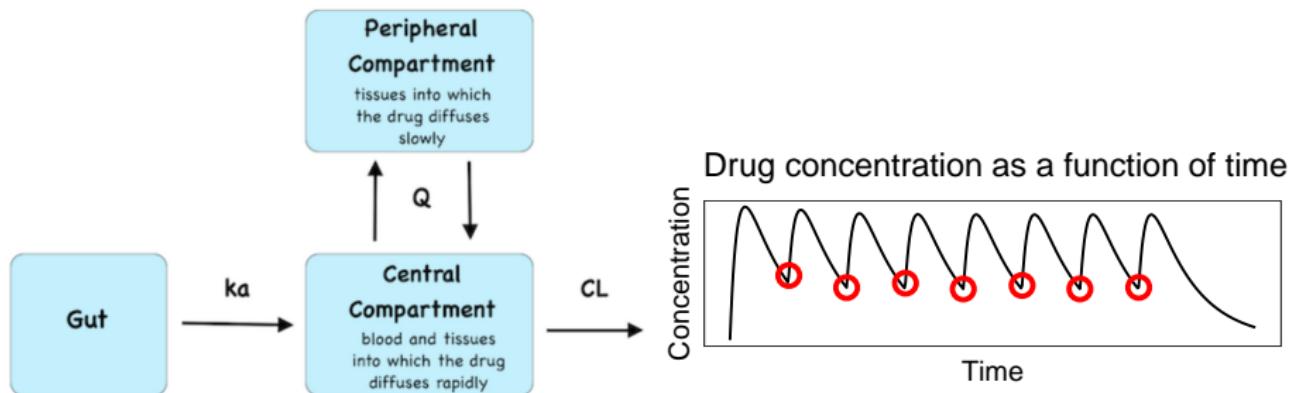


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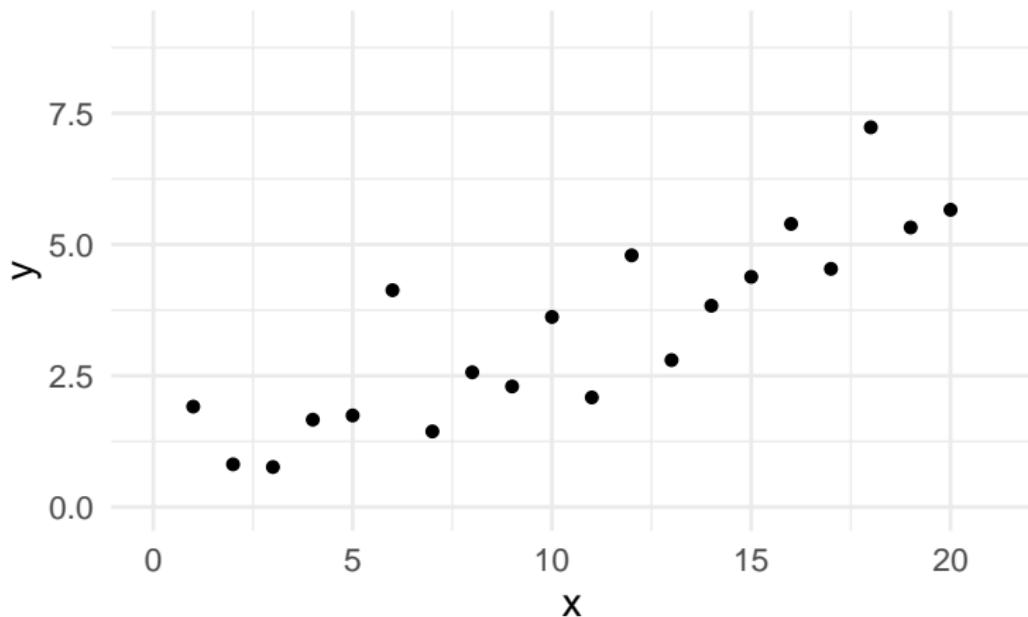


- Model fitted with 500 adults, extrapolation to children?
- Maturation effect, 17 observations from children

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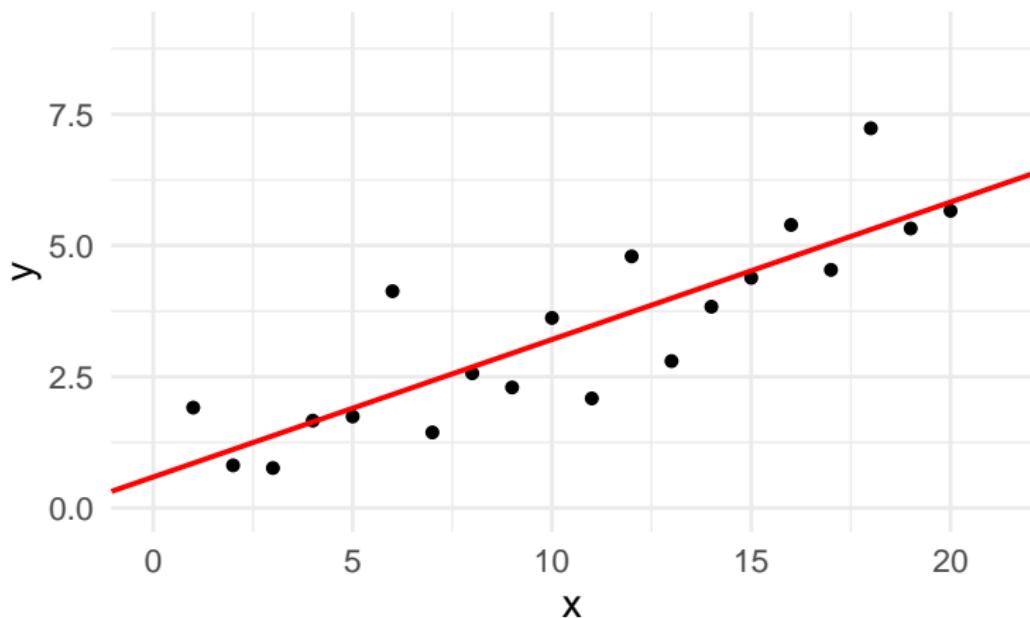
# Uncertainty in modeling

Data



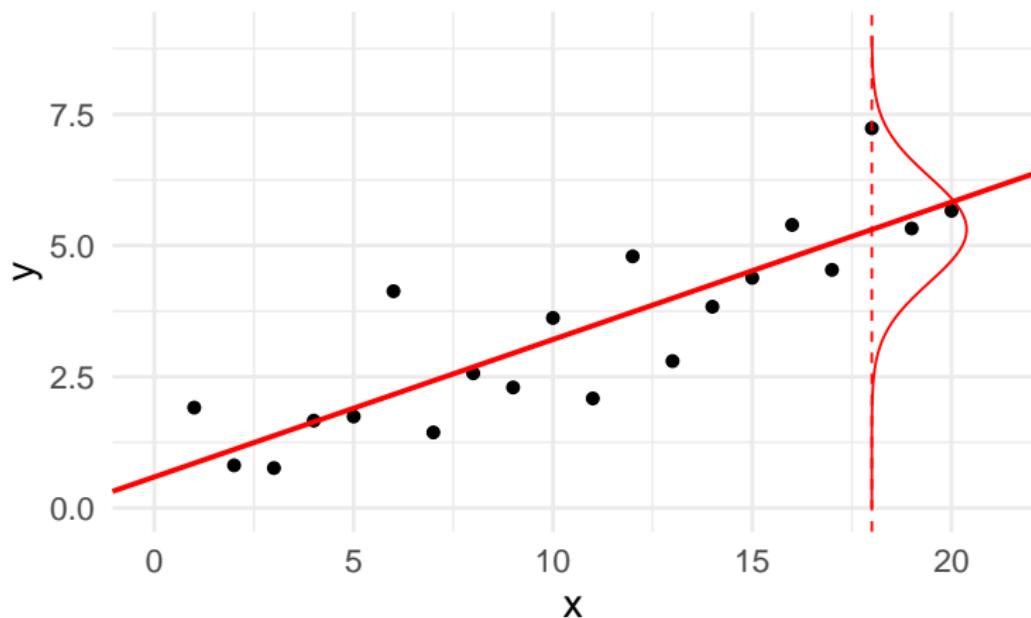
# Uncertainty in modeling

Posterior mean



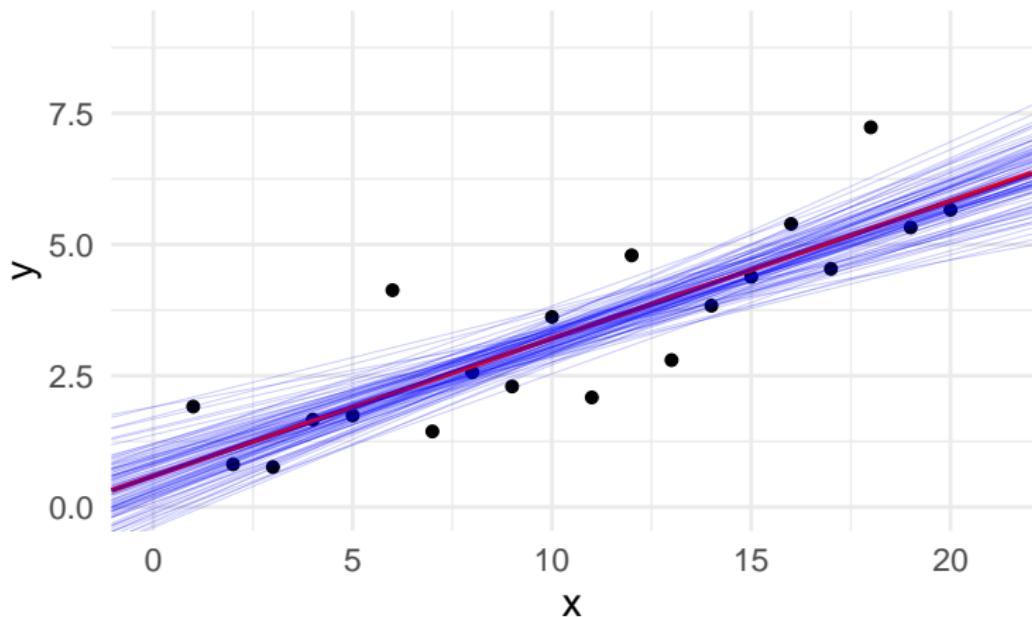
# Uncertainty in modeling

Predictive distribution given posterior mean



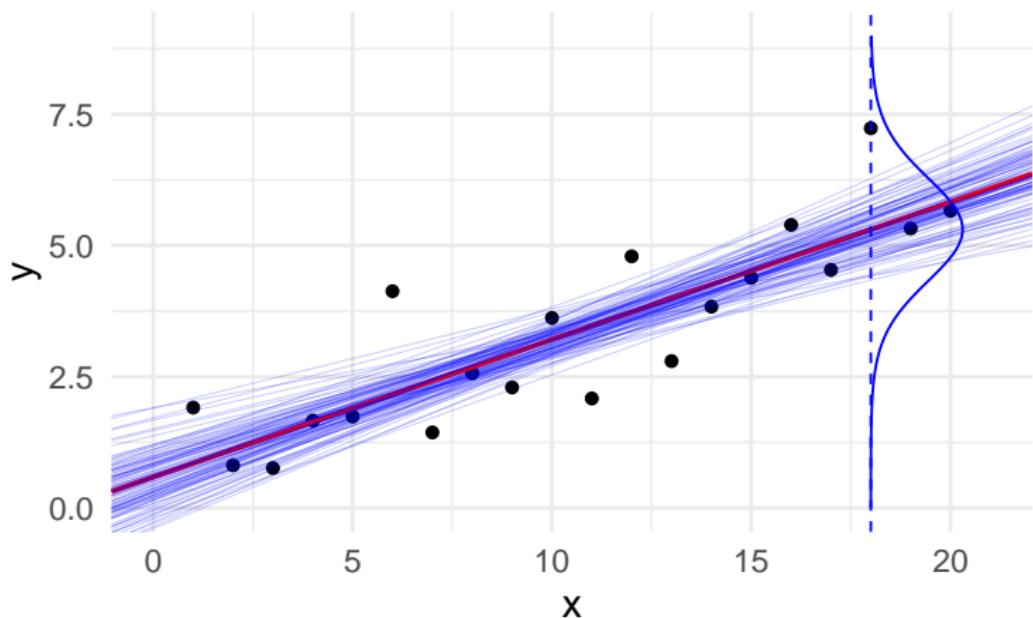
# Uncertainty in modeling

Posterior draws



# Uncertainty in modeling

Posterior draws and predictive distribution



# Bayesian probability theory

expert information

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expert information



mathematical model

+

uncertainty with probabilities

# Bayesian probability theory

expert information



data

mathematical model

+

uncertainty with probabilities

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expert information



mathematical model

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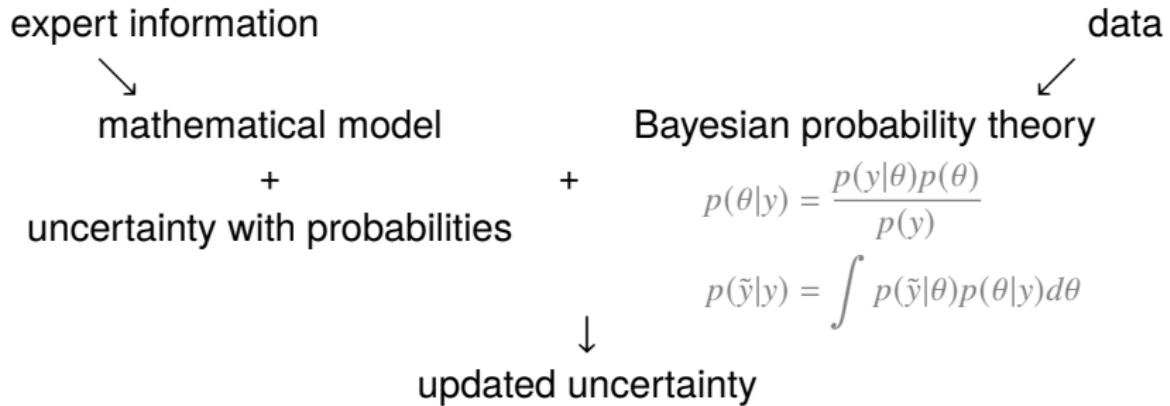
Bayesian probability theory



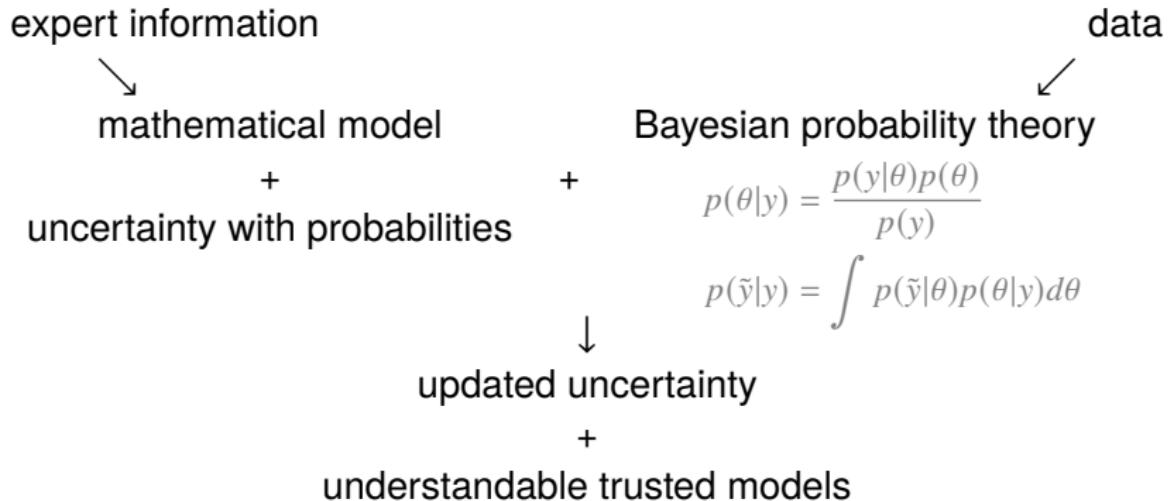
$$p(\theta|y) = \frac{p(y|\theta)p(\theta)}{p(y)}$$

$$p(\tilde{y}|y) = \int p(\tilde{y}|\theta)p(\theta|y)d\theta$$

# Bayesian probability theory



# Bayesian probability theory



# 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](http://mc-stan.org)

# Bayesian Data Analysis course

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  - need to understand the math part (prereq.)
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- 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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- 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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  - 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

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- $p(\theta | y = \#red, \#yellow, \#red, \#red, \dots) = ?$
- 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  $\theta$  describes the aleatoric uncertainty
- Likelihood:  $p(y|\theta)$  as a function of  $\theta$  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  $\theta$  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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- 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

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

$\ln p(y | \theta)$

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

## Questions

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  - raise as many fingers
  - 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?