Aalto University
School of Electrical
Engineering

ELEC-E8103 Modelling, Estimation and Dynamic Systems

Introduction

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Course Information

ELEC-E8103 Modelling, Estimation and Dynamic Systems

- Responsible/main lecturer
  - Prof. Quan Zhou
- Other lecturers and course assistants
  - M.Sc. Artur Kopitca
  - Dr. Houari Bettahar
  - Taha Heidari
  - Hajiba Legrara
- Number of credits: 5 ECTs
- Teaching period: I-II
- Lectures (W36, W38, W40, W43, W45, W47)
  - Wednesdays 12:15-14:00
  - Thursdays 12:15-14:00
- Exercise sessions (W37, W39, W41, W44, W46, W48-49)
  - Please register in MyCourses, there are multiple groups
    - Contact sessions on Monday 14:15-16:00, 16:15-18:00, Wednesday 12:15-14:00,
    - Online sessions on Wednesday 16:15-18:00
  - Please select only one contact session per week

- Prerequisites
  - Programming in MATLAB, matrix and linear algebra, basic course in control engineering or relevant knowledge
    - Check Aalto B.Sc. Programme
- Assessment Methods and Criteria:
  - Home assignments (40%)
  - Final online exam (60%)
- Study Materials:
  - Handouts/lecture slides
  - Ljung, Modeling of dynamic systems, 1994
  - Additional book chapters to be specified

Pre-request brush up materials

- Matrix algebra in engineering
  - https://www.youtube.com/watch?v=IZcyZHomFQc&list=PLkZjai-2Jcxlg-Z1roB0pUwFU-P58tvOx
- Laplace Transformation engineering mathematics
  - https://www.youtube.com/watch?v=8oE1shAX96U
- Matlab and Simulink tutorials
  - https://youtu.be/g2ReUOquMwE
  - https://youtu.be/pFICO_syIls
  - https://youtu.be/vxzR3W2BcRk

Not all information in those videos are important for the course, but it can help you to quickly get the idea of some basic knowledge.

Talk to your classmate besides you, 5 minutes

- Getting familiar with your classmates

- You can also discuss what is model and modelling

Model

- https://www.google.com/search?q=model&tbm=isch

Model

From Wikipedia (2015):

- Model, modeling or modelling may refer to:
  - Model (abstract), a representation of a system using symbols, such as a flow chart, schematic, or equation
  - Model (physical), a representation of a system based on a concrete object, such as a globe or model airplane
    - Scientific model, an imperfect or idealized representation of a physical system
    - Scale model, a replica or prototype of an object

From Wikipedia (2023):

- A model is an informative representation of an object, person or system.
  - The term originally denoted the plans of a building in late 16th-century English, and derived via French and Italian ultimately from Latin modulus, a measure.[1]
- Models can be divided into physical models (e.g. a ship model or a fashion model) and abstract models (e.g. a set of mathematical equations describing the workings of the atmosphere for the purpose of weather forecasting).
  - Abstract or conceptual models are central to philosophy of science.[2][3]

WARNING: Wikipedia is not a reliable literature source, do not cite Wikipedia in your academic writing, e.g., formal reports, theses or papers, to support your reasoning or discussion.

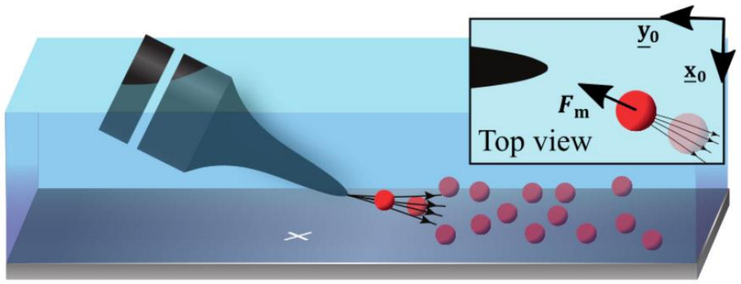
On the other hand, Wikipedia is a good starting point for quick exploration and pursuing original materials (maybe together with tools such as Google Scholar).

Model…

- From the textbook[1]: "Loosely put, a model of a system is a tool we use to answer questions about the system without having to do an experiment."
  - Mental models
  - Verbal models
  - Physical models
  - Mathematical models

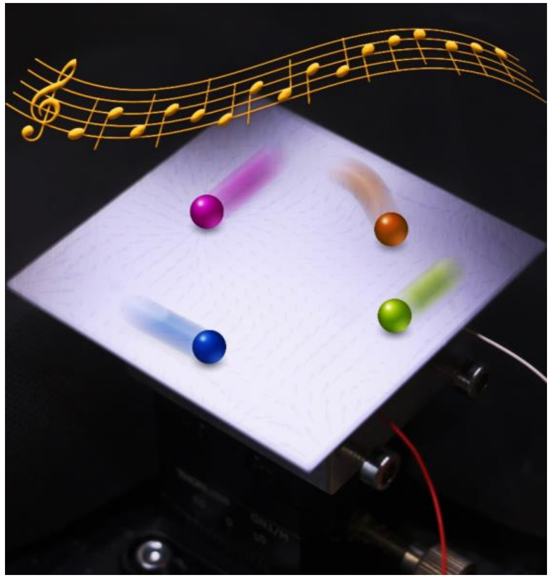
[1] Ljung, Modeling of dynamic systems, 1994.

Simulation Models



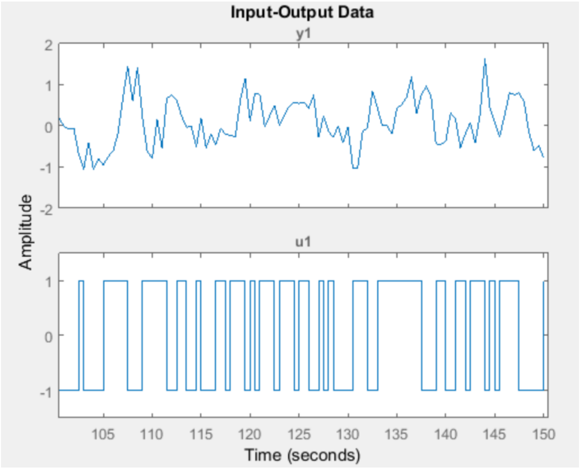
$$\mathbf{F}_\mathbf{m} = \frac{2}{3}\pi d_p^3 \rho_p M_p \frac{\beta M_n^2}{(4\beta\delta+1)^3}\mathbf{u}_{\mathbf{p-n}}$$

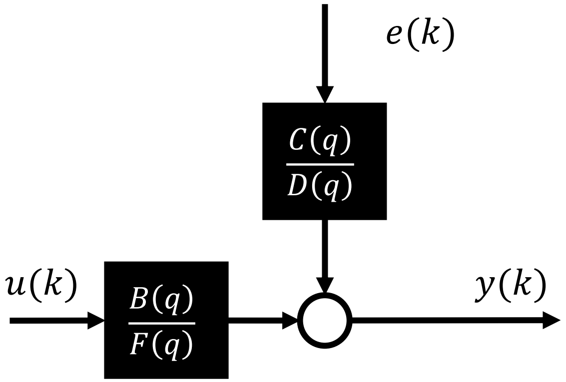
$$\mathbf{F}_\mathbf{d} = -3\pi\nu_f d_p \mathbf{v}_\mathbf{p}$$



$$\boldsymbol{\Delta p = u_n(p) + e}$$

- Simulation is a major goal for modelling
  - Only the simplest models can be represented in a closed form analytical solutions
  - A model is often more complicated, composed by block diagram, algorithms, programs
- A simulation model is usually referred to computer simulation model





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Modeling and Simulation

- In this course, we are dealing with
  - Mathematical modeling
    - To build a mathematical representation of systems
  - Simulation
    - To carry out experiments using a mathematical model instead of a real system

Systems

What is a system?

A **system** is a regularly interacting or interdependent group of units forming an integrated whole.

相互依赖

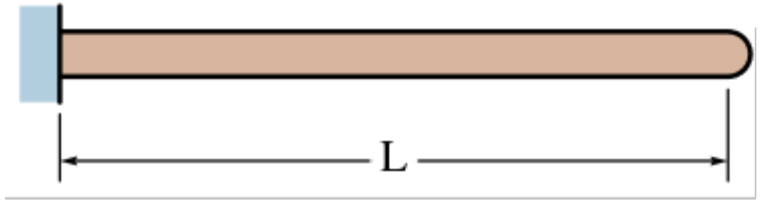
- Galaxy
- Solar system
- National grid
- Stock market
- Airplane
- Car
- Computer
- Mouse
- Microchip
- Cantilever
- Molecule
- Atom

- Earth Ecosystem
- Finnish nature
- Cloud
- Crowd
- Class
- Family
- Human body
- Hand
- Finger
- Neil
- Hair
- Cell

A **system** is a **thing,** physical or virtual, when you are considering how it works

How to build a model

How to build a model…



- How to build a mathematical model of a system, e.g., a cantilever?
  - What do we want to know?
    - How to use it to shoot a ball?
    - The integrity in a hot fluid flow?
    - What is the resonance frequency?
    - …
    - Let’s use a simple one: relationship between the deflection and the force applied at the end of the cantilever.

How to build a model …

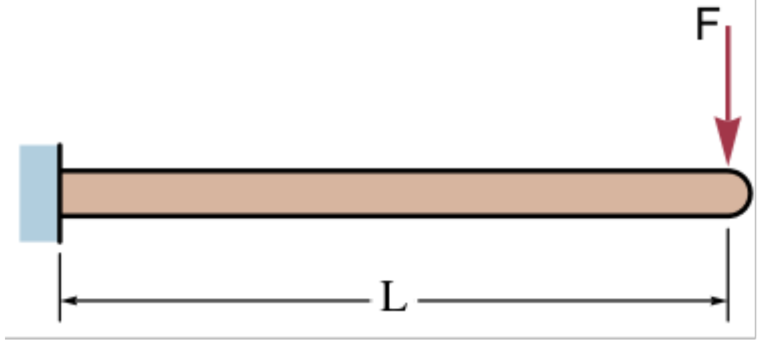
- Modelling based on theory and knowledge:
  - Elastic deflection

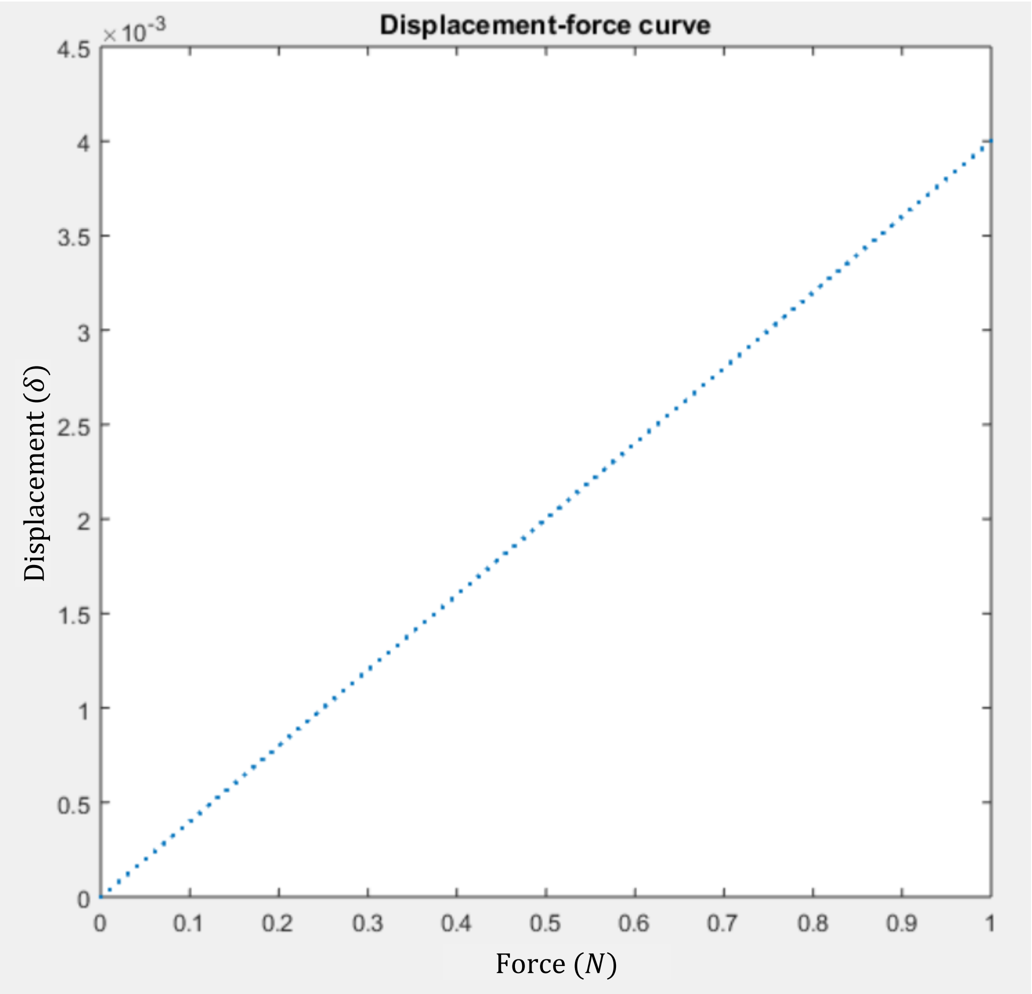
$$\delta = \frac{FL^3}{3EI}$$

  - where F is the applied force, L is the length of the beam, E is the Young's modulus, and I is the area momentum of inertia;

$$I = \frac{bh^3}{12}$$

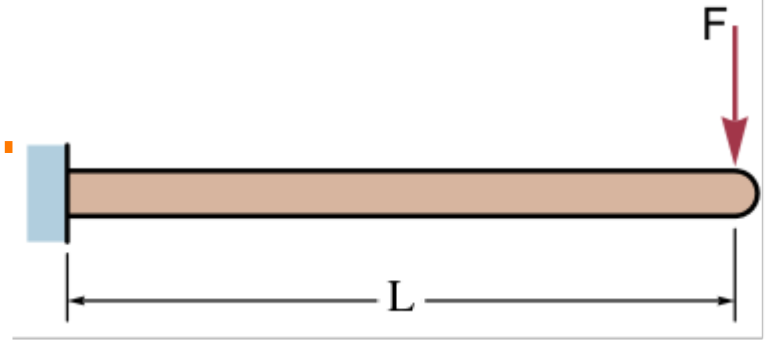
  - where b is the width of the beam, and h the height of the beam
- For a known material, from F, L, E, b, h, we can calculate δ, and vise versa, so we can easily simulate the results without build the hardware.
- How to build a model when the material is not known, i.e. E is unknown?





Displacement for cantilever, h = 5 mm, b = 1 mm, L = 100 mm, ignore bending

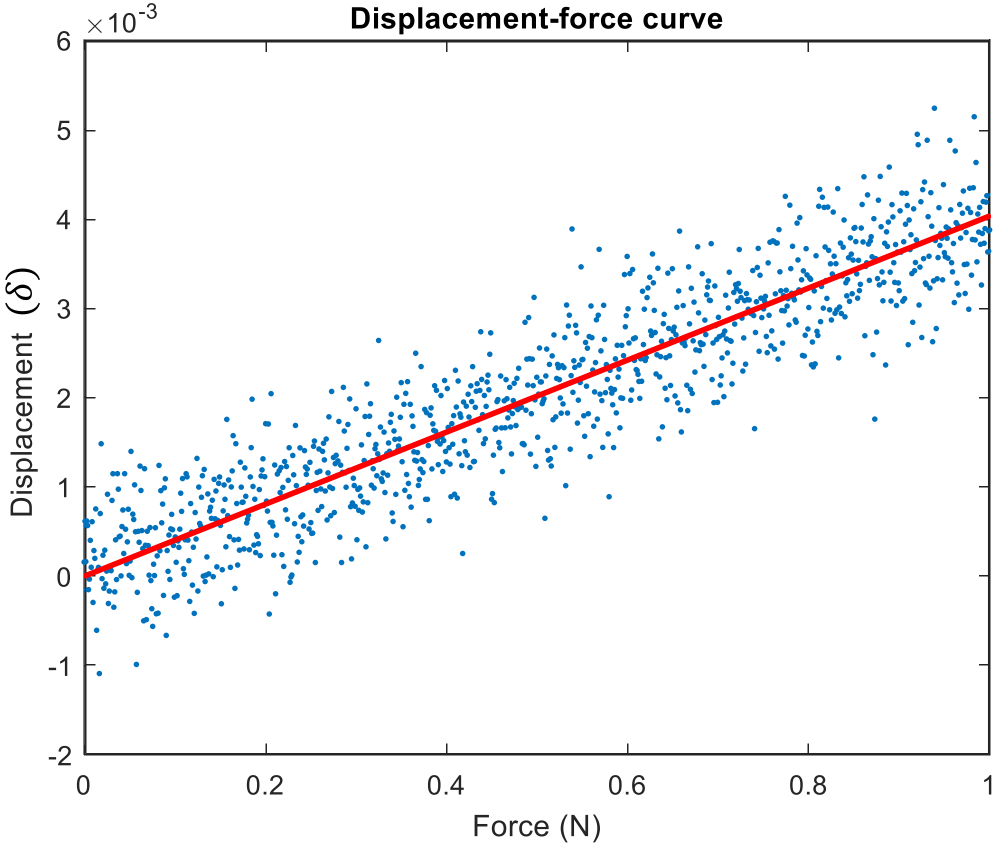
When the system is not fully known…



insight of the problem

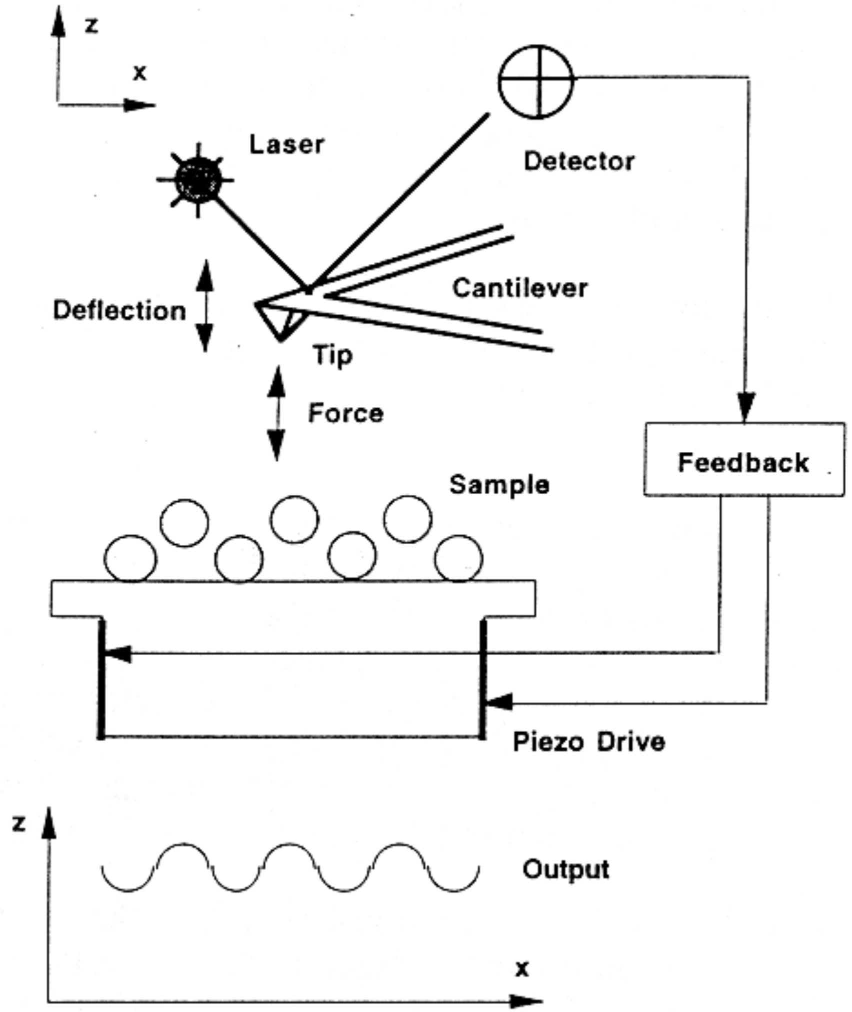
- If we know the material is isotropic, e.g., some kind of metal, but we do not know exactly,
  - we can try to estimate the Young's modulus E based on experimental data

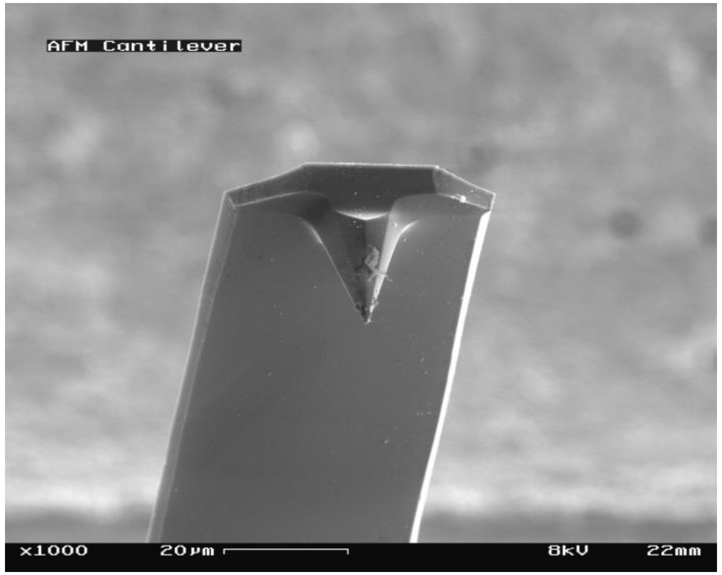
$$\delta = \frac{FL^3}{3EI} \quad \Longrightarrow \quad E = \frac{FL^3}{3\delta I}$$

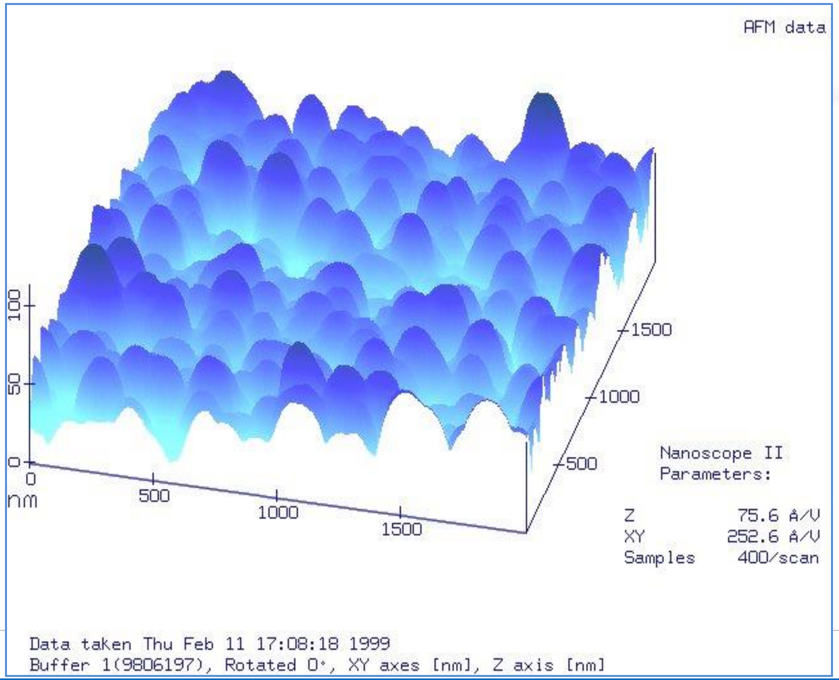


Really straight forward!

Atomic Force Microscope







The precursor to the AFM, the scanning tunneling microscope (STM), was developed by Gerd Binnig and Heinrich Rohrer in the early 1980s at IBM Research - Zurich, a development that earned them the 1986 Nobel Prize for Physics. Binnig invented the atomic force microscope and the first experimental implementation was made by Binnig, Quate and Gerber in 1986.

Model Examples: Species

Two species compete for the same food

How the population of the two species will change with time?

Population: $N_i(t)$

Birth rate: λ_i

Mortality rate: $\mu_i(N_1, N_2)$

$$\frac{d}{dt}N_1(t) = \big(\lambda_1 - \mu_1(N_1, N_2)\big)N_1(t)$$

$$\frac{d}{dt}N_2(t) = \big(\lambda_2 - \mu_2(N_1, N_2)\big)N_2(t)$$

What should be the μ_1 and μ_2, considering the two species are competing for food?

Model Examples: Species

- Two species compete for the same food
  - Population: $N_i(t)$
  - Birth rate: λ_i
  - Mortality rate: $\mu_i(N_1, N_2)$
- The model of the two species can be described as

$$\frac{d}{dt}N_1(t) = \left(\lambda_1 - \mu_1(N_1, N_2)\right)N_1(t)$$
$$\frac{d}{dt}N_2(t) = \left(\lambda_2 - \mu_2(N_1, N_2)\right)N_2(t)$$

- Assuming a simple mortality model

$$\mu_i(N_1, N_2) = \gamma_i + \delta_i(N_1 + N_2)$$

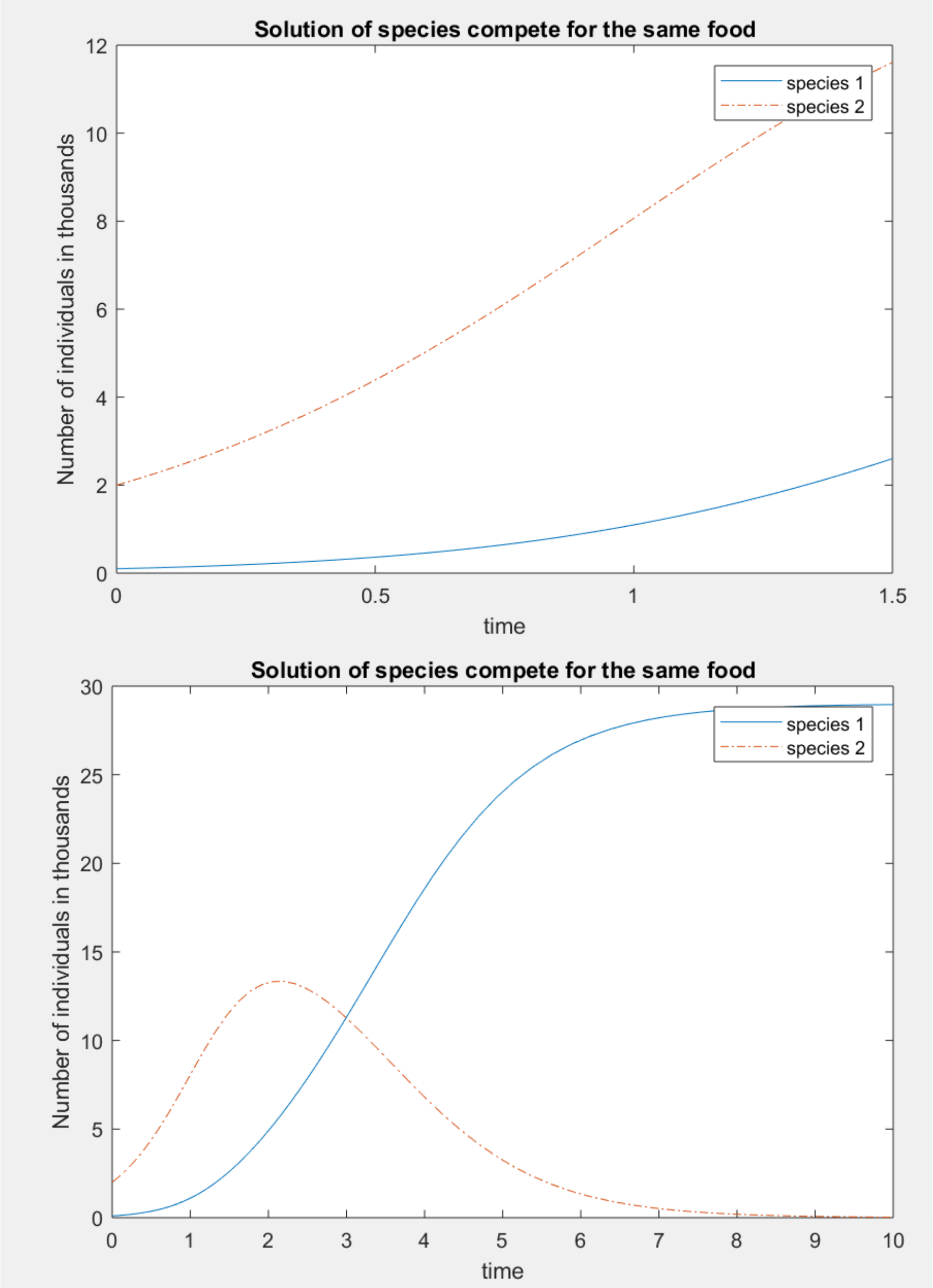
  - γ_i, δ_i are constants

Mortality rate factor due to aging, accidents

Mortality rate factor due to food availability

- If $\frac{\lambda_1 - \gamma_1}{\delta_1} > \frac{\lambda_2 - \gamma_2}{\delta_2}$, the second species will die out,
  - If $\gamma_1 = \gamma_2$ and $\delta_1 = \delta_2$, i.e., mortality rate of the two species are the same, the one with the high birth rate will remain
  - The winner will have a population of $\frac{\lambda_1 - \gamma_1}{\delta_1}$

$\lambda_1 = 3, \lambda_2 = 2, \gamma_1 = \gamma_2 = \delta_1 = \delta_2 = 0.1$



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Model Examples: Species

Predator and Prey

The first species preys on the second

Population: $N_i(t)$
Birth rate: λ_i
Mortality rate: $\mu_i(N_1, N_2)$

Mortality model for the 1st species

$$\mu_1(N_1, N_2) = \gamma_1 - \alpha_1 N_2$$

Mortality model for the 2nd species

$$\mu_2(N_1, N_2) = \gamma_2 + \alpha_2 N_1$$

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Model Examples: Predator and Prey

- The first species preys on the second
  - Population: $N_i(t)$
  - Birth rate: λ_i
  - Mortality rate: $\mu_i(N_1, N_2)$
- Mortality model for the 1st species

$$\mu_1(N_1, N_2) = \gamma_1 - \alpha_1 N_2$$

Mortality rate factor due to aging, accidents

- Mortality model for the 2nd species

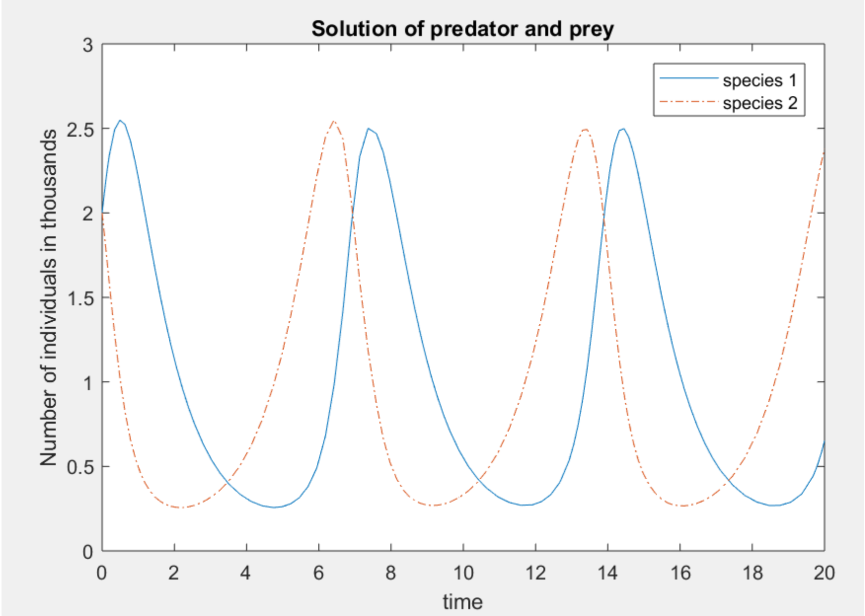
$$\mu_2(N_1, N_2) = \gamma_2 + \alpha_2 N_1$$

Mortality rate factor due to the other specie

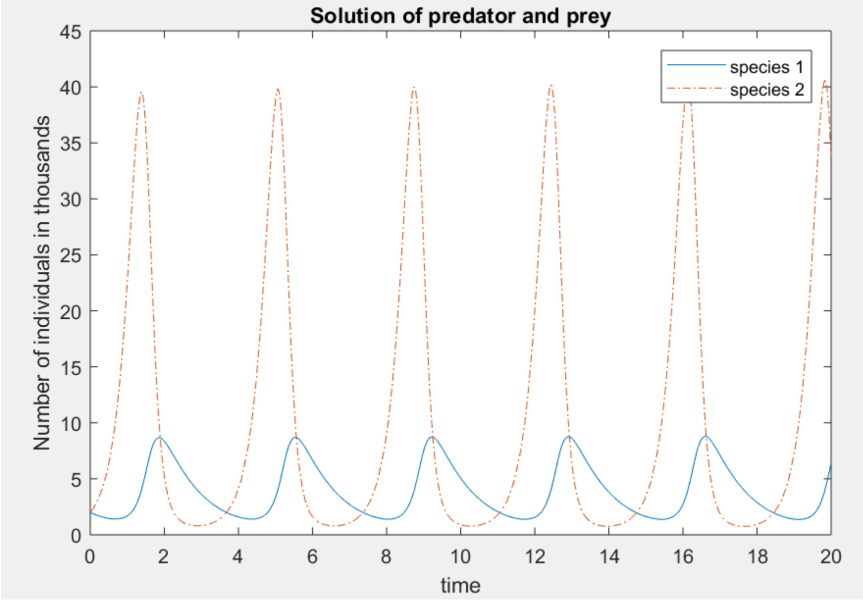
- System model

$$\frac{d}{dt} N_1(t) = \big(\lambda_1 - \mu_1(N_1, N_2)\big) N_1(t)$$
$$= (\lambda_1 - \gamma_1) N_1(t) + \alpha_1 N_1(t) N_2(t)$$
$$\frac{d}{dt} N_2(t) = \big(\lambda_2 - \mu_2(N_1, N_2)\big) N_2(t)$$
$$= (\lambda_2 - \gamma_2) N_2(t) - \alpha_2 N_1(t) N_2(t)$$

$(\lambda_1 = 1, \lambda_2 = 2), (\gamma_1 = 2, \gamma_2 = 1)(\alpha_1 = \alpha_2 = 1)$

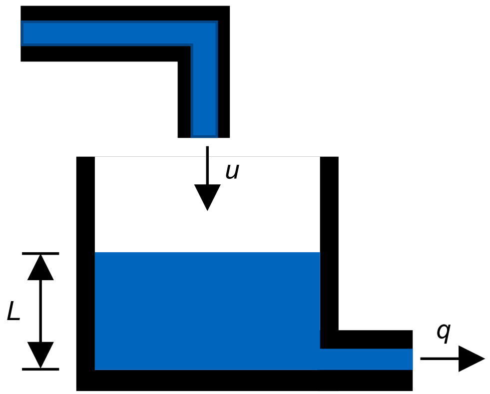


$(\lambda_1 = 1, \lambda_2 = 5), (\gamma_1 = 2, \gamma_2 = 2)\ (\alpha_1 = 0.1, \alpha_2 = 1$



Describe a real-world phenomena, see more in Lotka–Volterra equations

Model Examples: Flow System



- Cross section: A
- Outflow hole size: a
- Liquid level: L
- inflow rate: u
- Outflow rate: q

- Goal
  - Model of outflow as a function of inflow.
- The volume of the water in the tank:

$$\frac{d}{dt} A \cdot L(t) = u(t) - q(t)$$

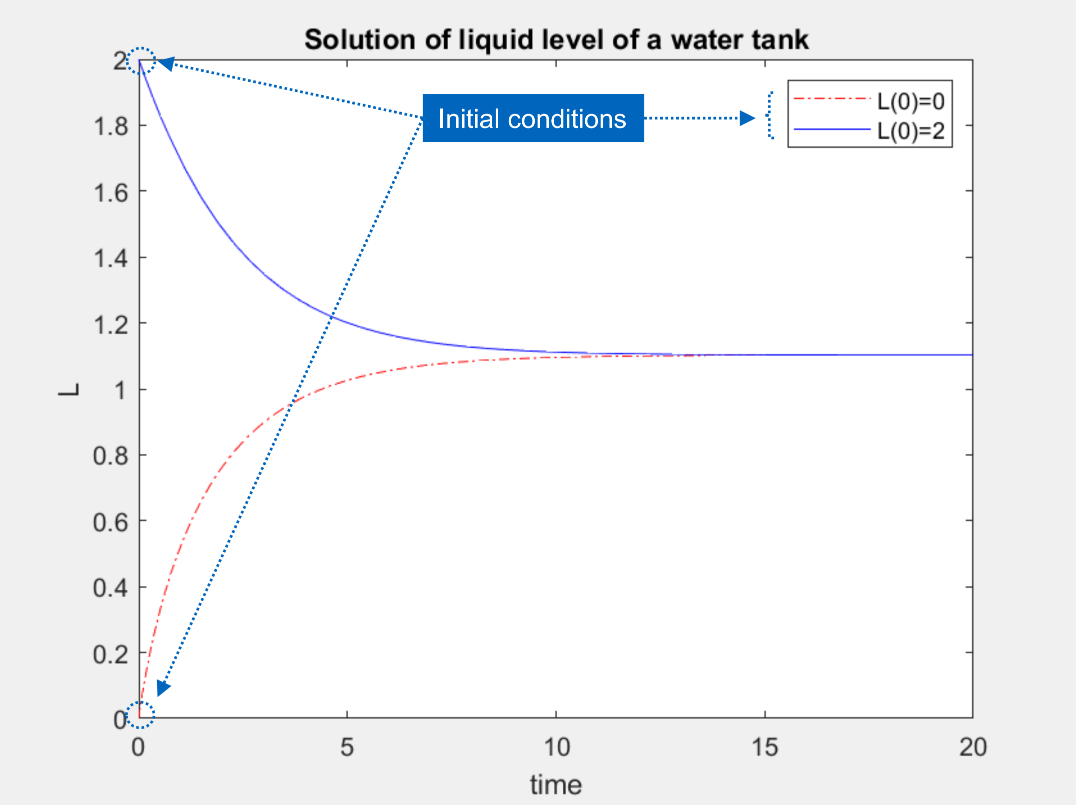
  - $q(t) = a\, v(t)$,
  - $v(t) = \sqrt{2gL(t)}$ from Bernoulli's law

- The explicit differential equation is:

$$\frac{d}{dt} L(t) = -\frac{a\sqrt{2g}}{A} \cdot \sqrt{L(t)} + \frac{1}{A} u(t)$$

- Outflow is:

$$q(t) = a\sqrt{2g} \cdot \sqrt{L(t)}$$



$$u = 1; \quad A = 1; a = \frac{1}{\sqrt{2g}}$$

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Questions for the previous examples?

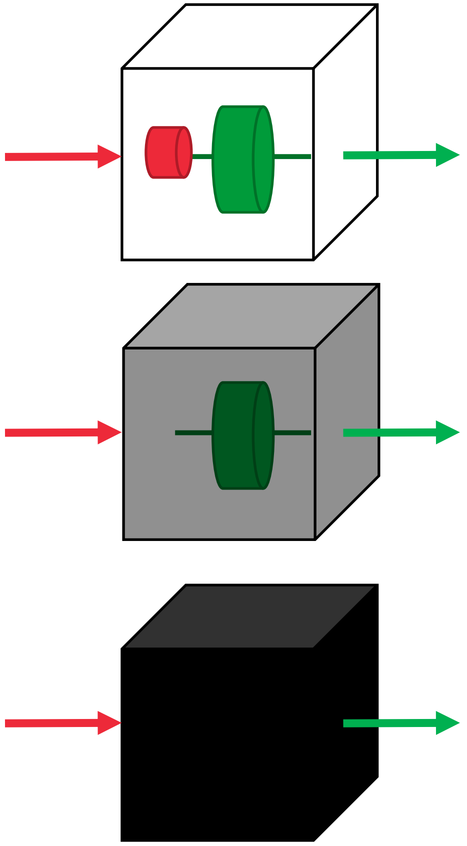
Type of mathematic models

- Linear vs. non-linear
  - Input-output relationship, linear or not
- Deterministic vs. Stochastic
  - Are we working with exact relationship or probabilistic ones?
- Dynamic vs. Static time.
  - Does the input-output relationship instantaneous or depending on the history?
- Continuous time vs. Discrete time
  - Time continuous or in sample form?
- Lumped vs. Distributed
  - Is the model varies spatially?
- Change vs. Event
  - Continuous signal or discrete occurring event?
- Time variant vs. time invariant
  - Does the model parameter varies with time?

Ask an AI if needed

Terminologies

- White box
  – Model based on theory, fully transparent
- Grey box
  – With partial theoretical structure of the model, complete the model with data
- Black box
  – The model is created completely from data (input and output relationships)



Model Verification

- All models requires verification/validation
  - Whatever model structure it is, white, grey or black
  - Experiments

- All models have a limited <u>domain of validity</u>
  - Examples:
    - 弹簧 Spring model is valid in the elastic region of the materials
    - Newton’s second law of motion is valid at low speed
    - Most physical laws assuming the phase of the matter is stable

Some comments of model

- Model is an approximation
- Important to know the goal of your model
  - What to model, and what aspects not to model
- All model need to be validated
  - If the model does not agree with measurement, usually the model is the problem
- An all-inclusive model is often a bad idea
  - Difficult to manipulated
  - Hard to understand
- A good model is simple and captures the key aspects
  - Simple is beauty

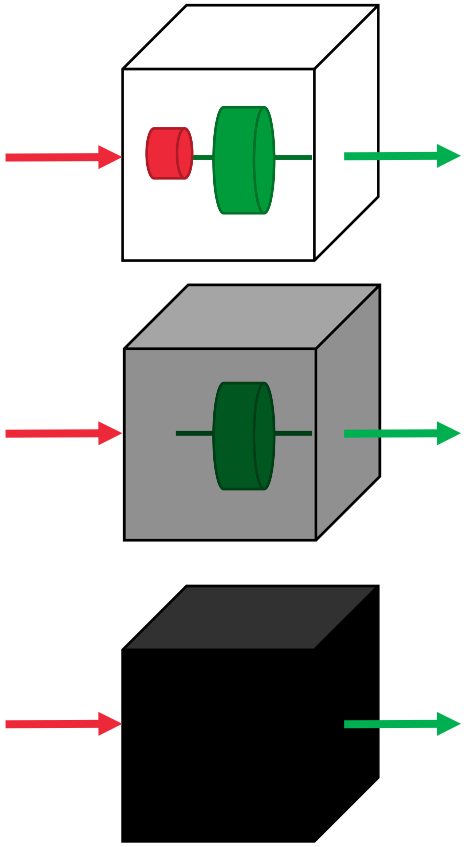
Expected Learning Outcomes of the Course

- Select proper modeling approach for specific problems,
- Formulate mathematical models of physical systems,
- Construct models of systems using modeling tools such as MATLAB and Simulink,
- Estimate the parameters of linear and nonlinear static systems from measurement data,
- Identify the models of linear dynamic systems from measurement data

This is an introduction course in modelling and estimation

Schedule of the course (tentative)

- Week 36, 38: Basics, White
- Week 40: Gray
- Week 43, 45: Black
- Week 47: Modeling using Python (tentative)
- Week 48-49: Final exercise



How the learning is done

- Theoretical lectures
  - Theoretical background (what is behind the tools, how things work)
- Practical lectures
  - How to use tools (attendance with your own laptop, lecture video will be recorded)
- Home exercises
  - Deep learning of the course contents
- Exercise sessions
  - Personalized learning / mentoring (important, facilitate learning)

Schedule

Lecture time: Wednesday 12:15-14:00, Thursday 12:15-14:00
Exercise time:

- Contact sessions (attend one only): Monday 14:15-16:00, 16:15-18:00, Wednesday 12:15-14:00
- Online session: Wednesday 16:15-18:00

Model answers are published after the deadline of each home exercise

Week	M	T	W	T		F	S	S
W35	Pre-course survey							
W36			Introduction (AS1)	Physical modelling (AS2)	EX1 out			
W37	EX1g1, EX1g2		EX1G3, EX1g4 (online)					Deadline EX1
W38	Grading		Simulation (AS1)	Simulink (AS2)	EX2 out			
W39	EX2g1, EX2g2		EX2g3, EX2g4 (online)					Deadline EX2
W40	Grading		Regression (AS1)	Curve fitting (AS2)	EX3 out			
W41	EX3g1, EX3g2		EX3g3, EX3g4 (online)					Deadline EX3
W42	Grading / Break week / Mid-term survey							
W43			Analysis of dynamic systems (AS1)	System identification 1 (AS2)	EX4 out			
W44	EX4g1, EX4g2		EX4g3, EX4g4 (online)					Deadline EX4
W45	Grading		System identification 2 (AS1)	System identification 3 (AS2)	EX5 out			
W46	EX5g1, EX5g2		EX5g3, EX5g4 (online)					Deadline EX5
W47	Grading		Modelling using Python (tentative, AS1)					
W48	Final EX published (tentative)							
W49	Deadline Final EX (tentative)							

Exercises

All exercises should be done **individually**, plagiarism is strictly forbidden for all home exercises and final exercise – check Aalto Code of Conduct

- Attending in exercise sessions is **not** mandatory, but **highly recommended** to get guidance on how to solve the problems
  - Regarded as the **critical part** of the course by previous students
- **Home exercises** count for 40% of your final grade
  - 5 home exercises
  - Each assignment is graded at question/sub-question level, where points is given if sufficient effort is demonstrated
- You are encouraged to discuss and support each other. Please joint the MS teams following this link. **Remarks:**
  - You can only discuss EX1-5. It is **forbidden** to discuss the final exercises.
  - For EX1-5, you should still do individually, plagiarism is strictly forbidden for all home exercises and final exercise.
- **Final exercise**, 60% of your final grade
  - 27.11-4.12 (the time is tentative). No discussion allowed.
- All exercises are submitted on Mycourses
- The final course grade will be calculated as below [0-5]:
  - [50%, 60%) → 1; [60, 70%) → 2; [70%, 80%) → 3; [80%, 90%) → 4; [90%, inf] → 5.

If you wish to attend exercise sessions, please reserve the respective groups in MyCourses.

Questions about the lecture and course?

- Pre-course survey

Reading for the lecture:
Ljung & Glad, Modeling of Dynamic Systems, 1994, Ch. 1-2