Modelling and Identification

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Institute for Automatic Control

WS 2017/18

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Organisational issues

- **Lecture:** Prof. Dr. Ping Zhang
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- **Exercise:** Dipl.-Ing. Thomas Leifeld
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  Office: 12/409

- **Language of the course:** English

- **Scope:** 4 hours per week (5 ECTS-Credits)

- **Script:** available on OLAT (password: cdc1718)

- **Exam:** written examination

Literature (1)

- Wernstedt. **Experimentelle Prozessanalyse**. VEB Verlag, 1989.
- R. Isermann, M. Münchhof. **Identification of Dynamic Systems**. Springer, 2011.
- T. Söderstrom, P. Stoica. **System identification**. Prentica Hall, 1989.
- L. Ljung. **System identification: Theory for the user**. Prentice Hall, 1999.
- M. Verhaegen, V. Verdult. **Filtering and system identification**. Cambridge University Press, 2007.

Literature (2)

- J. Mikles, M. Fikar. **Process modelling, identification and control**. Springer, 2007.
- C.M. Close. **Modeling and analysis of dynamic systems**. Wiley, 2002.
- H.E. Scherf. **Modellbildung und Simulation dynamischer Systeme: Eine Sammlung von Simulink-Beispielen**, Oldenbourg Verlag, 2009.

Introduction

- A number of control methods have been introduced in previous control courses.
- Many control methods (for instance, state feedback controller, MPC, observer design, usw.) are **model-based** and have gained wide acceptance in the industry.

How to get a model of the system to be controlled?

„Modelling and Identification of dynamic systems“

Technische Universität Kaiserslautern

Systems

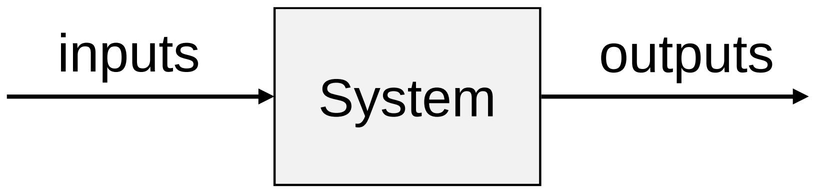
- **Technical systems**:

  Technical systems have the purpose of transformation, transportation and/or storage of matter, energy and/or information

- **Non-technical systems** (e.g. biological systems, economic systems)

Systems

- **Viewpoint of control engineers:**



- **Static systems**:

  The output signals depends not only on the present input signal values.

- **Dynamic systems:**

  The output signals depends not only on the present input signal values but also on the past values.

Modelling and identification

- **Objective**:

  Find a **mathematical model** in form of mathematical equations to describe the system

- **Requirement on a model:**

  The model should describe **certain aspects** of the real system behaviour **with sufficient accuracy**.

  - validity / accuracy
  - complexity

Classification of models

- Transfer function
- Differential equation
- Difference equation
- State space model
- Automaton
- Petri nets
- Boolean networks

Classification of systems

System	Characteristics	Model
Continuous-time systems with concentrated parameters	Signals $x(t)$ depend only on time t.	Ordinary differential equations (ODE) $\dot{x}(t) = f(x(t), u(t), t)$
Continuous-time systems with distributed parameters	Signals $x(t, r_1, r_2, r_3)$ depend not only on time t, but also on location represented by space coordinates.	Partial differential equations (PDE)
Discrete-time systems	Signals $x(k) \coloneqq x(t_k)$ are functions of discrete-time t_k	Difference equations $x(k+1) = f(x(k), u(k), k)$
Discrete event systems	The state changes only at discrete instances, when certain events occur.	Petri nets, automata

Classification of systems

System	Characteristics	Model example
Time-invariant system	Model parameters doesn‘t change with time	$\dot{x}(t) = Ax(t) + Bu(t)$ $y(t) = Cx(t) + Du(t)$
Time-varying system	Model parameters change with time	$\dot{x}(t) = A(t)x(t) + B(t)u(t)$ $y(t) = C(t)x(t) + D(t)u(t)$

Two special classes of time-varying systems that are much discussed:

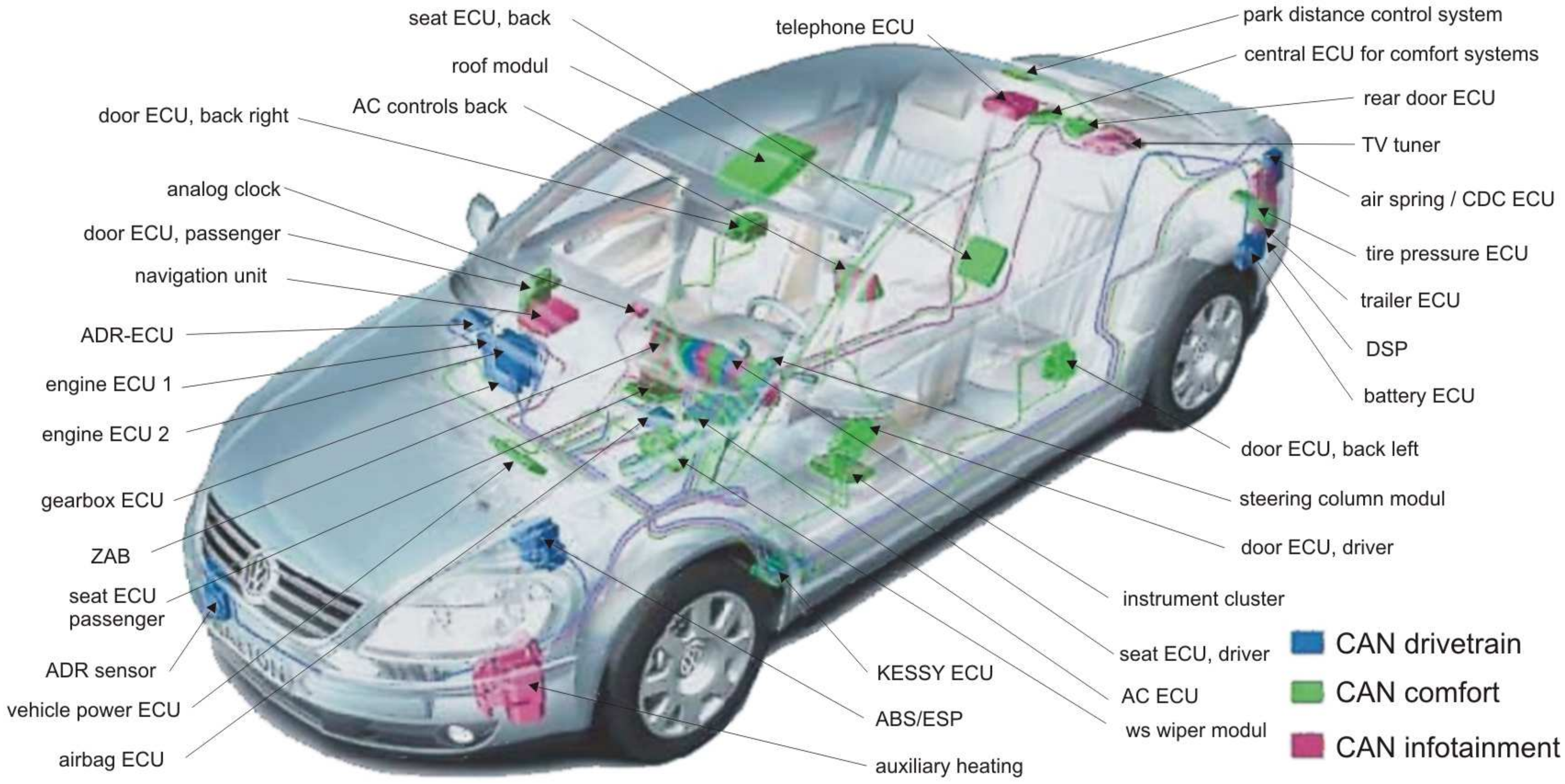
System	Characteristics	Model example
Periodic system	Model parameters change with time periodically	$\dot{x}(t) = A(t)x(t) + B(t)u(t)$ $y(t) = C(t)x(t) + D(t)u(t)$ $A(t+T) = A(t),$ $B(t+T) = B(t).$
Parameter-varying system	Model parameters depends on some parameter vector	$\dot{x}(t) = A(p)x(t) + B(p)u(t)$ $y(t) = C(p)x(t) + D(p)u(t)$

Classification of systems

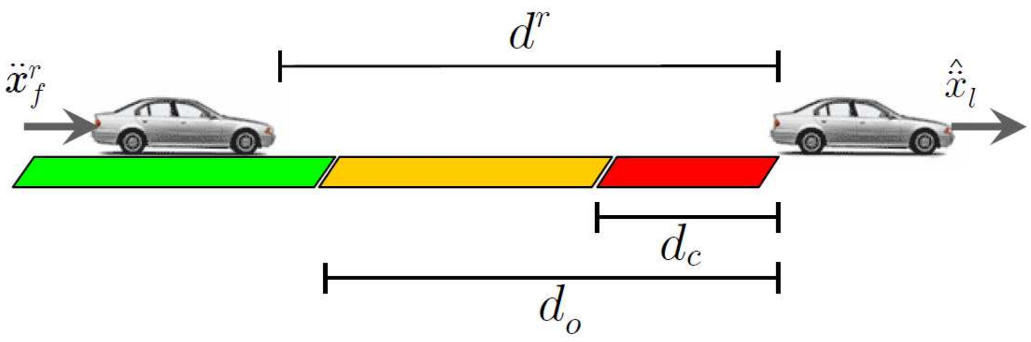
System	Characteristics	Model example
Linear systems	The principle of superposition is satisfied $u(t)=u_1(t)+u_2(t) \quad \Rightarrow \quad y(t)=y_1(t)+y_2(t)$ $u(t)=ku_1(t) \quad \Rightarrow \quad y(t)=ky_1(t)$	$\dot{x}(t)=Ax(t)+Bu(t)$ $y(t)=Cx(t)+Du(t)$
Nonlinear systems	The principle of superposition is not satisfied.	$\dot{x}(t)=f(x(t),u(t))$ $y(t)=h(x(t),u(t))$

Models of systems

The models that are used to describe a dynamic system depend on the modelling objectives!



Example: Vehicle distance control

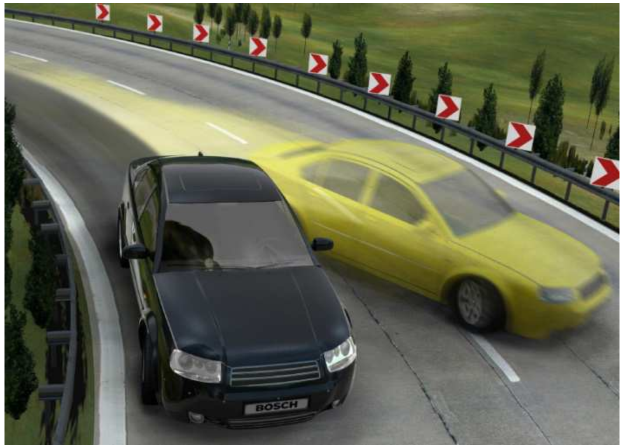


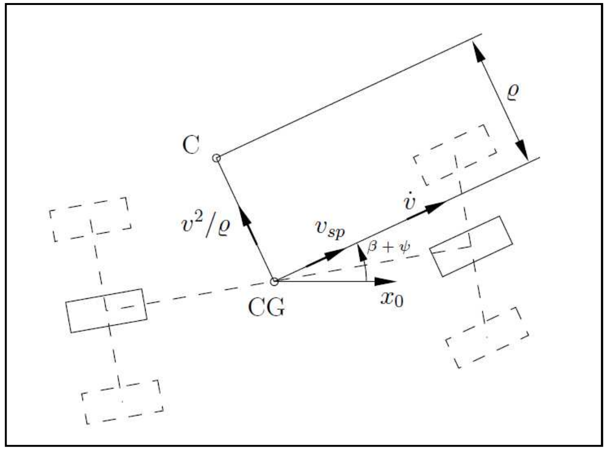
$$\ddot{d} = \ddot{x}_l - \ddot{x}_f$$

$$\ddot{d}^r = \hat{\ddot{x}}_l - \ddot{x}_f^r$$

$$d \to d^r\ (t)$$

Example: Lateral Dynamic Control of Cars





$$\begin{bmatrix} \dot{\beta} \\ \dot{r} \end{bmatrix} = \begin{bmatrix} Y_\beta/(mv) & Y_r/(mv)-1 \\ N_\beta/I_z & N_r/I_z \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \\ + \begin{bmatrix} Y_\delta/(mv) \\ N_\delta/I_z \end{bmatrix} \delta_L^* + \begin{bmatrix} -g/v \\ 0 \end{bmatrix} \sin\phi.$$

$$\begin{bmatrix} a_y \\ r \end{bmatrix} = \begin{bmatrix} Y_\beta/m & Y_r/m \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \beta \\ r \end{bmatrix} + \begin{bmatrix} Y_\delta/m \\ 0 \end{bmatrix} \delta_L^*$$

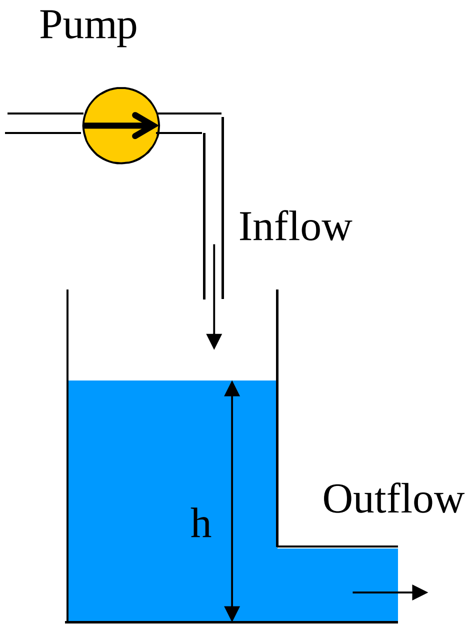
Modelling strategies

Depending on which information of the real system is available for modelling, there are different modelling strategies.

Information	Modelling strategy
Theoretical working principles of the system	Theoretical modelling (called also first-principle modelling)
Data collected during experiments or during system normal operation	Experimental modelling (called also identification)

Modelling strategies

Strategy 1: Theoretical modelling



Physical principles

Mass balance: $$A\frac{dh}{dt} = Q_{\text{inflow}} - Q_{\text{outflow}}$$

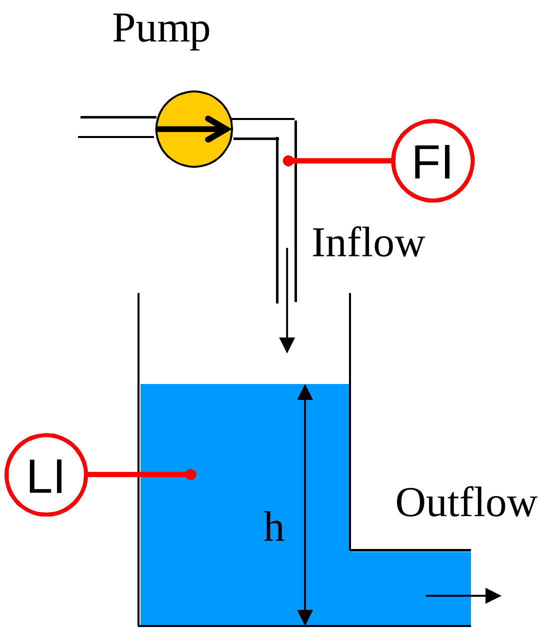
Torricelli‘ law: $$Q_{\text{outflow}} = aA_0\sqrt{2gh}$$

$$\boxed{A\frac{dh}{dt} = Q_{\text{inflow}} - aA_0\sqrt{2gh}}$$

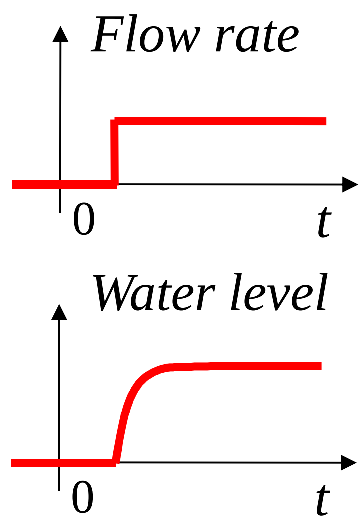
A: Cross-section area of the tank
A_0: Cross-section area of the outflow pipe
a, g: Konstante
h: water level
$Q_{\text{inflow}}, Q_{\text{outflow}}$: volume flow rate

Strategy 2: Experimental modelling

Do experiments !



Measurements

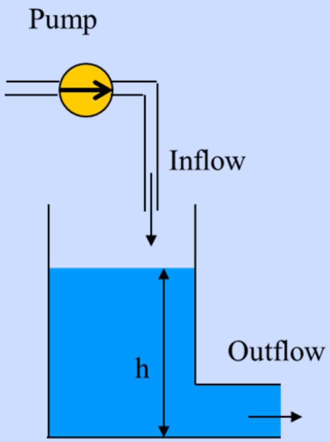
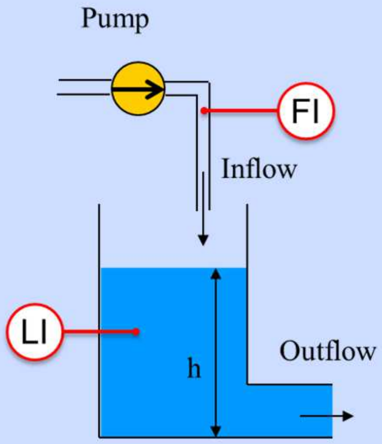
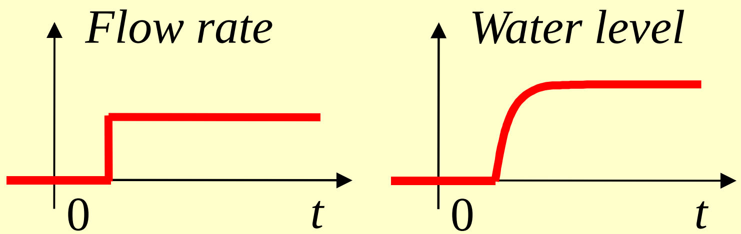


Step response

→ first order system

Modelling strategies

Example: One-tank system

Theoretical modelling	Experimental modelling
	
Mass balance: $A\frac{dh}{dt} = Q_{\text{inflow}} - Q_{\text{outflow}}$ Torricelli' law: $Q_{\text{outflow}} = aA_0\sqrt{2gh}$	
$A\frac{dh}{dt} = Q_{\text{inflow}} - aA_0\sqrt{2gh}$	$H(s) = \frac{K}{Ts+1} Q_{in\ flow}(s)$

Modelling strategies

	Theoretical modelling	Experimental modelling (identification)
Information Basis	Physical and chemical principles (e.g. balance equations)	Experiments on the system and measurements of system inputs and outputs
Results	Physical parameteric models (often state equations)	Input-output models (often differential equations)

Modelling strategies

Theoretical modelling

- **Advantages:**
  - Good reconstruction of system structure
  - Model parameters are related to system components
  - Applicable over a wide range of operating conditions
- **Disadvantages:**
  - Typically the model includes some model parameters that are not readily available
  - Not applicable, if physical principles are not clear
  - For complex systems, it is often rather time-consuming and the resulting model may be too complex.

Modelling strategies

Experimental modelling (identification)

- **Advantages:**
  - It is easier to develop
- **Disadvantages:**
  - It doesn‘t describe the internal structure of the system
  - Should be used with caution for operating conditions that were not included in the experimental data
  - Sometimes, experiments on the real system or some special test input signals are not allowed.
  - Needs much knowledge of control theory

Basic procedure of modelling

- Specify the goal of modeling
- Understand the working mechanism of the system
- In case of theoretical modelling, set up the system equations. In case of experimental modelling, do experiments, collect the input and output data and then apply the identification approach
- Validate the model

Application areas of models

- Gain knowledge about the plant behaviour
- Model-based controller design (e.g. IMC, MPC, Robust control, etc)
- Fine-tuning of controller parameters
- Model-based process supervision and fault diagnosis
- Model-based prediction of signals
- Training simulator (train the operators, support the operators, judge the effect of intervention)
- Real-time optimization (find optimal operating point by means of mathematical optimization techniques)

Scientific communities

- IFAC (International federation of Automatic Control) Technical Committee 1.1 „**Modelling, Identification and Signal Processing"**
- GMA Technical Committee 1.30 **„Modellbildung, Identifizierung und Simulation in der Automatisierungstechnik"**
- An important topic in the field of control theory and control engineering
- Numerous publications in scientifc journals and conferences
- Get-Together: IFAC Symposium on System Identification (triennial event)

Organisation of this course

Chapter 1: Introduction

Chapter 2: Theoretical Modelling

Chapter 3: Experimental modelling

Chapter 4: Least-Squares methods

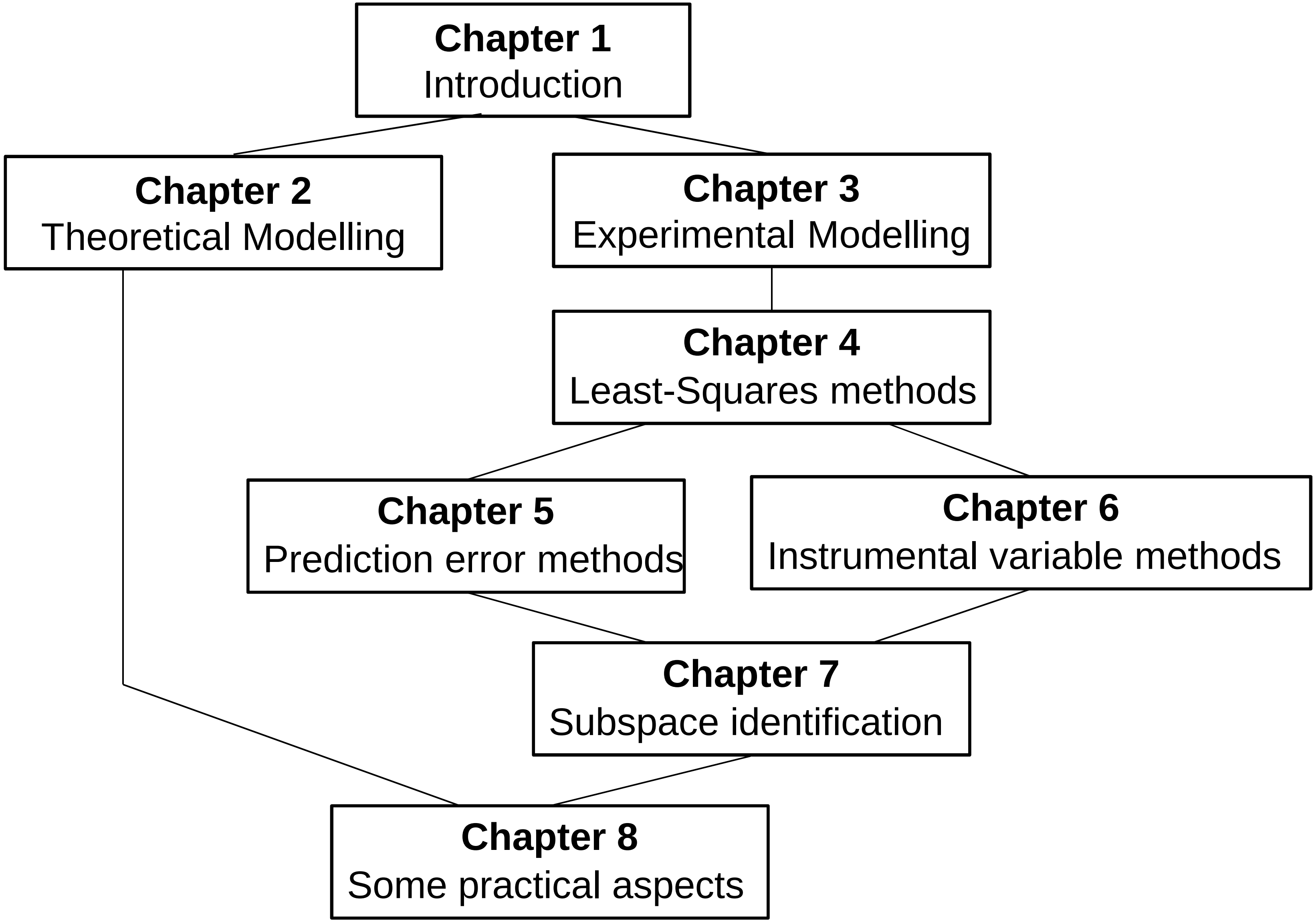
Chapter 5: Prediction error methods

Chapter 6: Instrumental variable methods

Chapter 7: Subspace identification methods (SS model!)

Chapter 8: Some practical aspects

Organisation of this course



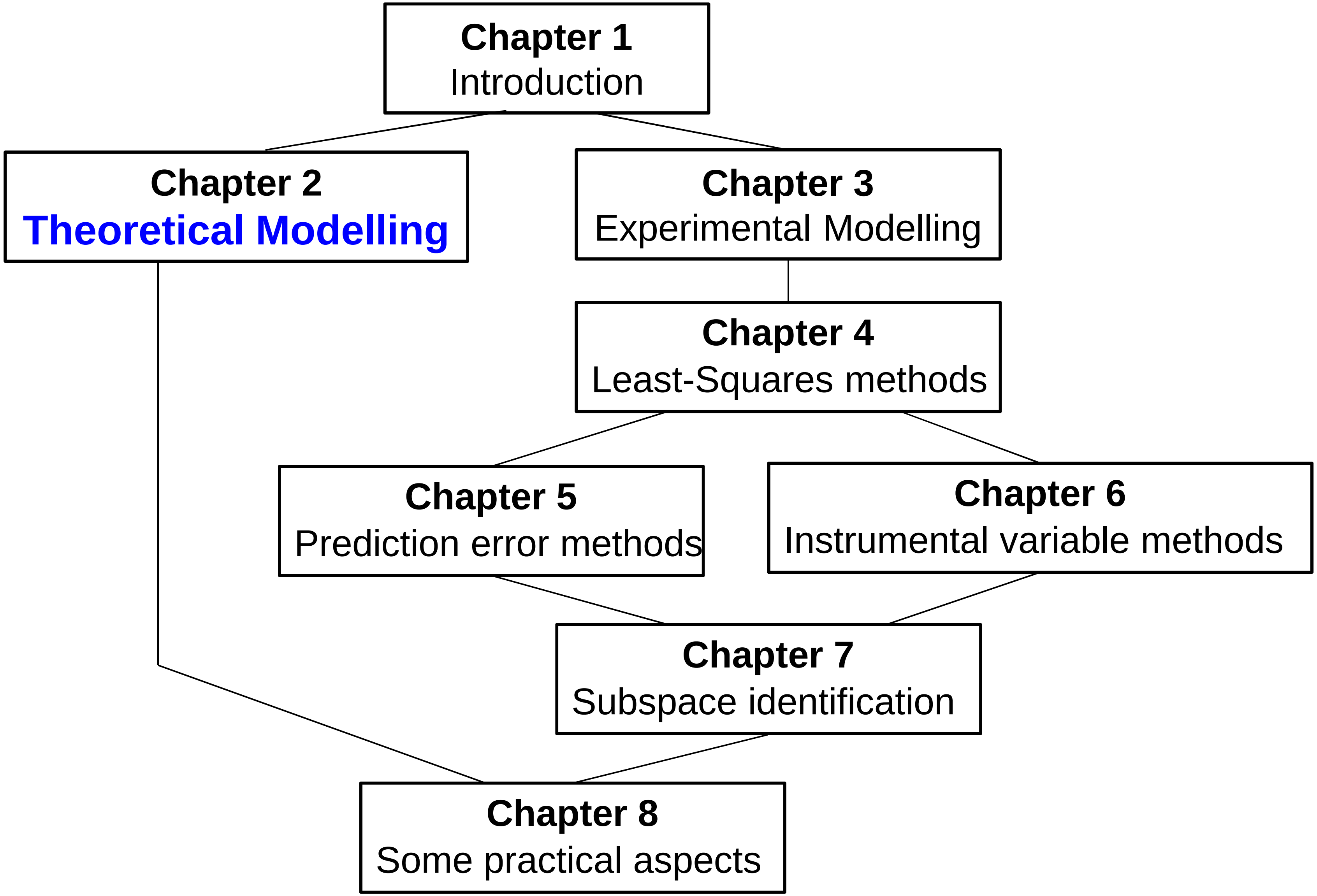
Learning goals

After the course, you should

- Be familar with the basic principles of important modelling and identification approaches
- Be able to derive first-principle model of systems with moderate complexity
- Be able to apply a suitable approach to identify the required model of a given process with the help of Matlab toolboxes
- Be able to organize an identification project (data collection, pre-processing of data, etc)

Organisation of this course

Organisation of this course



Chapter 2

Theoretical modelling

Basic procedure of theoretical modelling

- Specify the goal of modelling
- Understand the working mechanism of the system
- Label the variables in the system (inputs, outputs, internal variables)
- Write all quantitative relations among the variables (e.g. conservation equations)
- Transform the model into the form that is required by the end user
- **Validate the model**

Conservation laws

- Conservation laws are important basis of theoretical modelling.
- Conservation of **mass** and **energy** are the most very often used conservation laws.
- Conservation of mass (without chemical reaction):

$$\{rate\ of\ mass\ accumulation\} = \{rate\ of\ mass\ in\} - \{rate\ of\ mass\ out\}$$

- Conservation of mass (with chemical reaction):

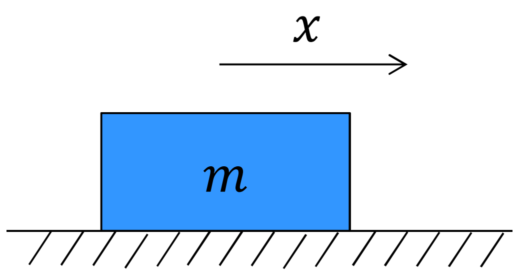
$$\{rate\ of\ component\ \ i\ \ accumulation\} = \{rate\ of\ component\ \ i\ \ in\} - \{rate\ of\ component\ \ i\ \ out\} + \{rate\ of\ component\ \ i\ \ produced\}$$

- Conservation of energy

$$\{rate\ of\ energy\ accumulation\} = \{rate\ of\ energy\ in\} - \{rate\ of\ energy\ out\}$$

Mechanical systems

Kinetics of translation:



- Movement is described by
  - Position $q(t)$
  - Velocity $v(t) = \dot{q}(t)$
  - Acceleration $a(t) = \dot{v}(t) = \ddot{q}(t)$
- A moving mass m has momentum $B(t) = mv(t)$
- Newton's law of inertia: $F(t) = \dot{B}(t)$

  If m is constant, then $F(t) = ma(t) = m\dot{v}(t) = m\ddot{q}(t)$
- The work done by force $F(t)$ is $W(t) = \int F(t)dr$.
- The power is $P(t) = \dot{W}(t) = F(t)v(t)$
- **Force balance**: $F_{sum} = ma$

Mechanical systems

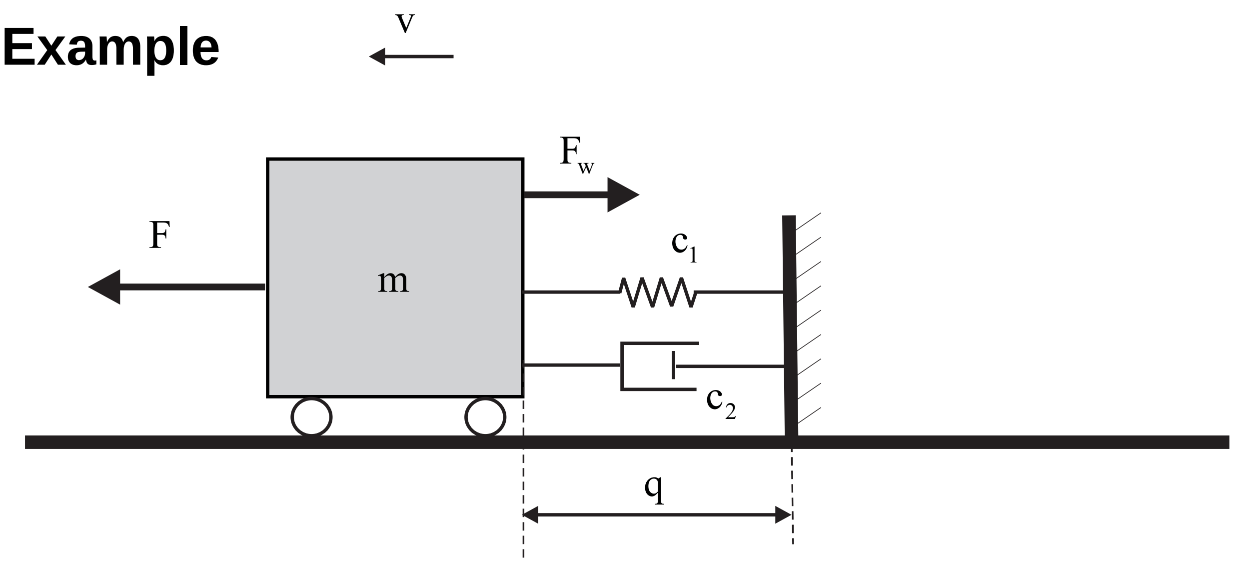
Kinetics of rotation (rigid body around its mass center)**:**

- Movement is described by
  - Rotation angle $\theta(t)$
  - Angular velocity $\omega(t) = \dot{\theta}(t)$
  - Angular acceleration $\alpha(t) = \dot{\omega}(t) = \ddot{\theta}(t)$
- Angular momentum $H(t) = J\omega(t)$, J is the rotational inertia
- Rotational version of the law of inertia: $M(t) = \dot{H}(t)$, M: Torque

  J is constant → $M(t) = J\dot{\omega}(t)$
- The work done by torque $M(t)$ is $W(t) = \int M(t)d\theta$.
- The power is $P(t) = \dot{W}(t) = M(t)\omega(t)$
- **Torque balance**: $M_{sum} = J\dot{\omega}$

Mechanical systems

Example



m: mass

c_1: spring constant

c_2: damping factor

F: driving force

F_w: disturbance imposed by wind

Force balance:

$$F - c_1 q - c_2 \dot{q} - F_w = m\ddot{q}$$

i.e. $$m\ddot{q} + c_2 \dot{q} + c_1 q = F - F_w$$

Exercise: Get the state space model