Automatic Control

FACULTY OF ENGINEERING, LTH

LUND UNIVERSITY

FRTF05 - Automatic Control, Basic Course (China)

Reglerteknik, allmän kurs i Kina, 7.5 hp

This is the web page for the basic course in Automatic Control (FRTF05) held at Beihang University (BUAA), Beijing, China.

News

- **[15 October 2019]** the schedule for the 2019 course is online and updated

Course Schedule

- Schedule [updated 2019-10-15]

Course Material

The course is based on a set of compendiums:

- Tore Hägglund: Automatic Control, Basic Course – Lecture Notes. Department of Automatic Control, Lund University, 2018.
- Automatic Control, Basic Course – Collection of Exercises. Department of Automatic Control, Lun
- Automatic Control, Basic Course – Lab

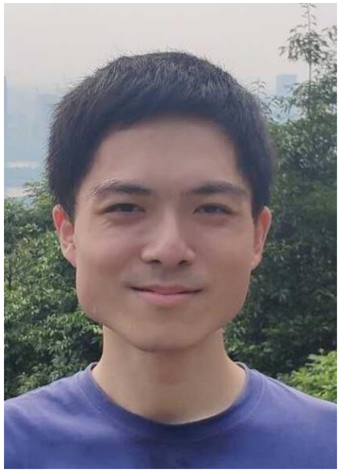
Material and slides from colleagues and courses at http://www.control.lth.se

Who are we?

Shengqian Han
(韩圣千)

Anders Robertsson

Richard Pates



Dasen Wei (魏大森)

Gautham Nayak Seetanadi

Who (and where) are we?

Mika Nishimura

Contact information

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- Richard Pates (L6-14)
  - richard.pates@control.lth.se office: New main building F413
- Gautham Nayak Seetanadi (E4-14, lab 2,3)
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www.control.lth.se

Automatic Control
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Automatic Control

31 OCTOBER

Digit@LTH breakfast seminar: From AIML@LU to 'AI Lund' and forward (Kalle Åström et.al)

From: 2019-10-31 09:00 **to:** 10:00
Type: Seminarium

[more]

08 NOVEMBER

Master's thesis presentation by Dennis Dalenius: Reverse osmosis temperature control

From: 2019-11-08 10:30 **to:** 11:00
Type: Seminarium

[more]

19 NOVEMBER

Robotveckan på LTH 2019

From: 2019-11-19 09:45 **to:** 2019-11-21 16:00
Type: Övrigt

[more]

Open PhD positions in Automatic Control

Welcome to apply for a PhD position in Automatic Control. Deadline November 8, 2019.

International MSc programme in Machine Learning, Systems and Control starts in the fall of 2020

Apply now! Last application date: Jan 15, 2020

Associate Senior Lecturer in Machine Learning

Machine learning is a broad subject and in this call we state three different subject directions, coupled to three departments. The position is part of the Wallenberg AI, Autonomous Systems and Software Program (WASP). Last day for application i October 31, 2019. Welcome to apply.

Current Courses (lp 1)

- Automatic Control, Basic Course for ED
- Multivariable Control
- System Identification
- Applied Robotics
- Optimization for Learning

Upcoming Courses (lp 2)

Course program

- Collected in syllabus on course home page

AUTOMATIC CONTROL, BASIC COURSE (FRTF05)

Course Syllabus, Fall 2019

Higher education credits: 7.5 ECTS (one eighth of a year of full-time studies).
Grading scale: Fail, 3, 4, 5.
Level: G2 (Secondary basic level).
Language of instruction: English.
Course coordinator: Richard Pates, Dep. of Automatic Control, Lund University, Sweden.
Recommended prerequisites: Calculus in One Variable, Calculus in Several Variables, Linear Algebra, Linear Systems or Systems and Transforms.
Assessment: Written exam, three laboratory exercises.
Further information: The course is given at Beihang University (BUAA) in Beijing, China.
Home page:

`http://www.control.lth.se/education/engineering-program/frtf05-automatic-control-basic-course-china/`

Aim

The aim of the course is to give knowledge about the basic principles of feedback control. The course will give insight into what can be achieved with control—the possibilities and limitations. The course mainly covers linear continuous-time systems.

Laboratory exercises

The course contains three mandatory laboratory exercises (3h15min each). Each laboratory exercise will be given at two occasions. It is mandatory to sign up for one occasion per exercise through the course homepage. The location for the labs will be updated soon.

Activity	Date	Time	Topics
Lab 1	Nov 6 (Wed)	19:00-22:15	Empirical PID control.
	Nov 7 (Thu)	19:00-22:15	
Lab 2	Nov 20 (Wed)	19:00-22:15	Modeling and calculation of PID controller.
	Nov 21 (Thu)	19:00-22:15	
Lab 3	Nov 27 (Wed)	19:00-22:15	State feedback and observer design.
	Nov 28 (Thu)	19:00-22:15	

You will work in groups of two or three students. For the labs you should ideally work in mixed Swedish, Chinese groups.

The manuals for Labs 2 and 3 contain preparatory exercises that must be solved before the laboratory exercise. At the start of Lab 2, a quiz with two review questions are given. You must give correct answers to both questions in order to proceed with the laboratory exercise. Sign-up lists for the laboratory exercises will be available on the course web page.

Lab sign-up

two alternatives each for Lab-exercises

Lab Sessions

The labs sessions are roughly 3h15m each (19:00-22:15) and held in F-532, New Main Building.

Choose mixed groups of Lund and Beihang students. The sign-up pages are linked below.

Sign-up link for Labs (Swedish students use their STiL-id, Chinese students will get mail with sign-up id)

Note: When the sign-up for an activity closes (before each session) the lists will be taken down. Take a note of your chosen time!

- Lab 1: sign-up
- Lab 2: sign-up
- Lab 3: sign-up

The guidelines for the labs are given in

- *Lab 1*
- *Lab 2*
- *Lab 3*

Do this already today!

Additional Material

- Mathematical repetition
- Mathematical repetition - solutions
- Matlab-file with useful automatic control commands
- Johan Löfberg's (ISY, LiU) minseg-pms Sensor(pdf) DCmotor(pdf) PID(pdf) Balance(pdf)

Lecture Slides

- Lecture 1 [updated 20171113]

Sign-up with your StiL
(Chinese students will get StiL by mail)

Automatic Control, Basic Course (China), ht2 2019

name(time/location)	groups	students
AK China Lab 1		
Lab 1, Thursday (Nov 7 (Thu) 19:00-22:15 in F-532 NewMainBuilding)	0/19	0/19
Lab 1, Wednesday (Nov 6 (Wed) 19:00-22:15 in F-532 NewMainBuilding)	0/19	0/19

Enroll and Form Groups

Automatic Control, Basic Course (China), ht2 2019

AK China Lab 1, Lab 1, Thursday (Nov 7 (Thu) 19:00-22:15 in F-532 NewMainBuilding)

Already registered for this session

Number of free workstations: 19

Enroll students for the session:

StiL 1

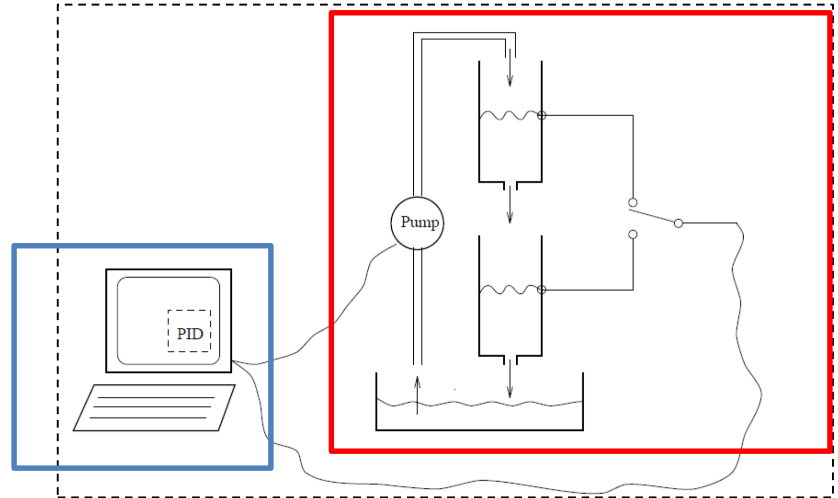
enroll

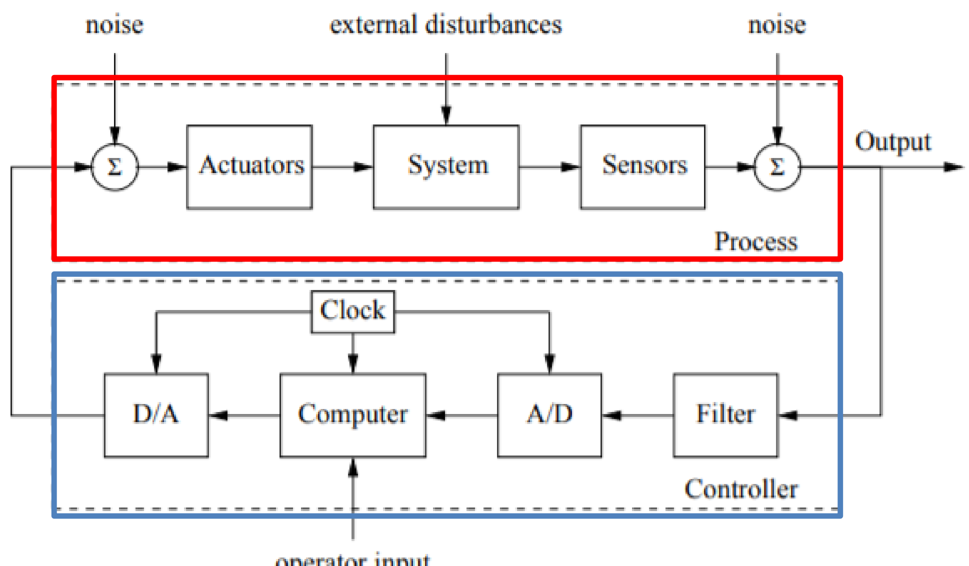
What is the connection?

Dujiangyan

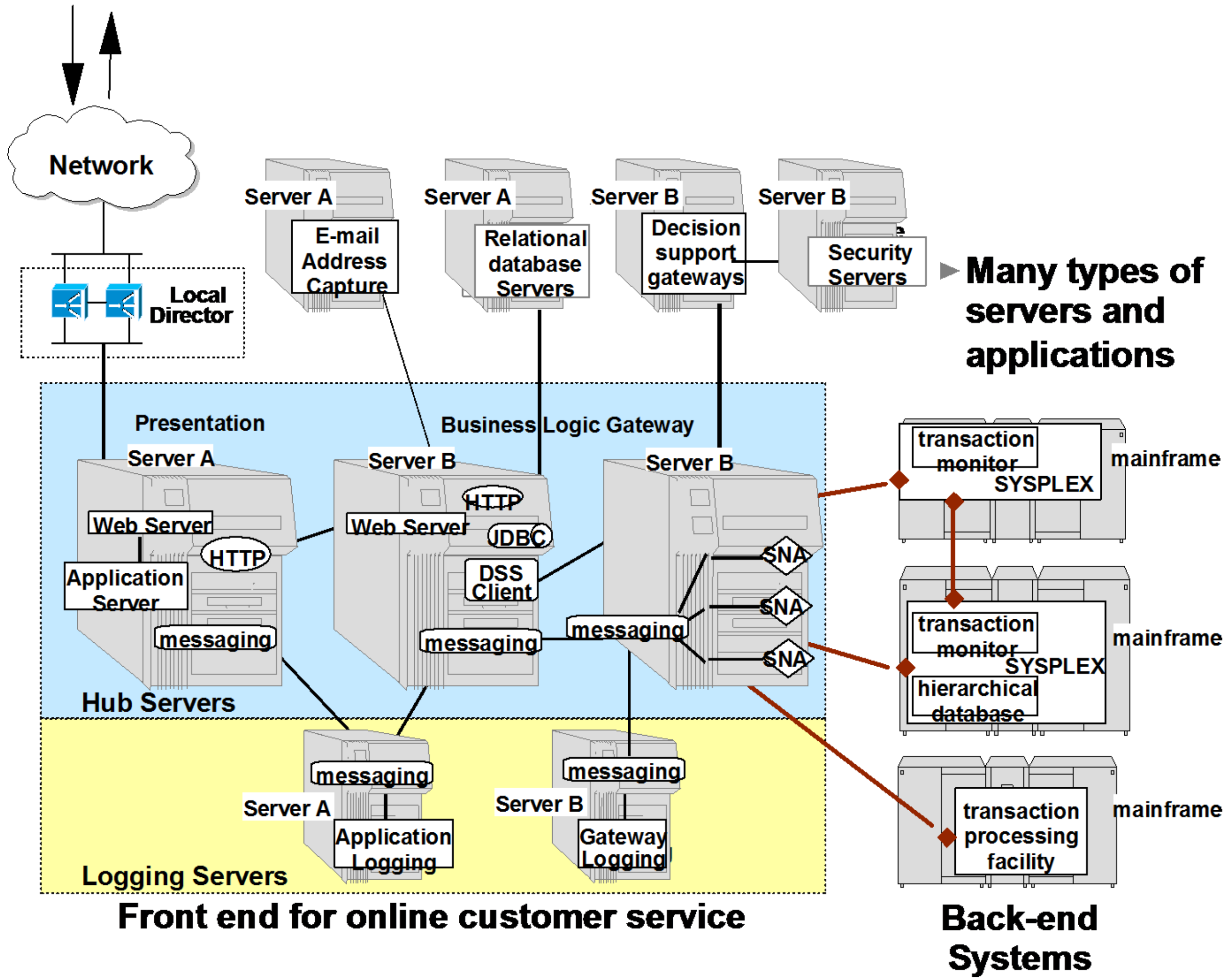
Guardian Ox at Summer Palace, Beijing

Labs 1 & 2


Pump
PID


noise
external disturbances
noise
Σ
Actuators
System
Sensors
Σ
Output
Process
Clock
D/A
Computer
A/D
Filter
Controller
operator input

Example: Control of Server Systems



Multi-tier systems of
Web browsers, business logic and databases

Feedback at various levels

Queue Control

IBM, HP, Microsoft, Amazon, ….

Challenges:

- Modeling formalisms (DES, ODEs, queuing theory, …)
- Design of software and computing systems for controllability

Literature

The course is based on the following compendiums:

- Tore Hägglund: *Automatic Control, Basic Course – Lecture Notes*. Department of Automatic Control, Lund University, 2014.
- *Automatic Control, Basic Course – Collection of Exercises*. Department of Automatic Control, Lund University, 2014.
- *Automatic Control, Basic Course – Laboratory Manuals*. Department of Automatic Control, Lund University, 2012.
- *Automatic Control, Basic Course – Collection of Formulae*. Department of Automatic Control, Lund University, 2012.

As reference textbook, we recommend

- Karl Johan Åström & Richard Murray: *Feedback Systems: An Introduction to Scientists and Engineers*. Princeton University Press. Second edition (2016) is available for free download at:

  `http://www.cds.caltech.edu/~murray/amwiki`

Lectures and Exercises on Tuesdays and Wednesdays will be given at Old Main Building 407.
Lectures and Exercises on Thursdays will be given at Old Main Building **Middle** 404.

Week	Date	Time	Activity	Topics
44	Oct 29 (Tue)	15:00-16:35	L1	Introduction. The PID controller.
	Oct 29 (Tue)	16:40-18:15	L2	Process models.
	Oct 31 (Thu)	14:00-15:35	E1	Process models. Linearisation.
45	Nov 5 (Tue)	15:00-16:35	L3	Impulse and step response analysis.
	Nov 5 (Tue)	16:40-18:15	E2	System representations. Block diagrams.
	Nov 6 (Wed)	14:00-15:35	L4	Frequency analysis.
	Nov 6 (Wed)	15:50-17:25	E3	Poles and zeros. Impulse and step responses.
	Nov 7 (Thu)	14:00-15:35	L5	Feedback and stability.
46	Nov 12 (Tue)	15:00-16:35	L6	The Nyquist stability criterion and stability margins.
	Nov 12 (Tue)	16:40-18:15	E4+E5	Frequency response. Bode and Nyquist diagrams. Preparation for Lab 2.
	Nov 14 (Thu)	14:00-15:35	L7	The sensitivity function and stationary errors.
47	Nov 19 (Tue)	15:00-16:35	L8	State feedback.
	Nov 19 (Tue)	16:40-18:15	E6	The Nyquist stability criterion and stability margins.
	Nov 20 (Wed)	14:00-15:35	L9	State estimation.
	Nov 20 (Wed)	15:50-17:25	E7	Stationary errors and controllability.
	Nov 21 (Thu)	14:00-15:35	L10	Output feedback and pole-zero cancellation.
48	Nov 26 (Tue)	15:00-16:35	L11	Lead-lag compensation
	Nov 26 (Tue)	16:40-18:15	E8+E9	Observability. State Estimation.
	Nov 28 (Thu)	14:00-15:35	L12	PID Control
49	Dec 3 (Tue)	15:00-16:35	L13	Controller structures and implementation
	Dec 3 (Tue)	16:40-18:15	E10+E11	Lead-lag compensation. Frequency analysis. PID design.
	Dec 4 (Wed)	14:00-15:35	L14	Synthesis example. Course Round-up.
	Dec 4 (Wed)	15:50-17:25	E12+E13	Controller structures. Synthesis.
	Dec 5 (Thu)	14:00-15:35	Old Exam	

Examination

The mandatory parts of the course are

- the three laboratory exercises,
- the written exam.

The final grade is based only on the result from the written exam.

You may bring the collection of formulae[1] and a pocket calculator (without any control software) to the exam.

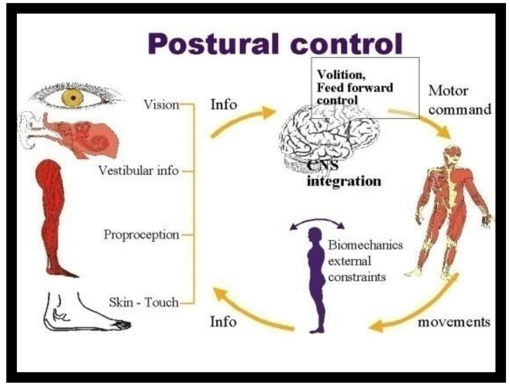
The exam for the Swedish students will be held in January 2020

The exam for the Chinese students will be held in December 2019

The corrected exams will be available for inspection at the Department of Automatic Control in Lund. Inspection date will be announced online.

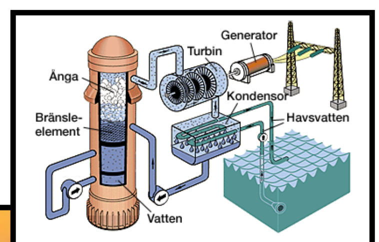
Feedback in the course

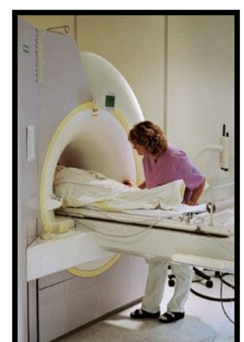
- CEQ
  - Reporting afterward (batch)
  - Improvements for next year
- Student representatives
  - Part of continuous feedback system



What is Automatic Control?
Before we start...

Anders Robertsson



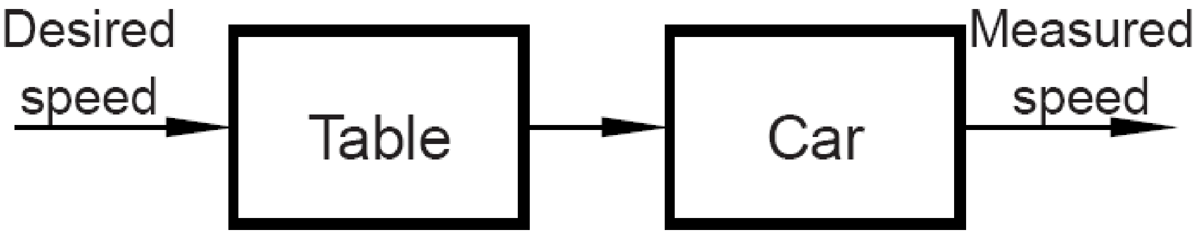


Based on mtrl from Bernhardsson, K-E Årzen et al

Overview

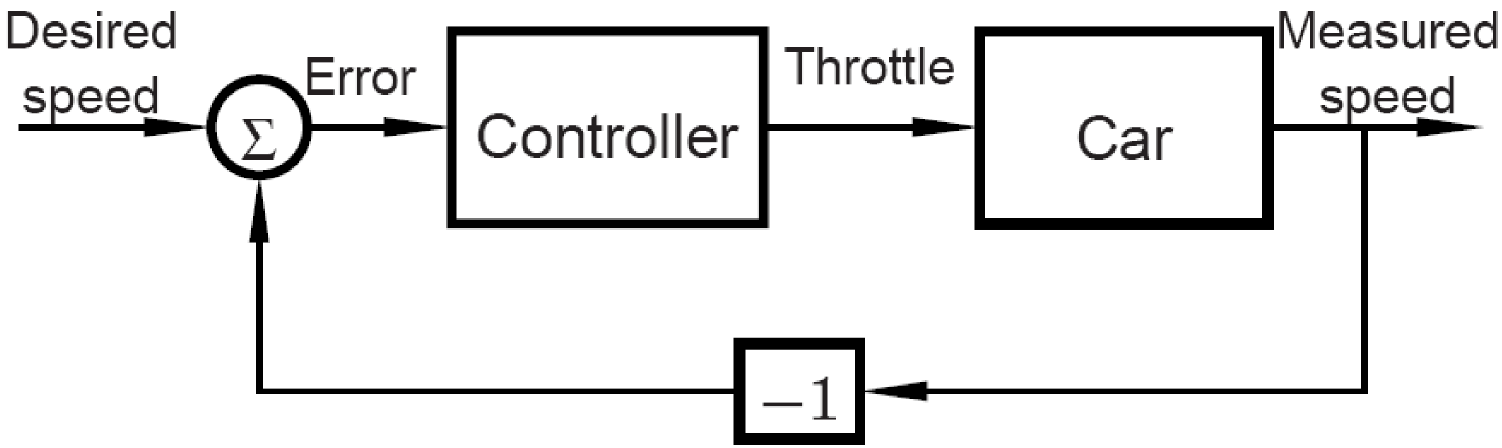
- Introductory example: Automatic Speed Control
- Where do we find control algorithms?
- How to do it?
- How does it differ from signal processing and what other courses are there then?
- Examples
  - Web-server control
  - Resource allocation in communication and computer systems

Speed control: "Open loop"



- Open loop
- Problems?

Speed control: Feedback



- Closed loop
- Simple controller:
  - Error > 0: increase throttle
  - Error < 0: decrease throttle

Feedback

A very powerful principle

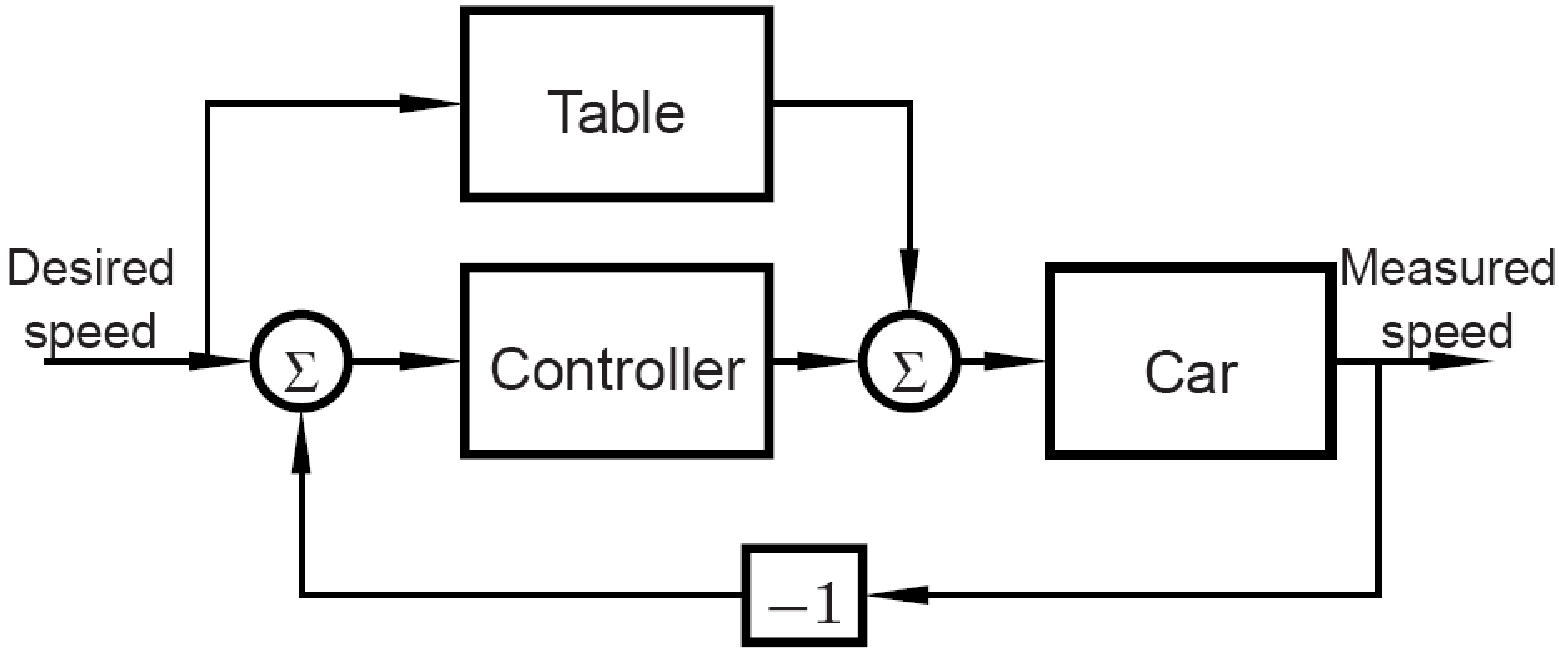
+ Attenuates disturbances
+ Reduces sensitivity to process variations
+ Does not demand very detailed models
  (cmp with Feedforward)
- Can amplify measurement noise
- Can cause instability

Feedforward (open loop)

Analyze and determine on beforehand what to do.

+ Reduces effect of measurable disturbances
+ Allows for fast reference changes without introducing a control error
- Demands good model of process
- Demands stable system

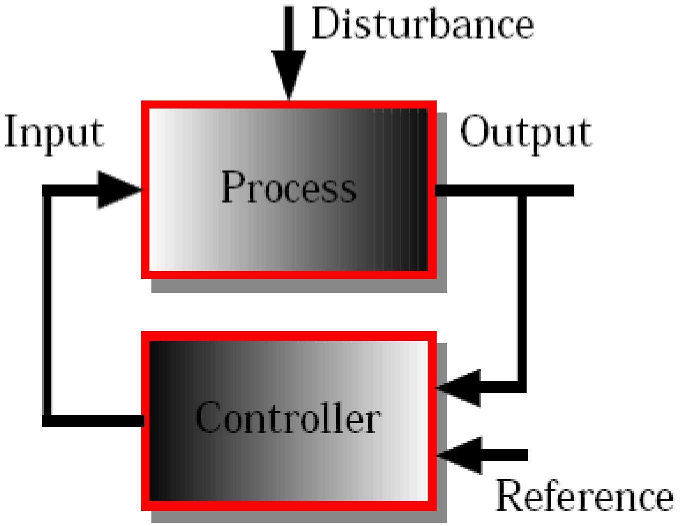
Feedforward+ Fedback



Use of **models** and **feedback**

Activities:

- Modeling
- Analysis and simulation
- Control design
- Implementation



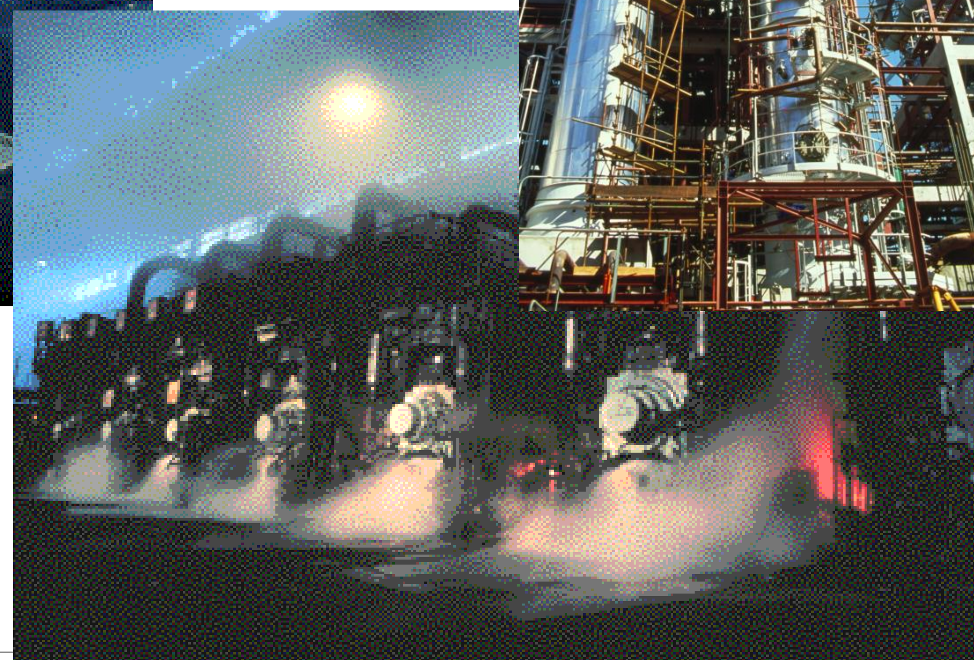
Where do we find control?

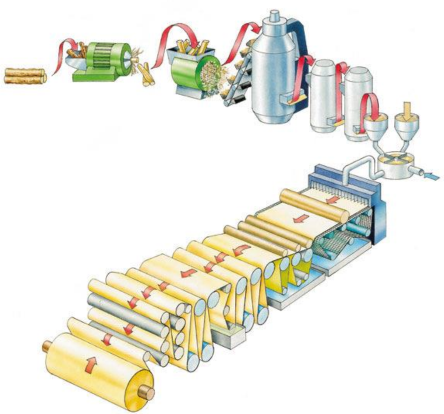
Where do we find control?

Everywhere !

Power Generation and Distribution

Process Control





Buildings

Design & Energy Analysis

Windows & Lighting

Natural Ventilation

Indoor Environment

Elevators

Safety

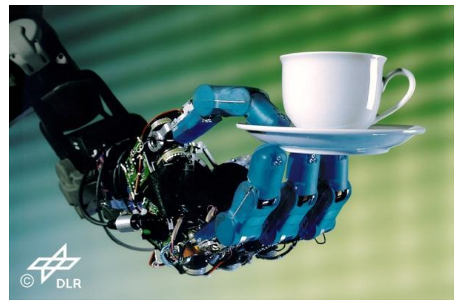
HVAC

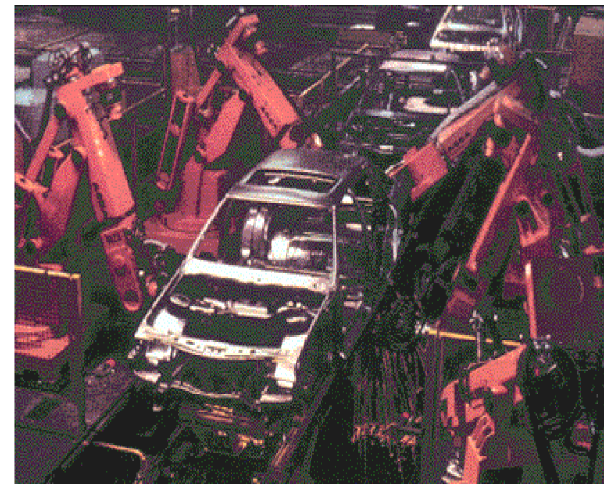
Vibration damping

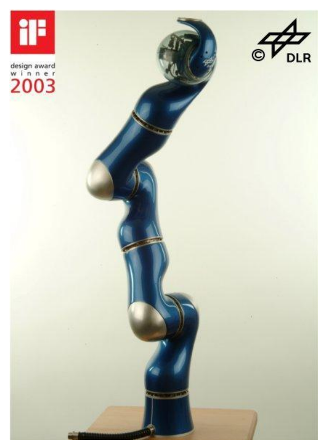
Sensors, Networks,Communications, Controls

Slide from UTRC

Manufacturing robotics



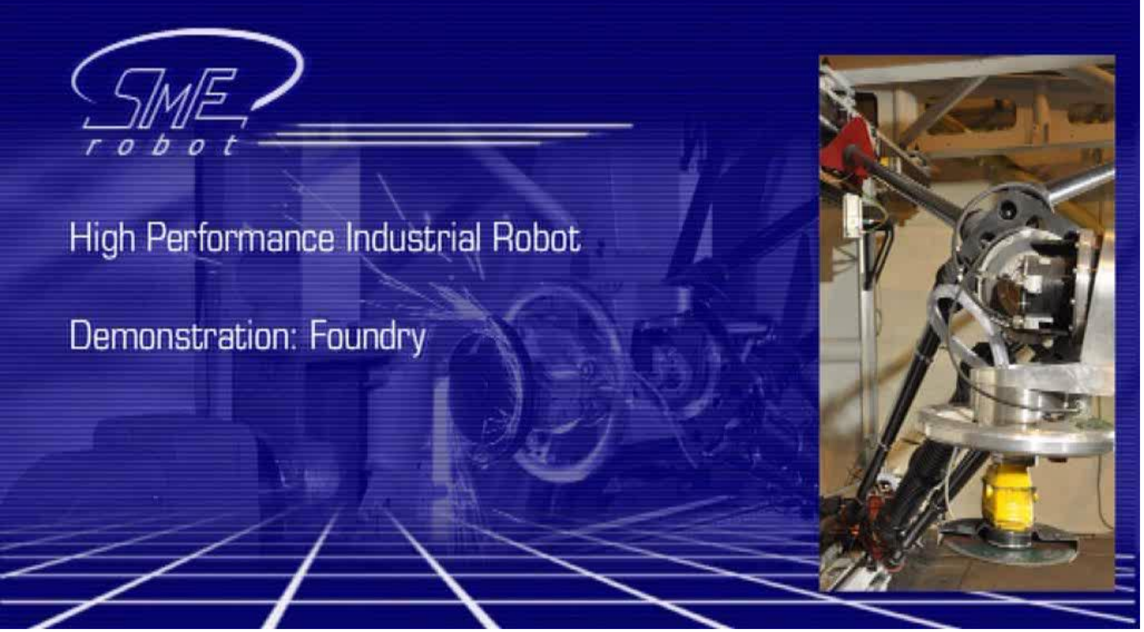




Small and large in very different domains…

http://video.google.se/videoplay?docid=1210345008392050115&ei=tznoSrXwKqDQ2wLP1I2PDw&q=humanoid+robot&hl=sv&client=firefox-a#

http://www.youtube.com/watch?v=W1czBcnX1Ww



http://www.smerobot.org

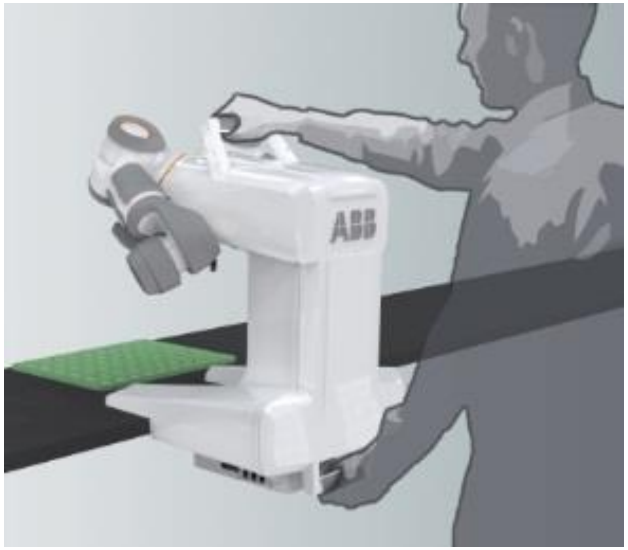
http://www.smerobot.org/15_final_workshop/download/half%20resolution/D1_Parallel_Kinematic_512x288_500kBit.wmv

The Fanta Challenge

http://www.youtube.com/watch?v=SOESSCXGhFo

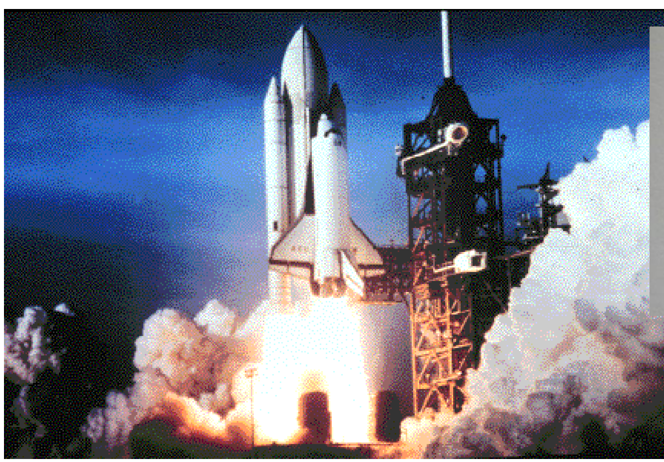
Dart- and ball-catching robot

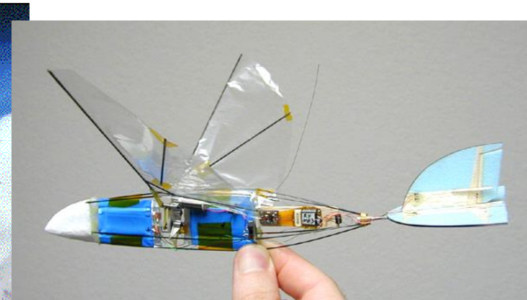
http://www.youtube.com/watch?v=Fxzh3pFr3Gs



http://www.youtube.com/watch?v=7JgdbFW5mEg&list=PL13509A9A50E93865

Vehicles



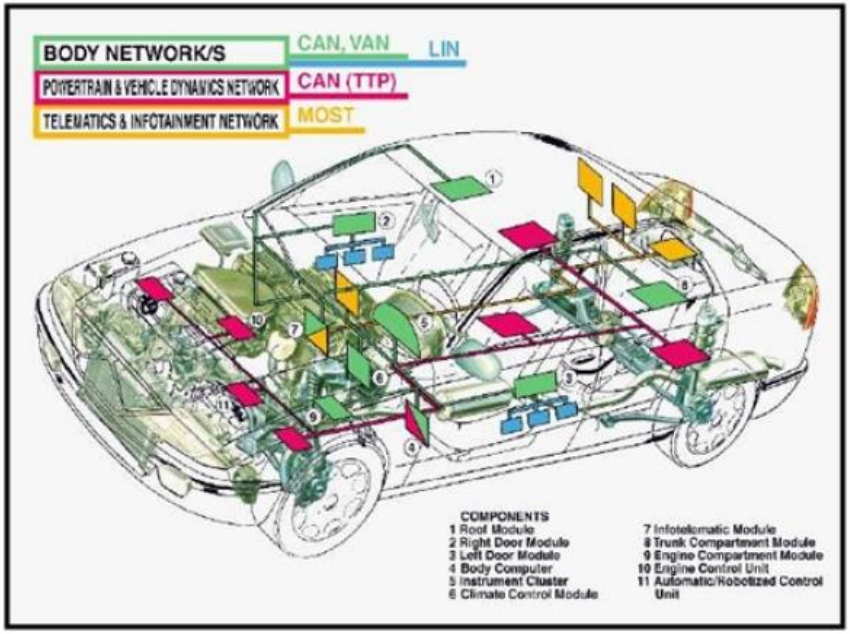


Example: Modern Cars

- **Embedded control systems in modern car** (brakes, transmission, engine, safety, climate, emissions, …)

40-100 ECUs in a new car

~ 2-5 miljon lines of code



Automotive

Strong technology driver

Engine control

Power trains

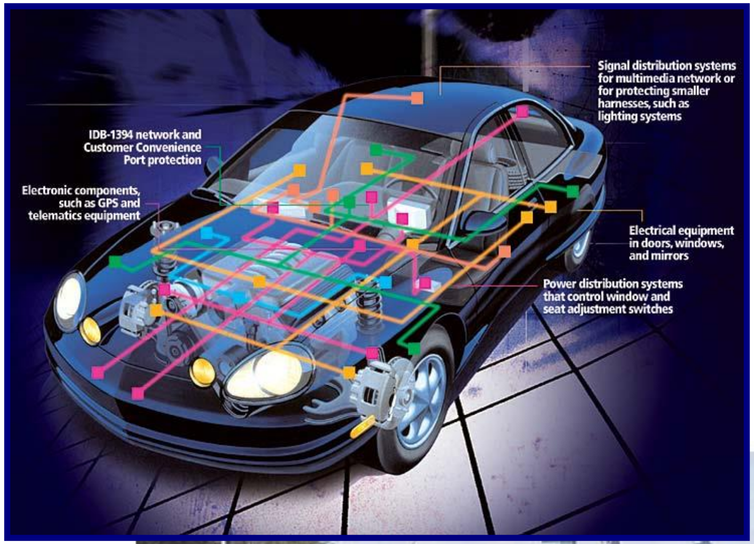
Cruise control

Adaptive cruise control

Traction control

Lane guidance assistance

Traffic flow control



Automotive

Strong technology driver

Engine control

Power trains

Cruise control

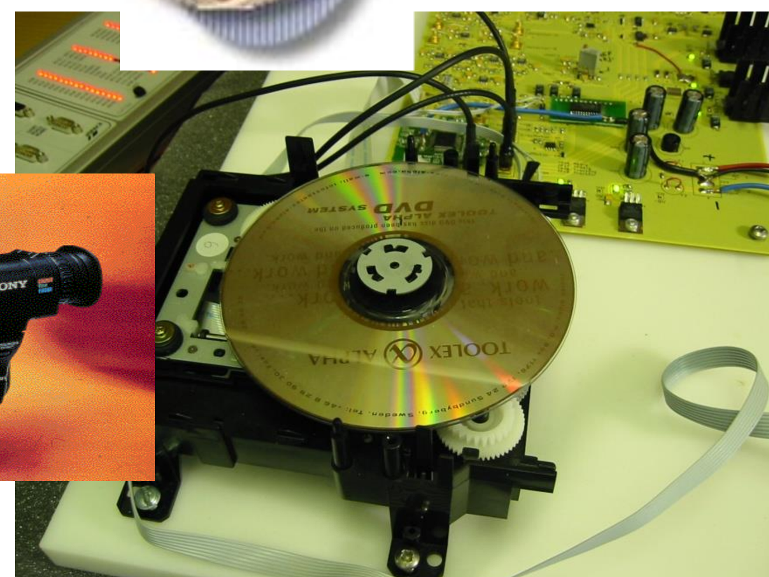
Traction control

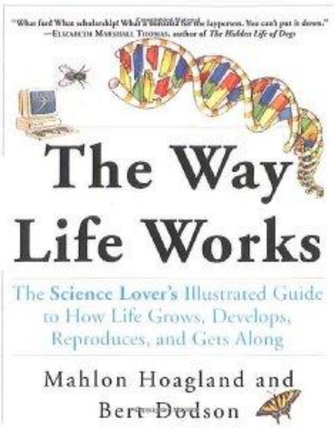
Road-Tire Friction Estimation for AFS Vehicle Control

Master thesis work by

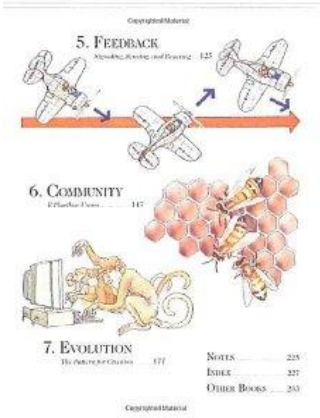
Andreas Andersson

Consumer Electronics





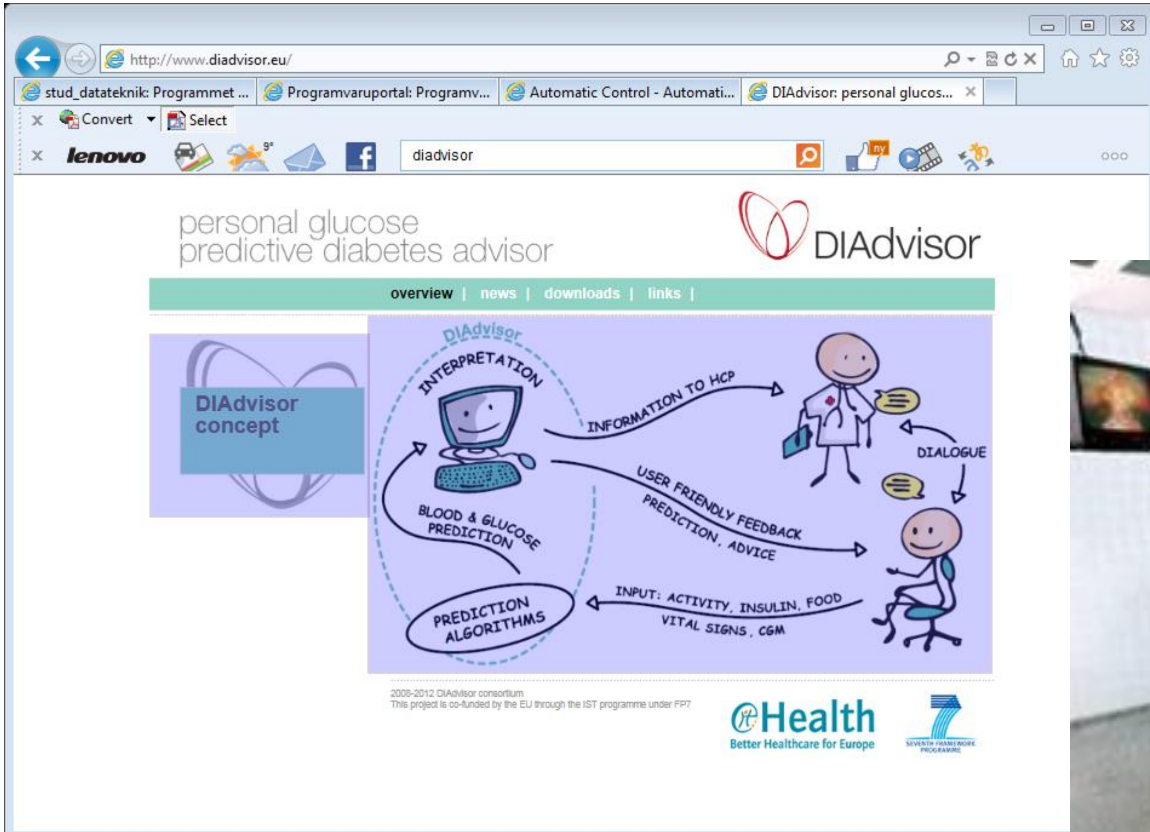
Biology



Feedback is a central feature of life. The process of feedback governs how we grow, respond to stress and challenge, and regulate factors such as body temperature, blood pressure, and cholesterol level. The mechanisms operate at every level, from the interaction of proteins in cells to the interaction of organisms in complex ecologies.

Mahlon B Hoagland and B Dodson The Way Life Works Times Books 1995

Control in medical applications



http://www.intuitivesurgical.com/

http://www.diadvisor.eu/

http://www.youtube.com/watch?v=

Error control of software systems [L.Sha]

- *The idea* behind error control of software is to use ideas similar to the ideas used in feedback control in order to *detect malfunctioning software* components and, in that case *fall back on, a well-tested core software component* that is able to provide the basic application service with guarantees on performance and safety.

- Provide techniques and tools that support making the semantic assumptions of each software component explicit and machine checkable.

Error control of software systems [L.Sha]

- *The idea* behind error control of software is to use ideas similar to the ideas used in feedback control in order to *detect malfunctioning software* components and, in that case *fall back on, a well-tested core software component* that is able to provide the basic application service with guarantees on pe

- Provide techniqu
making the semantic assumptions of each software component explicit and machine checkable.

Automatic Control- *The Hidden Technology*

- Used everywhere
- Very successful
- A prerequisite for several products and systems
- Not so visible
  - Except for when things go wrong!
- Why?
  - Easier to see and market applications than principles, methods and ideas.

http://www.youtube.com/watch?v=K4h9qJ6NG9E

JAS – the sequel

http://www.youtube.com/watch?NR=1&v=mkgShfxTzmo

http://www.youtube.com/watch?v=OVr6QJzW094

Stockholm water festival 1993

How to do it?

How do we design a controller?

- We choose the controller structure and parameters so that the *closed-loop system* get a desired **dynamic** behaviour.

- “The technology to get things to behave as you want them”

Example: differential equations

$$\frac{dx}{dt} + 3x(t) = 1$$
$$x(0) = 0$$

$$\frac{dx}{dt} - 4x(t) = 1$$
$$x(0) = 0$$

Which is the ”good solution” and which solution is **”bad”**

i.e., **stable** vs **unstable ?**

Differential equations

$$\frac{dx}{dt} + 3x(t) = 1$$
$$x(0) = 0$$

$$\frac{dx}{dt} - 4x(t) = 1$$
$$x(0) = 0$$

$$x(t) = \frac{1}{-3} \cdot \left(e^{-3 \cdot t} - 1\right)$$

$$x(t) = \frac{1}{4} \cdot \left(e^{4 \cdot t} - 1\right)$$

stable

unstable

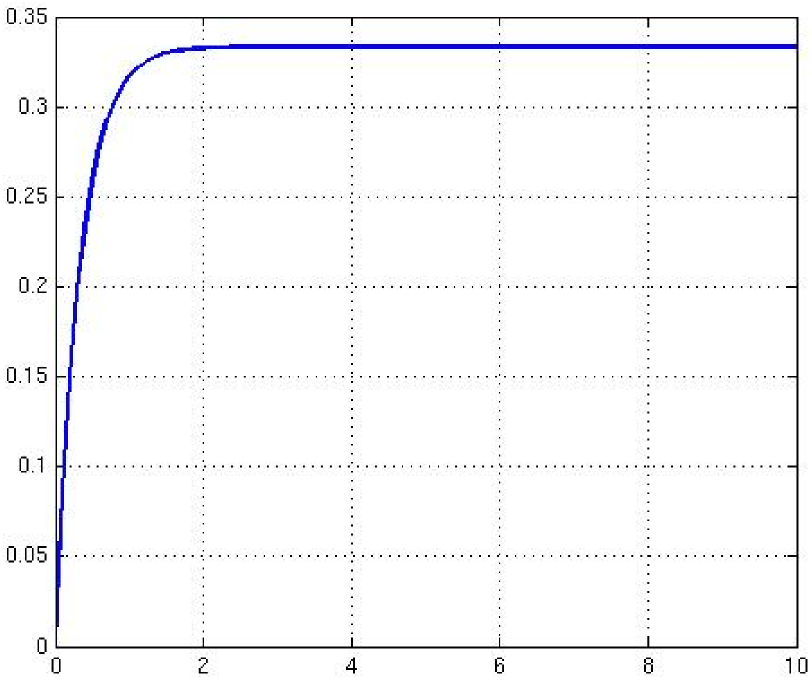
Differential equations

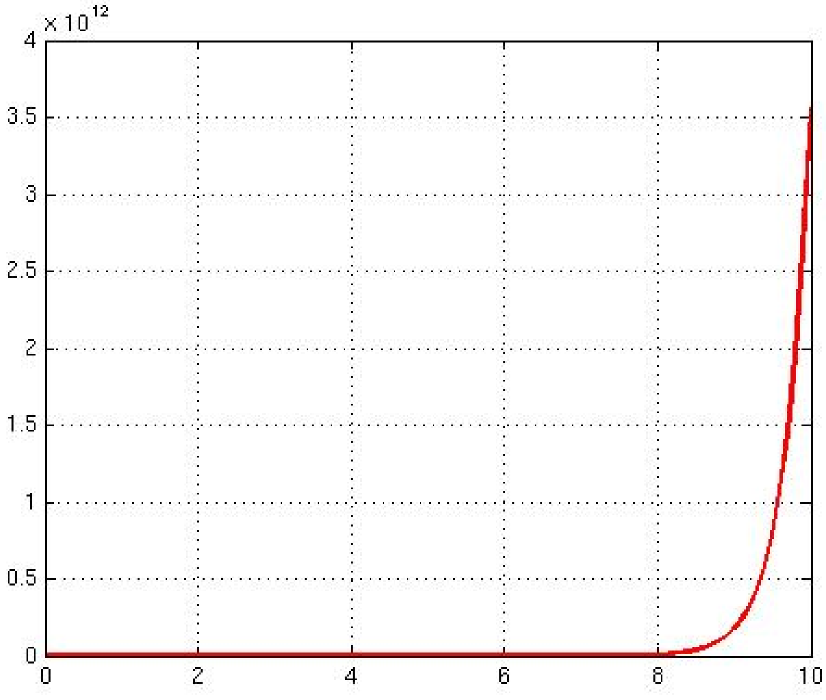
$$x(t) = \frac{1}{-3} \cdot \left(e^{-3 \cdot t} - 1\right)$$

$$x(t) = \frac{1}{4} \cdot \left(e^{4 \cdot t} - 1\right)$$

stable

unstable

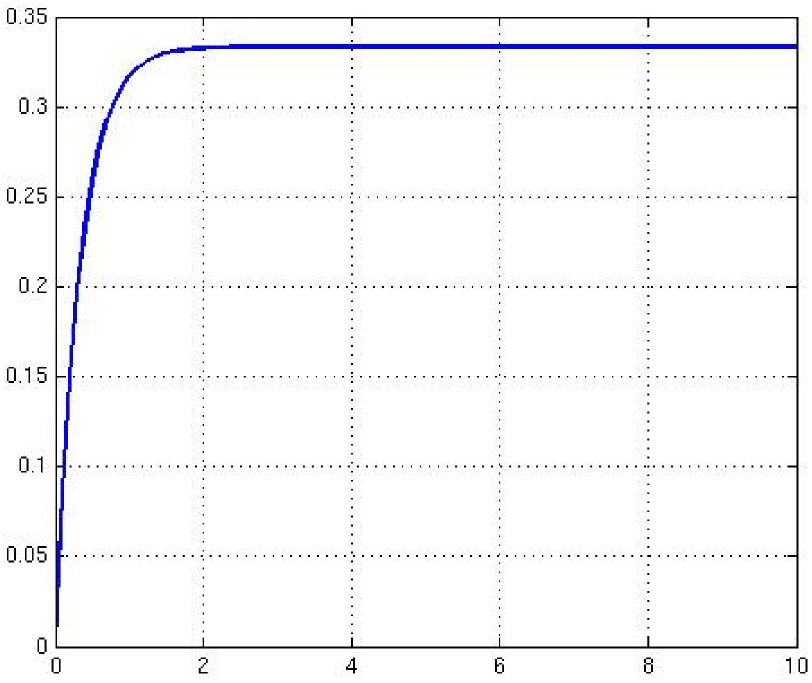


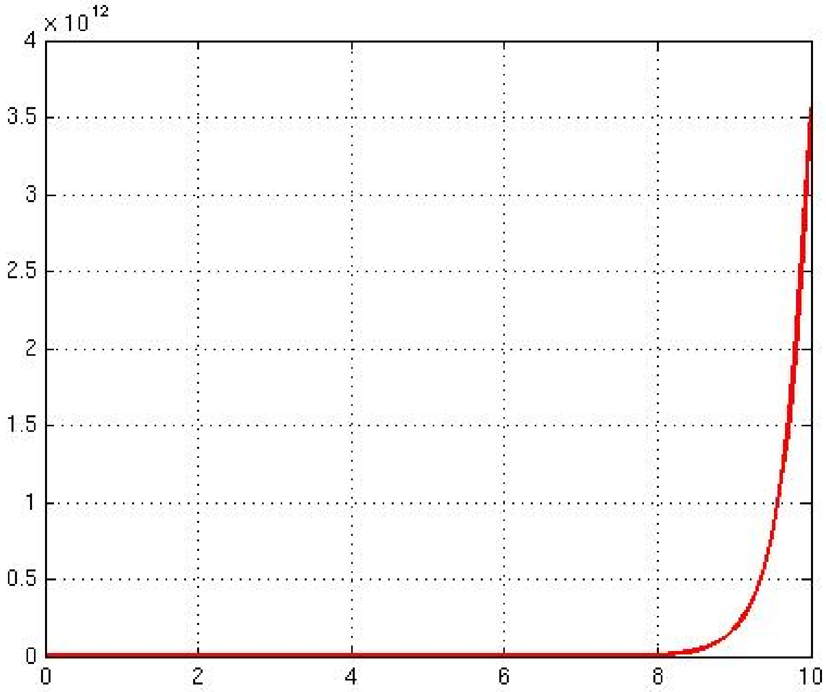


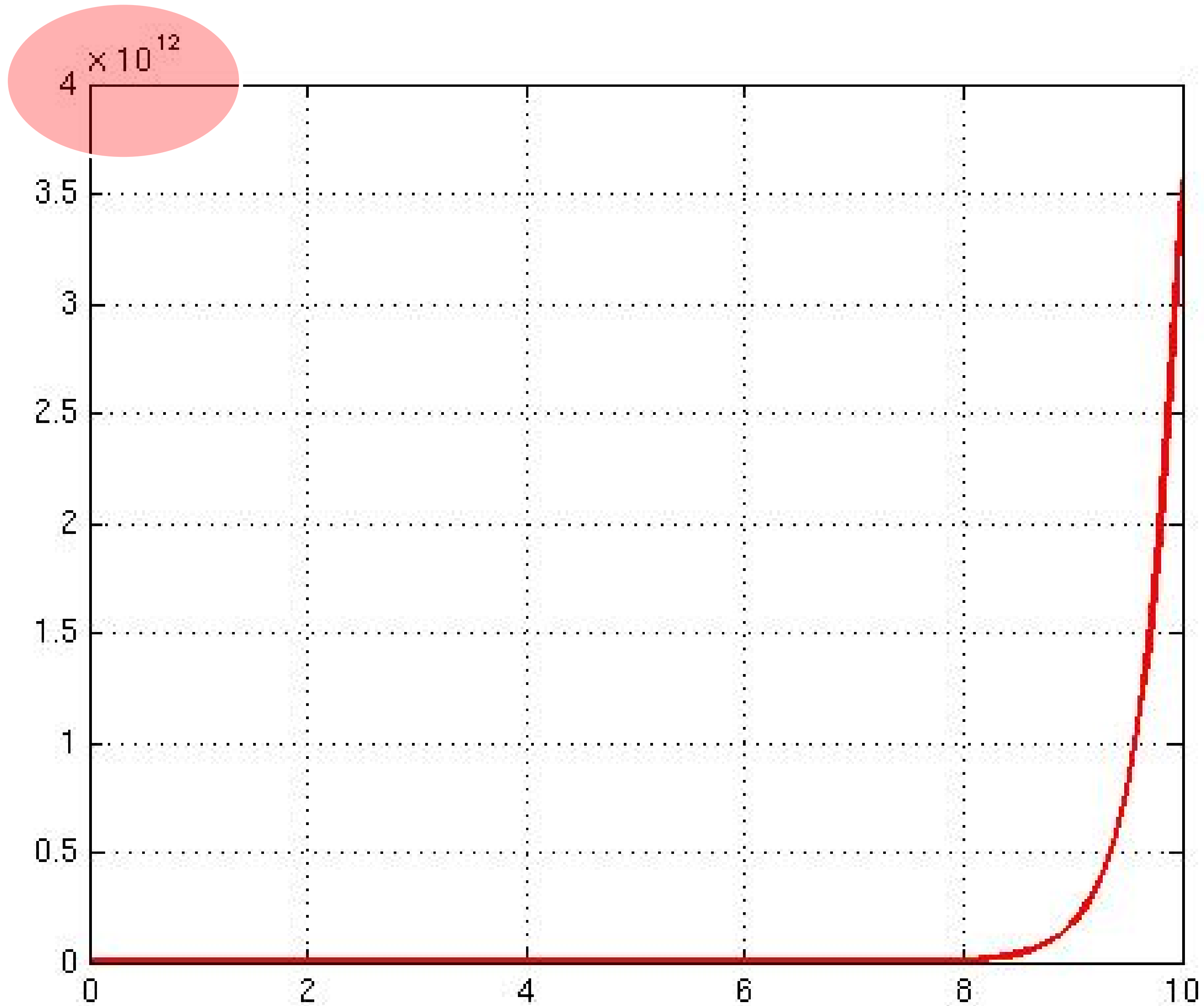
Differential equations

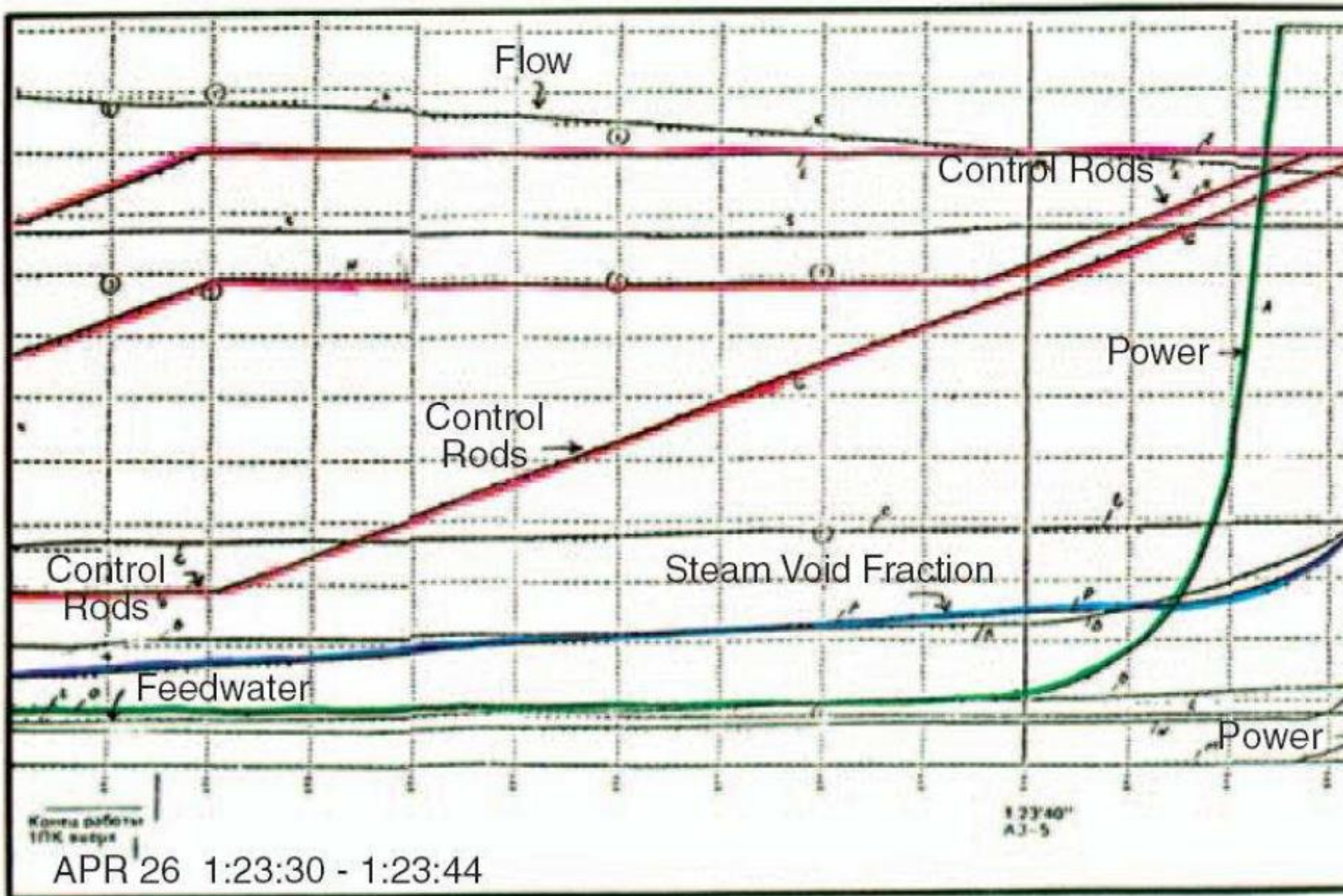
$$x(t) = \frac{1}{-3} \cdot \left(e^{-3 \cdot t} - 1\right)$$

$$x(t) = \frac{1}{4} \cdot \left(e^{4 \cdot t} - 1\right)$$






× 10^12
4
3.5
3
2.5
2
1.5
1
0.5
0
0
2
4
6
8
10



Flow
Control Rods
Power
Control
Rods
Control
Rods
Steam Void Fraction
Feedwater
Power
APR 26 1:23:30 - 1:23:44

Figure 2. *Chernobyl nuclear power plant shortly after the accident on 26 April 1986.*

Basic Control course in a minute

You decide the control!

Is the solution to

$$\frac{dx}{dt} - 4x(t) = u(t)$$

stable or unstable?

Remark: $u(t)$ is a control signal which we can choose...

Control course in one minute

Choose e.g.,

$$u(t) = 1 - Kx(t)$$

which gives the closed-loop system

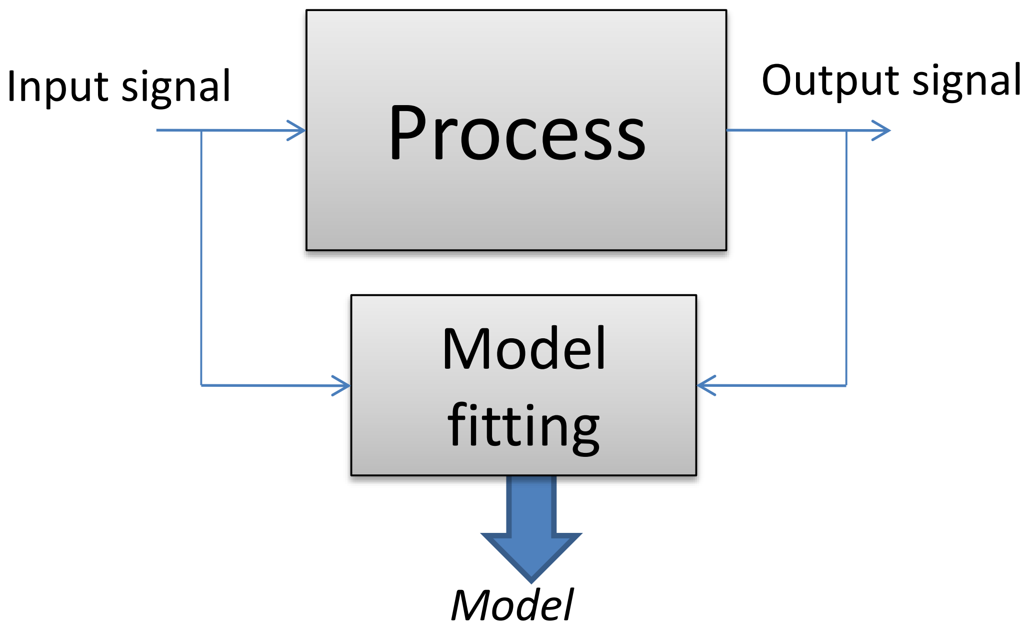
$$\frac{dx}{dt} - 4x(t) + Kx(t) = 1$$

If K > 4 we get an exponentially stable closed-loop system!

With help of K we determine how fast the closed-loop system should behave **(i.e., we modify the dynamics**)

Where do the models come from?

- Either physical modelling
  - First principles in physics, chemistry, mechanics…
- … or via system identification



Frequency analysis

- Gives a description how the system/process reacts at different frequencies

”Low frequency – slow time-scale”

”High frequency – fast time-scale”

Resonance frequencies?

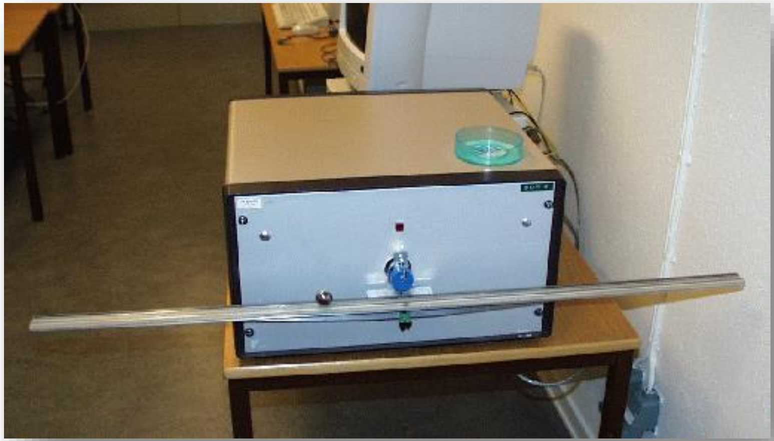
Universal Theory

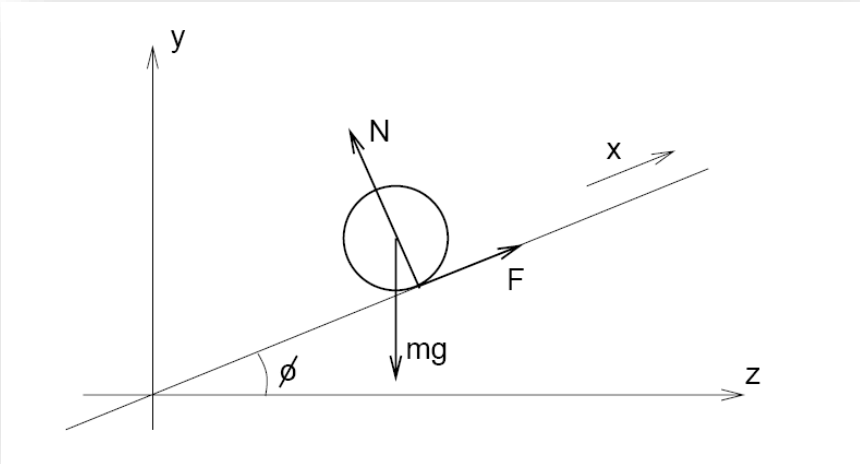
- Same math and methods in a lot of domains.

Regardless if it is a mechanical, electrical, chemical … system we want to control we use the same methods and mathematical models

- The theory is very general!
  - Principles
  - Methods
  - Tools
- Courses for F, E, D, C, M, I, Pi, K, B, W, N
- Very broad job market
- Axis, Google, Ericsson, ABB, Tetra Pak, Haldex, Volvo, consultants …..

Example: Ball and beam





Force balance equations → nonlinear differential eqs. → approximate with linear diff. eqs.

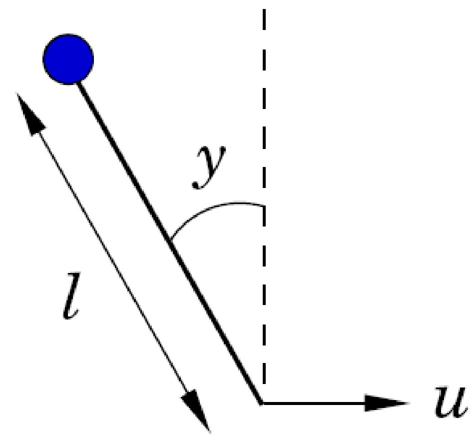
$$m(\ddot{x} - x\dot{\phi}^2) = -mg\sin\phi - \frac{2}{5}m\ddot{x}.$$

→

$$m\ddot{x} = -mg\phi - \frac{2}{5}\ddot{x}$$

[Control of a ball on a beam, adjusted Td-parameter]

Example: Inverted Pendulum



A simple second-order model is given by

$$\frac{d^2y}{dt^2} = \omega_0^2 \sin y + u\,\omega_0^2 \cos y$$

where $\omega_0 = \sqrt{\frac{g}{l}}$ is the natural frequency of the pendulum.

Example: Inverted Pendulum

Linearization around the upright equilibrium gives the state-space model

$$\frac{dx}{dt} = \begin{pmatrix} 0 & 1 \\ \omega_0^2 & 0 \end{pmatrix} x + \begin{pmatrix} 0 \\ \omega_0^2 \end{pmatrix} u$$
$$y = \begin{pmatrix} 1 & 0 \end{pmatrix} x$$

Unstable linear system

If one linearizes around the downward equilibrium and add some viscous damping proportional to the angular velocity you get asymptotically stable solutions.

Example: Inverted Pendulum

Linearization around the upright equilibrium gives the state-space model

$$\frac{dx}{dt} = \begin{pmatrix} 0 & 1 \\ \omega_0^2 & 0 \end{pmatrix} x + \begin{pmatrix} 0 \\ \omega_0^2 \end{pmatrix} u$$

$$y = \begin{pmatrix} 1 & 0 \end{pmatrix} x$$

Unstable linear system

However stabilizing control is sensitive to delays…

Example: Inverted Pendulum

- Good control demands feedback from **both** angle and angular velocity.

- Angular velocity?
  - Sensor which measures angular velocity
  - Sensor which only measures angle and calculates angular velocity through *difference approximation*

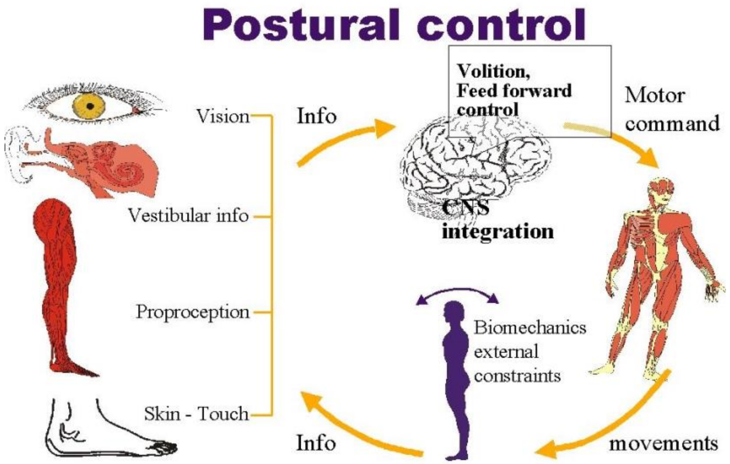
$$\frac{dv}{dt} = \frac{v(k) - v(k-1)}{T_s}$$

  - Filter which uses physical model of pendulum

Example: Segway

www.segway.com

Other inverted pendula



nonlinear dynamic

- Can cause a lot of unexpected behavior!

"Limit cycles"

Listen to Yoda!