Automatic Control
a Perspective

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Åström Kumar – Control a Perspective

Automatica 50 (2014) 3-43

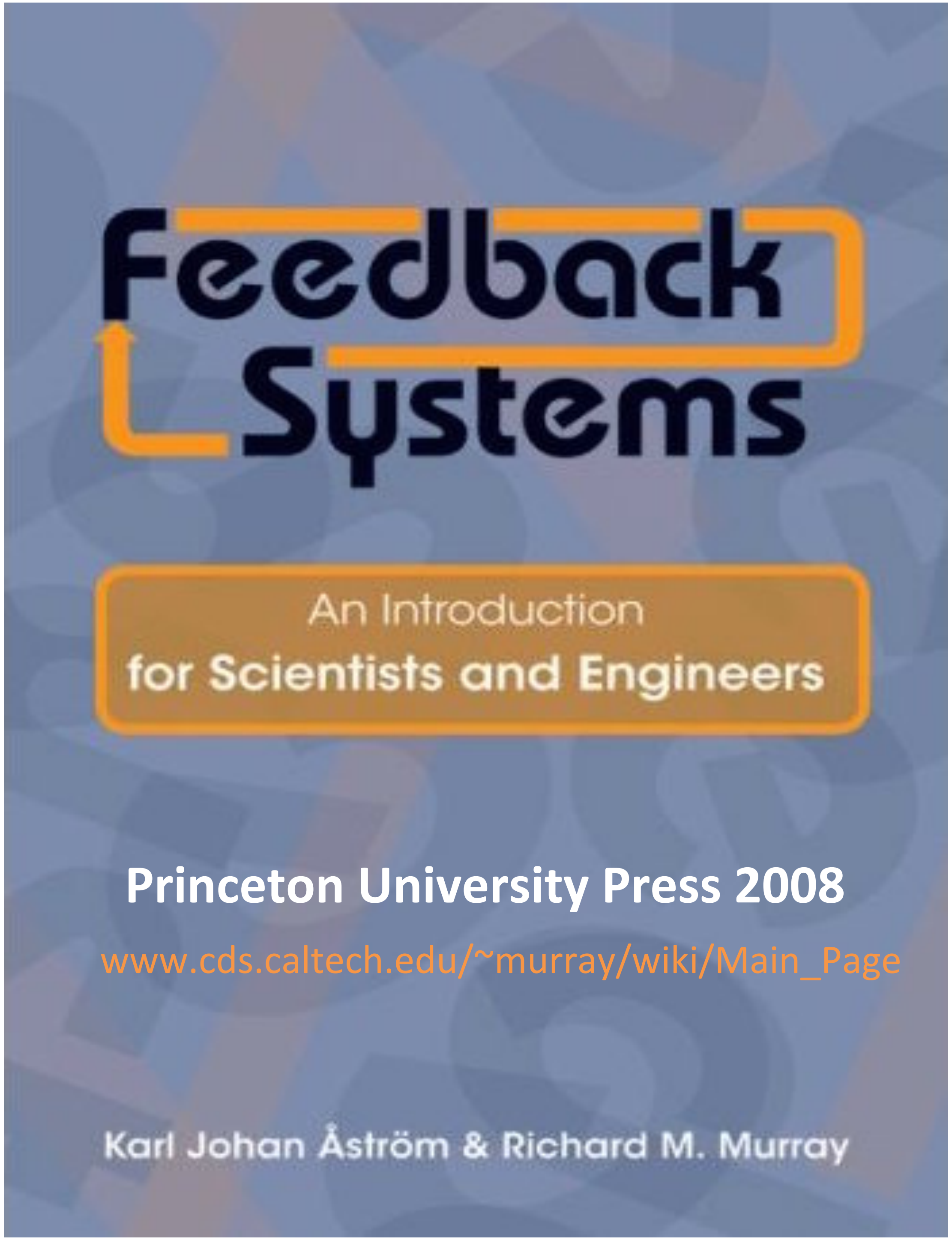
Tasting the Power of Feedback

The Field Emerges

The Golden Age

Widening the Horizon

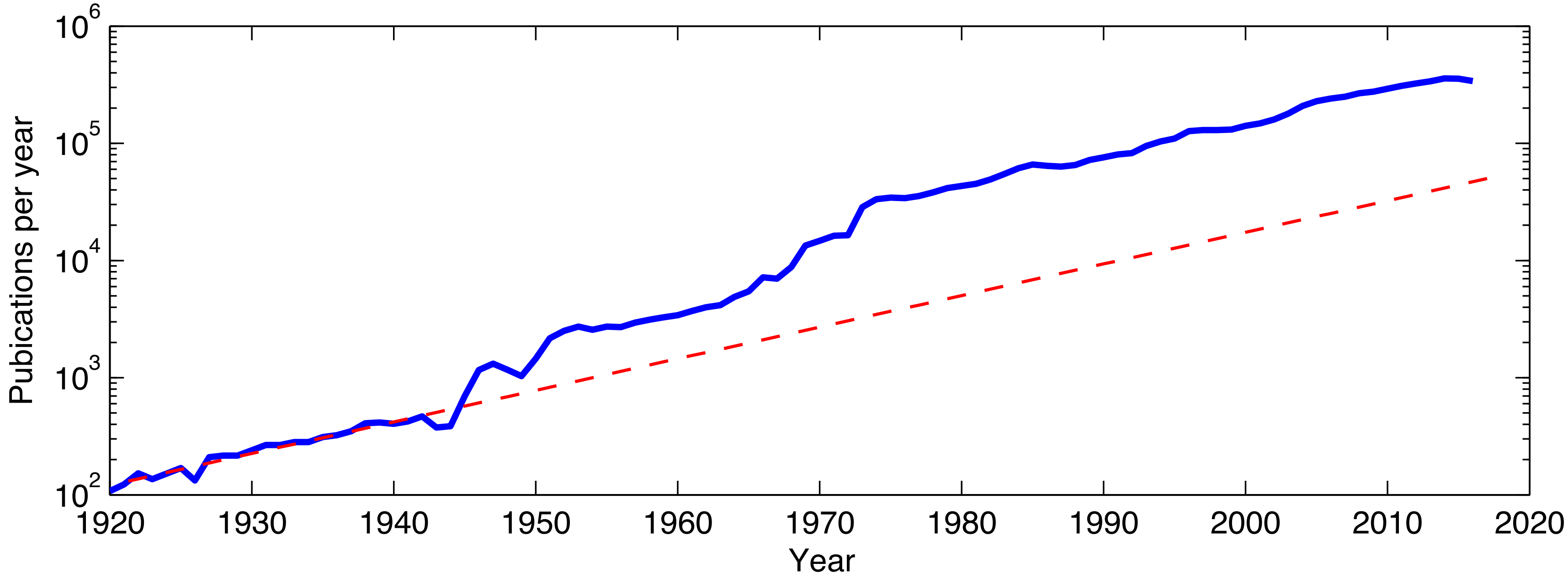
Interplay of Theory & Practice



Princeton University Press 2008

www.cds.caltech.edu/~murray/wiki/Main_Page

Publications per year



Number of publications with the word control in title, abstract or keywords Scopus

A Broad Picture

There are examples of control from ancient time but control became widely used in the industries that emerged in the 19th and 20th centuries: steam power, electric power, ships, aircrafts, chemicals, telecommunication. Control was sometimes an enabling technology (aircraft, telecom). Similarities between different applications were not recognized.

Control became a separate engineering discipline in the 1940s and it has developed rapidly ever since. Today there are applications expanding everywhere and there are great new research challenges.

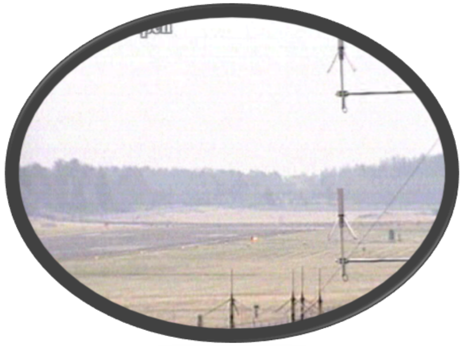
What is Control?

- Requirements: Specifications
- Architecture: System structure, sensors, actuators, computers, communication, HMI
- Modeling and simulation: Physics and data
- Control Design: Models, algorithms and logic
- Implementation: Verification and validation
- Commissioning and tuning
- Operation: Diagnostics, assessment, fault detection
- Reconfiguration and upgrading

The Royal Insurance buliding Montreal 1861-1951

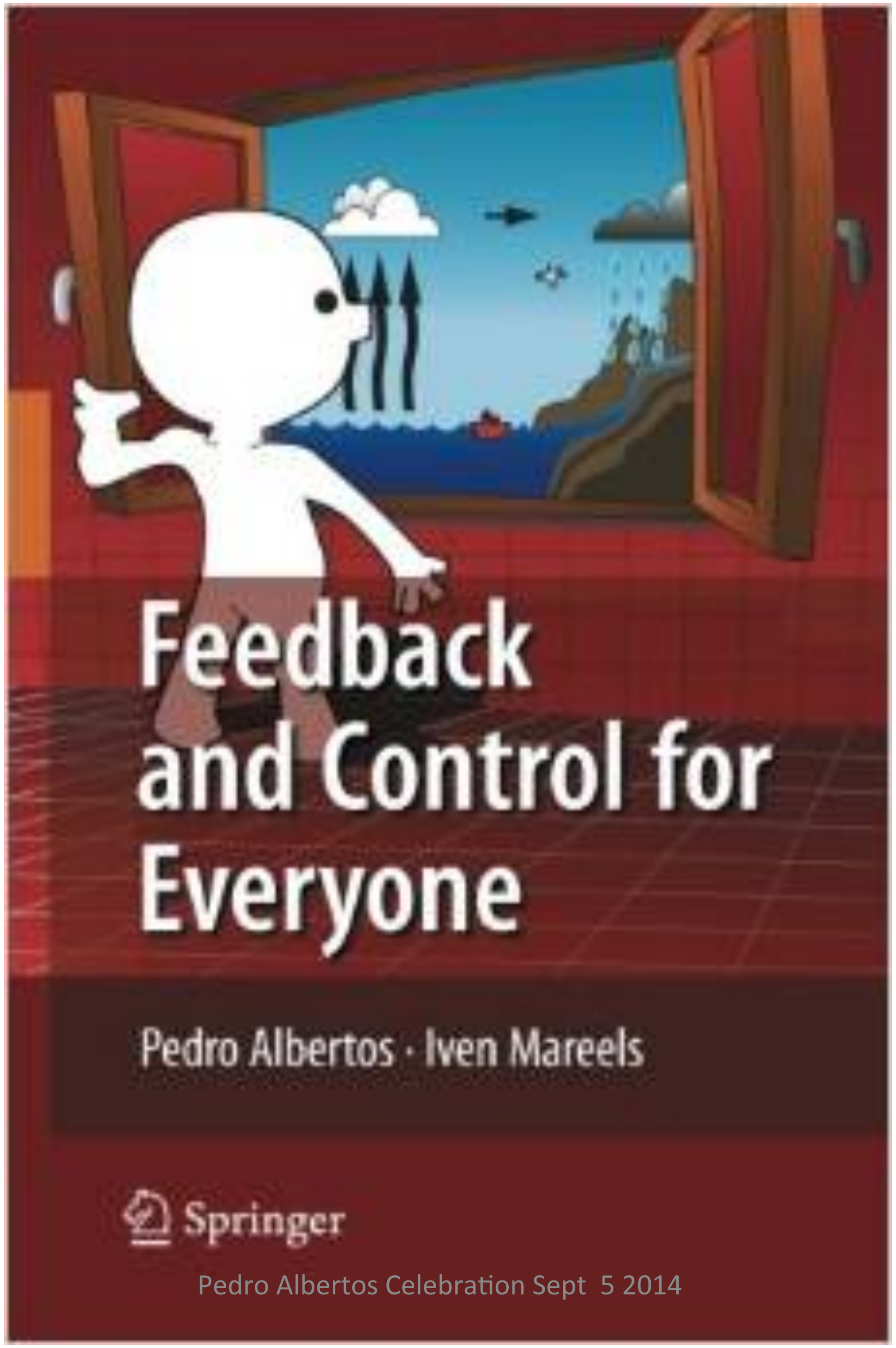
Solid foundations has been a hallmark of the control community

The Hidden Technology



- ☺ Widely used
- ☺ Very successful
- ☹ Seldom talked about
- 😐 Except when there is a disaster
- 😐 Why?

  Easier to talk about devices than ideas.
- 😐 Control inside!


Feedback and Control for Everyone
Pedro Albertos · Iven Mareels
Springer

1. Introduction

2. Tasting the Power of Feedback

3. The Field Emerges

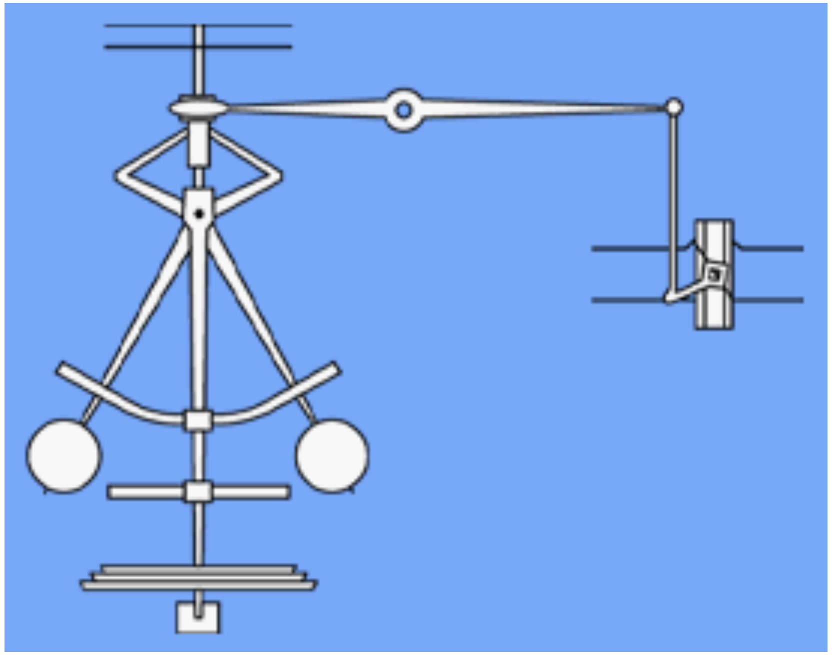
4 The Golden Age

5 A New Era?

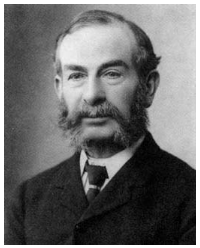
6 Summary

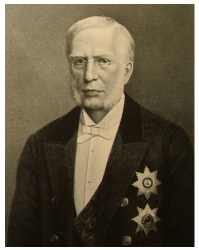
Power Generation

- Problem: Make machines rotate with constant velocity
- Solutions: Governors &Turbine controllers
- Side effects: stability theory
- Watt & Maxwel & Routh
  Stodola & Hurwitz
  Vyshnegradski, Lyapunov
  Tolle's textbook 1905






Process Control

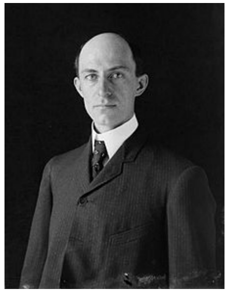
- Problem: Keep pressure, temperature and concentration constant

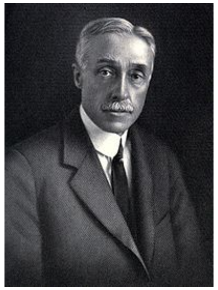
- Solution: The PID controller
- Side effects: Industrial standard system, sensors, valves, controllers, communication.
- Ziegler-Nichols tuning rules 1942

Flight Control

- Problem: How to fly?
- Solution: Understand dynamics. Wright Brothers: Focus on maneuverability, stabilize with manual control
- Side effects: Autopilots, flight dynamics

Sperry 1914





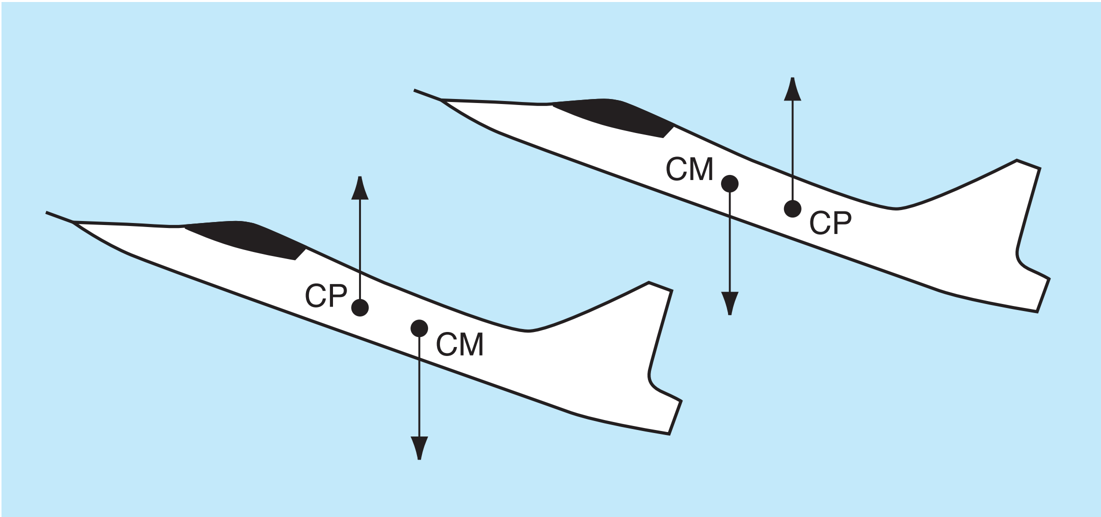
Autonomy flight 1947

Wilbur Wright 1901

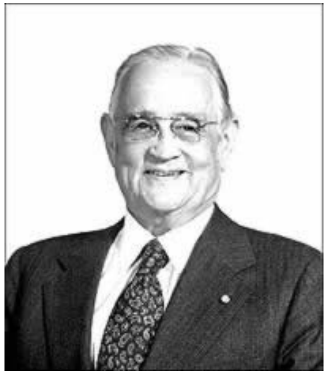
We know how to construct airplanes.
Men also know how to build engines. Inability to balance and steer still confronts students of the flying problem. When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance

Wilbur Wright Western Society of Engineers 1901

Stability and Manoeverability



- Wright brothers: unstable but maneuvrable aircraft
- JAS Gripen unstable at subsonic speed, stable in supersonic speed
- Nicholas Minorsky: *It is an old adage that a stable ship is difficult to steer*



Draper on Wright

The Wright Brothers rejected the principle that aircraft should be made inherently so stable that the human pilot would only have to steer the vehicle, playing no part in stabilization. Instead they deliberately made their airplane with negative stability and depended on the human pilot to operate the movable surface controls so that the flying system - pilot and machine - would be stable. This resulted in increased manoeuvrability and controllability.

The 43rd Wilbur Wright Memorial Lecture before the Royal Aeronautical Society, May 19 1955.

Birds

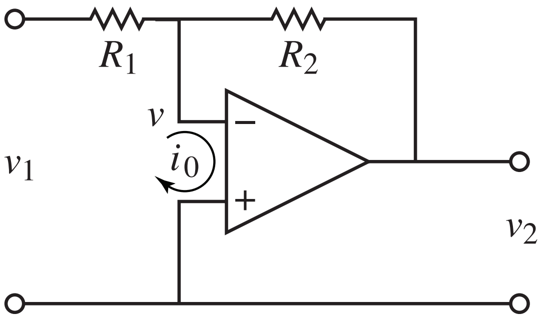
advantages of instability

The earliest birds pterosaurs, and flying insects were stable. This is believed to be because in the absence of a highly evolved sensory and nervous system they would have been unable to fly if they were not stable. To a flying animal there are great advantages to be gained by instability. Among the most obvious is manoeuvrability. It is of equal importance to an animal which catches its food in the air and to the animals upon which it preys. It appears that in the birds and at least in some insects the evolution of the sensory and nervous systems rendered the stability found in earlier forms no longer necessary.

John Maynard Smith The Importance of the nervous sytem in the evolution of aimal flight.
Evolution, 6 (1952) 127-9.

Telecommunication

- Problem: Phone communication over long distances? How to make a good amplifier from bad components (vacuum tubes)
- Solution: The feedback amplifier (Black)
- Side effects: Stability and design theory (Nyquist, Bode)



$$\frac{v_2}{v_1} = -\frac{kR_2}{R_1 + R_2 + kR_1} \approx -\frac{R_2}{R_1}$$

ASEA on Nyquist

We had designed controllers by making simplified models, applying intuition and analyzing stability by solving the characteristic equation. (At that time, around 1950, solving the characteristic equation with a mechanical calculator was itself an ordeal.) If the system was unstable we were at a loss, we did not know how to modify the controller to make the system stable. The Nyquist theorem was a revolution for us. By drawing the Nyquist curve we got a very effective way to design the system because we know the frequency range which was critical and we got a good feel for how the controller should be modified to make the system stable. We could either add a compensator or we could use extra sensor.

Free translation from seminar by Erik Persson ABB in Lund 1970.

The Power of Feedback

- Accurate systems from imprecise components (Feedback amplifier)
- Reduce effects of disturbances and component variations Power systems, Process control)
- Regulate, stabilize and shape behavior (Aerospace)
- Drawbacks

  Risk of instability

  Sensor noise is fed into the system

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The Scene of 1940

Widespread use of control in many fields

- Power generation and distribution
- Process control
- Autopilots for ships, aircrafts and torpedos
- Missile guidance and control
- Telecommunications

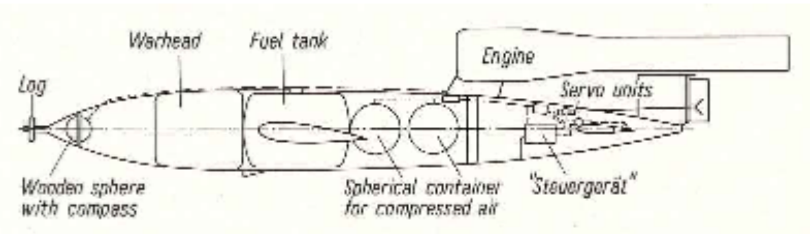
The similarities were not recognized

The Discipline Emerges

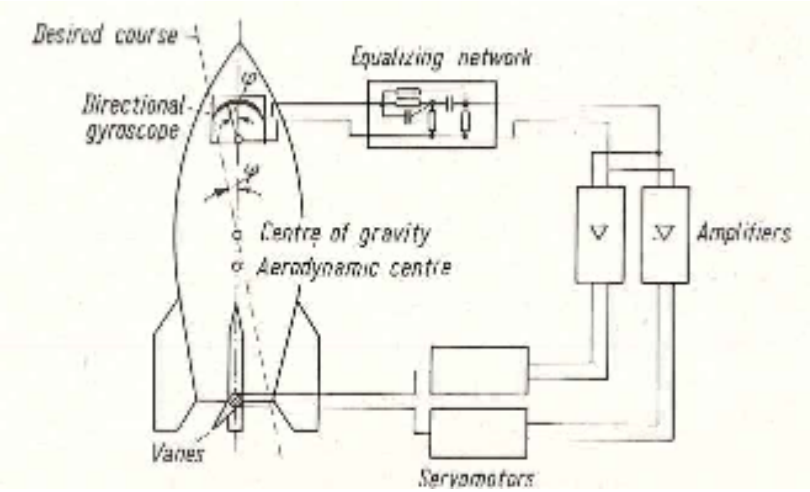
- Drivers: The war effort, gunsights, radar,..
- Concepts: Feedback, feedforward
- Design tools: Block diagrams, transfer functions
- Simulation: Analog computing
- Implementation: Analog computing
- Holistic view of theory and applications

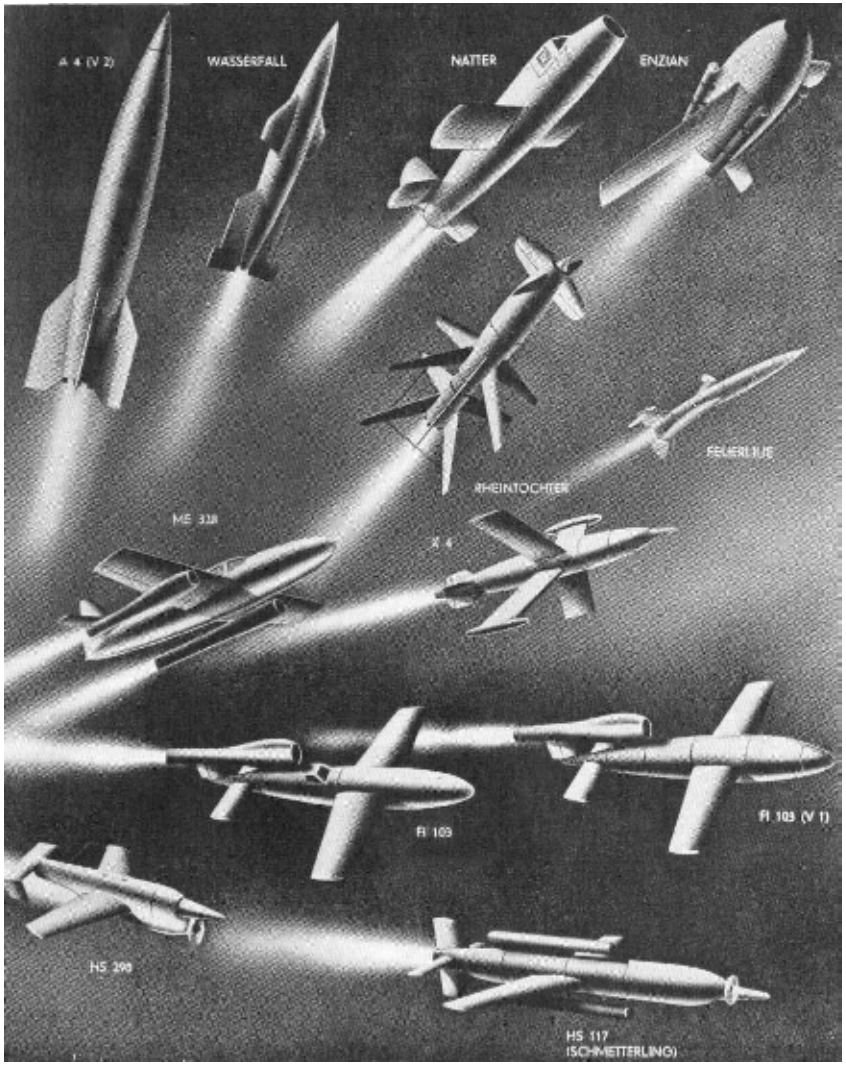
German Missiles

V1 Cruise missile

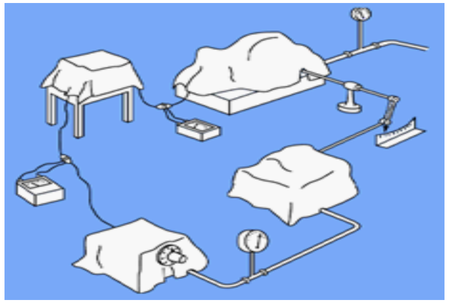


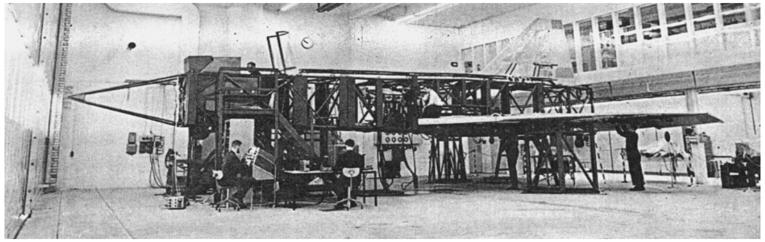
V2 Ballistic missile

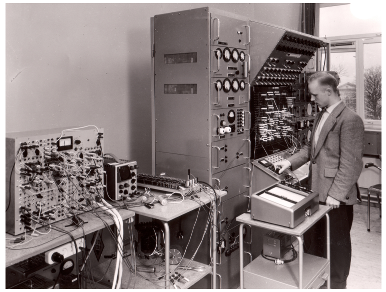




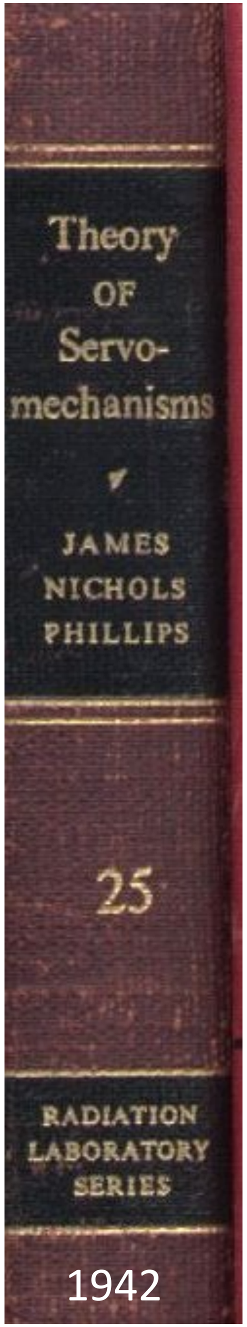
Servomechanisms







- Theory
  - Complex variables
  - Laplace Transforms
- System Concepts
  - Feedback
  - Feedforward
- Design
  - Frequency Response
  - Graphical Methods
- Analog simulation
- Implementation



Servomechanism Theory

Hubert M. James

Professor of Physics Purdue University

Nathaniel B. Nichols

Director of Research Taylor Instrument Companies

Ralph S. Phillips

Associate Professor of Mathematics University of Southern California

Office of Scientific Research and Development

National Defence Research Committee

Control was multidisciplinary from the beginning

Consequences

Education

Application

Industrialization

Organisation

Journals

Conferences

IFAC

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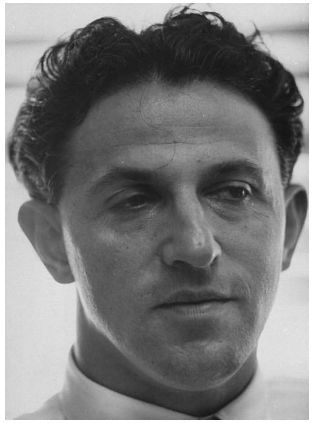
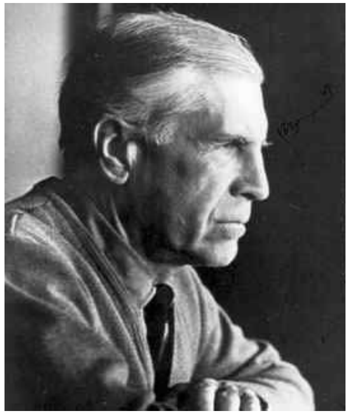
The Golden Age

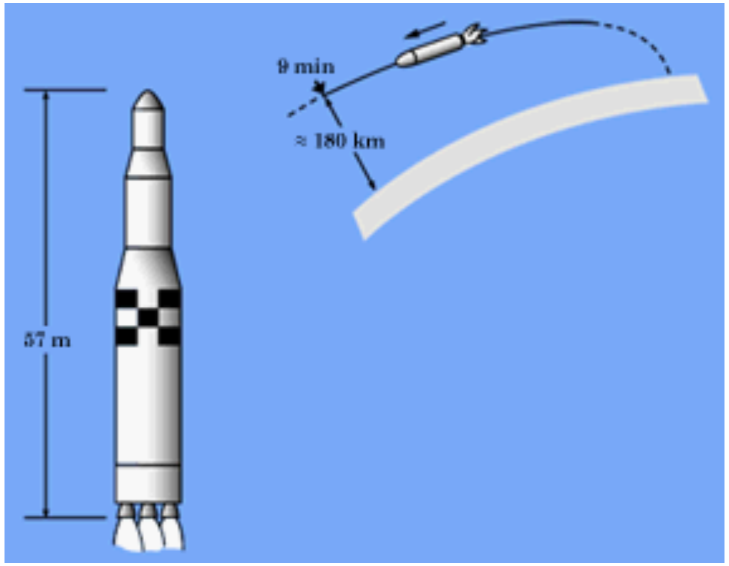
- Drivers: space, computer control, mathematics
- Rapid growth of subspecialities:
  Optimal, stochastic, nonlinear, ...
- Computational tools
- Impressive development of theory
  Stellar scientists
- Holistic view was lost!

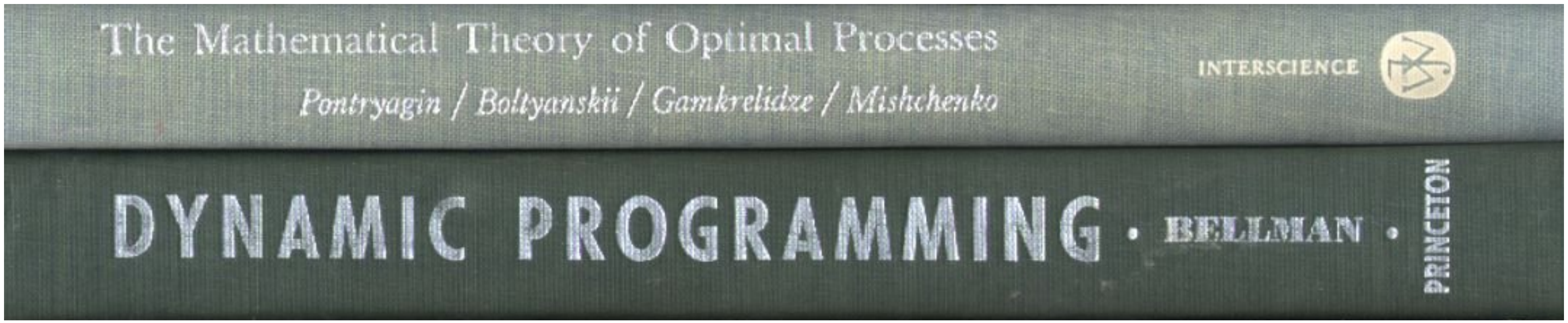
Optimal Control

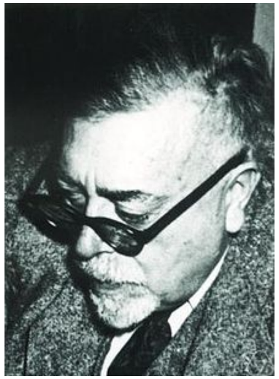
- Hamilton, Jacobi, Bellman 1957
- Euler, Lagrange, Pontryagin 1962







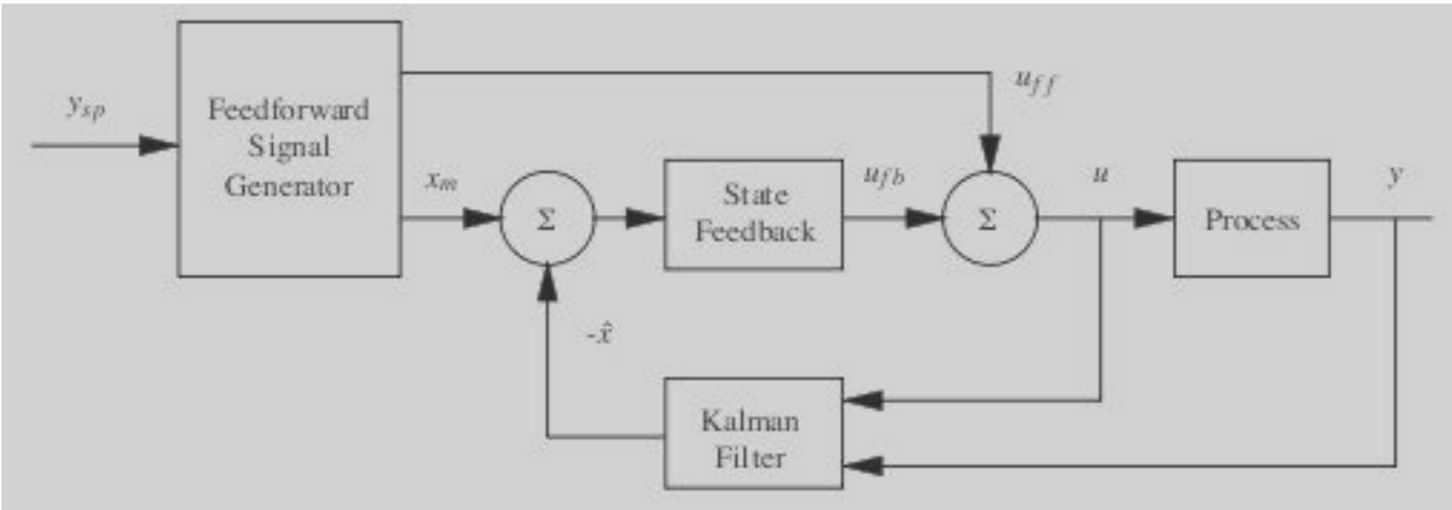




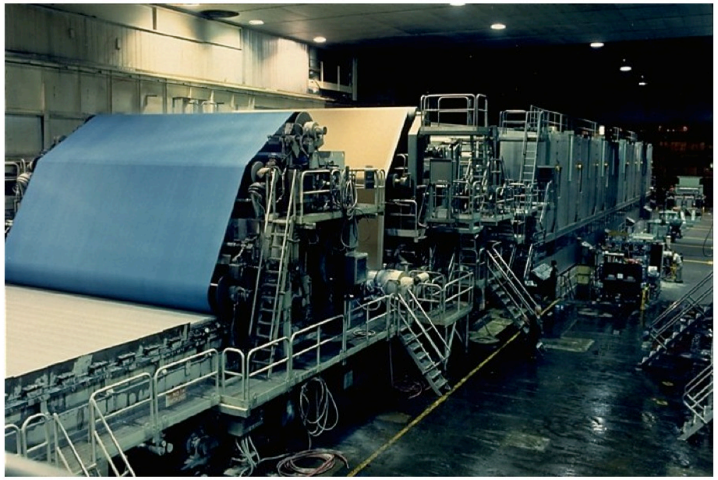
Kalman Filtering

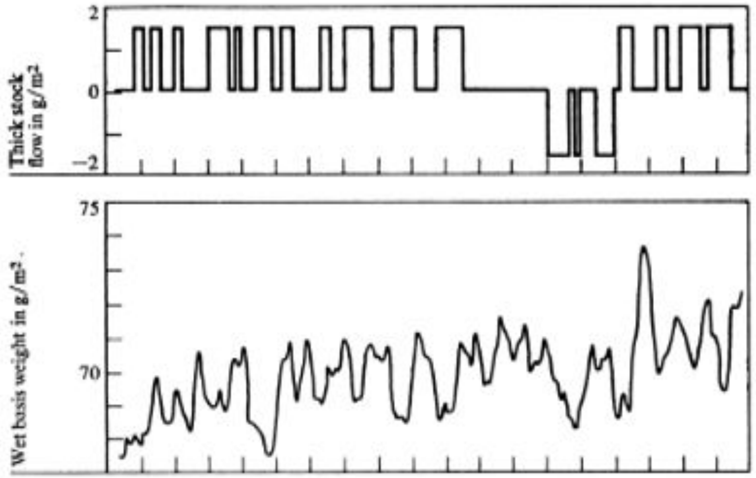
Kalman 1961:

- Efficient way to filter signals
- Combine measurements and mathematical model to estimate process state
- New controller structure based on Kalman filter, state feedback and feedforward generator

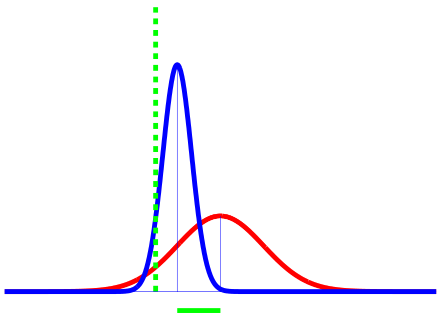


System Identification





Billerud IBM Project 1962-66
Regulation of quality variables



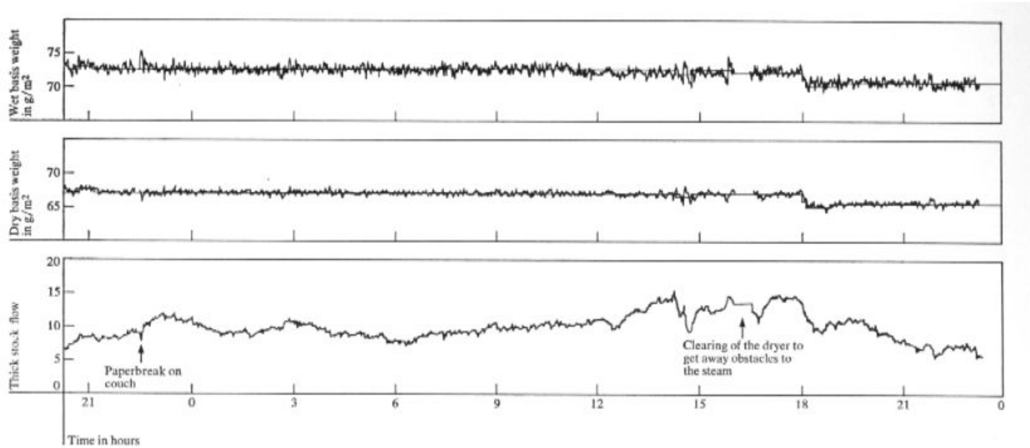
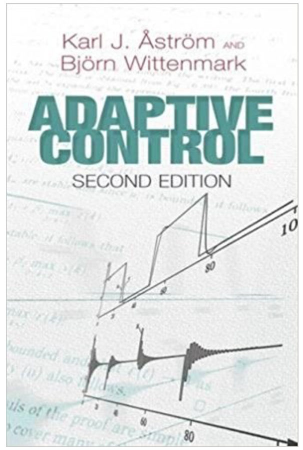


Figure 7 Results of test run with on-line control of basis weight.

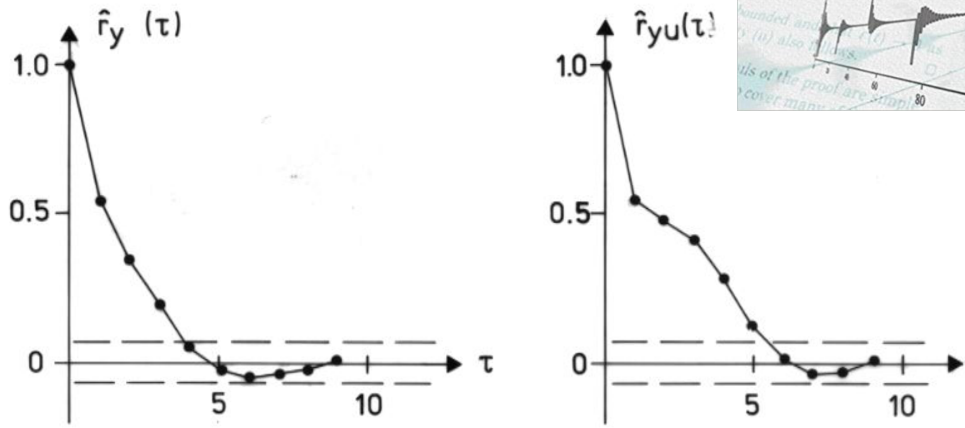
K. J. Åström and T. Bohlin. “Numerical identification of linear dynamic systems from normal operating records.” In Proc. IFAC Conference on Self-Adaptive Control Systems, Teddington, UK, 1965.

K. J. Åström. “Computer control of a paper machine—An application of linear stochastic control theory.” IBM Journal of Research and Development, **11:4**, pp. 389–405, 1967.

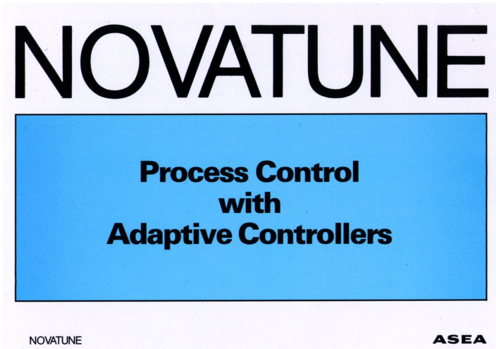
Adaptive Control



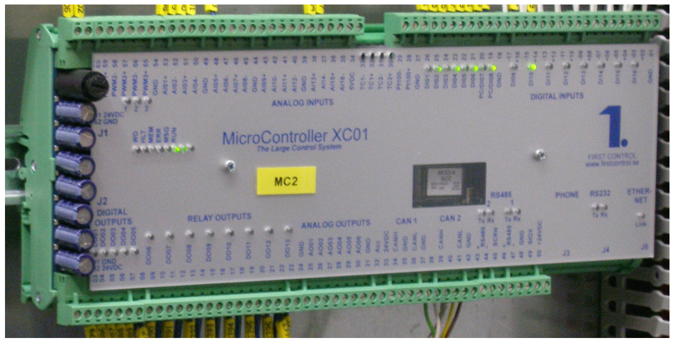
- The self-tuning regulator
- Moving average control
- Theory (insight)
- Case studies
- Adaptive feedforward
- Industrial experience
- Harris index



Borisson Syding 1975
Network control 2000 km



Winner of IEEE CSS Control Technology Award
FIRST CONTROL SYSTEMS AB

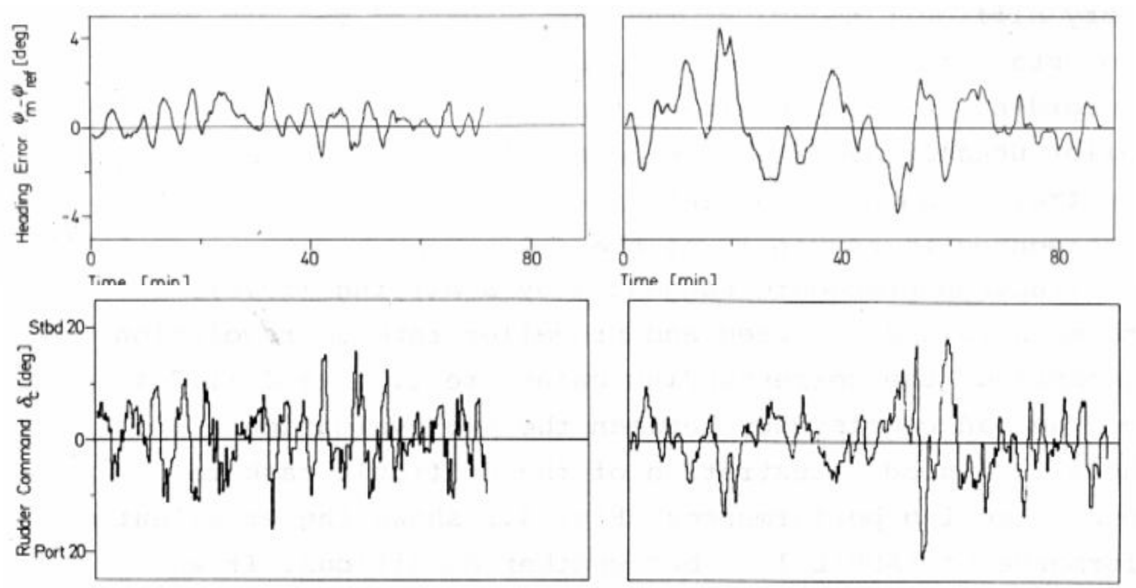


Adaptive Ship Steering

Kockumation

NORTHROP GRUMMAN
DEFINING THE FUTURE

Adaptive PID



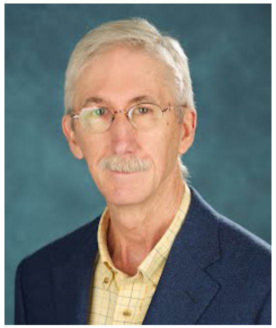
- ➢ 3 % reduction in fuel consumption
- ➢ Physics based configuration

C. G. Källström, K. J. Åström, N. E. Thorell, J. Eriksson, and L. Sten. “Adaptive autopilots for tankers.” Automatica, **15**, pp. 241– 254, 1979.

Robust Control

- Classic Bode: non-minimum phase is important
- State space: reachability and observabilty
  Robustness of state feedback $g_m = \infty$, $p_m = 60^o$
  Non-robustness of output feedback
- Robust Control: Youla, Zames, 4 author paper:
  Doyle, Glover, Khargonekar, Francis
- Fundamental limitations (back to Bode)
  Delays and RHP poles are important



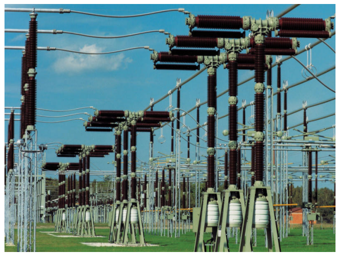


Applications

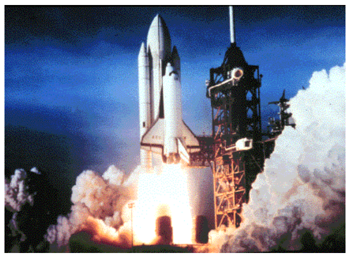
Traditional fields expanding and new fields emerging

- Power Systems
- Process Control
- Aerospace
- Automotive
- Buildings
- Robotics

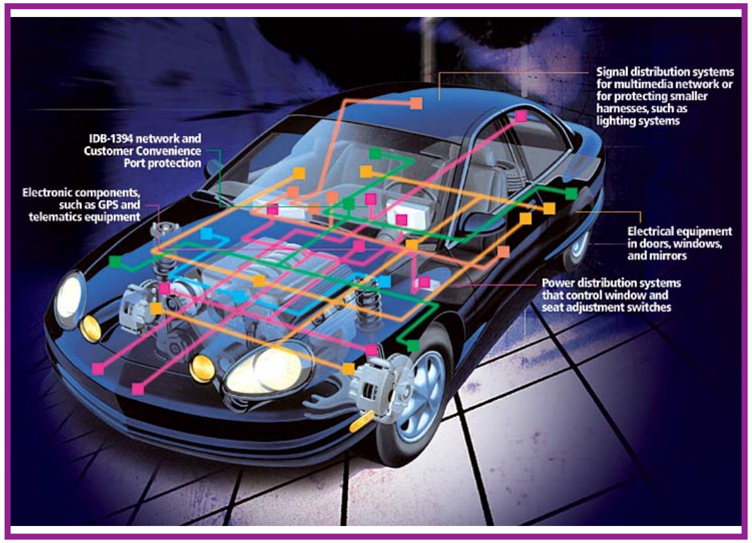
- Computer Systems
- Global enterprise control
- Advertising
- Mobile phones
- Art and games
- Physics and Biology







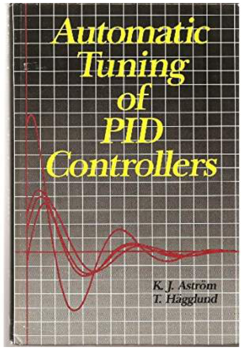

Automotive



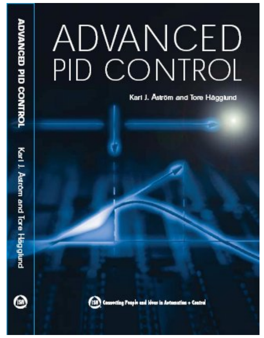
- ➢ Strong technology driver

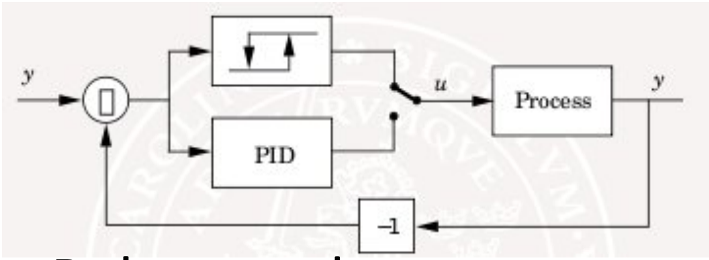
  Microcontroller, Autosar

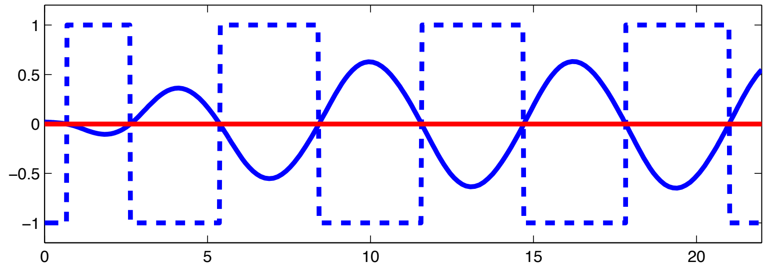
- ➢ Power trains
- ➢ Adaptive cruise control
- ➢ Collision avoidance
- ➢ Traction control
- ➢ Lane guidance assistance
- ➢ Traffic flow control
- ➢ Platooning

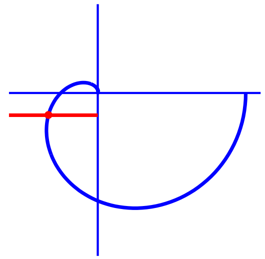


Relay Autotuning



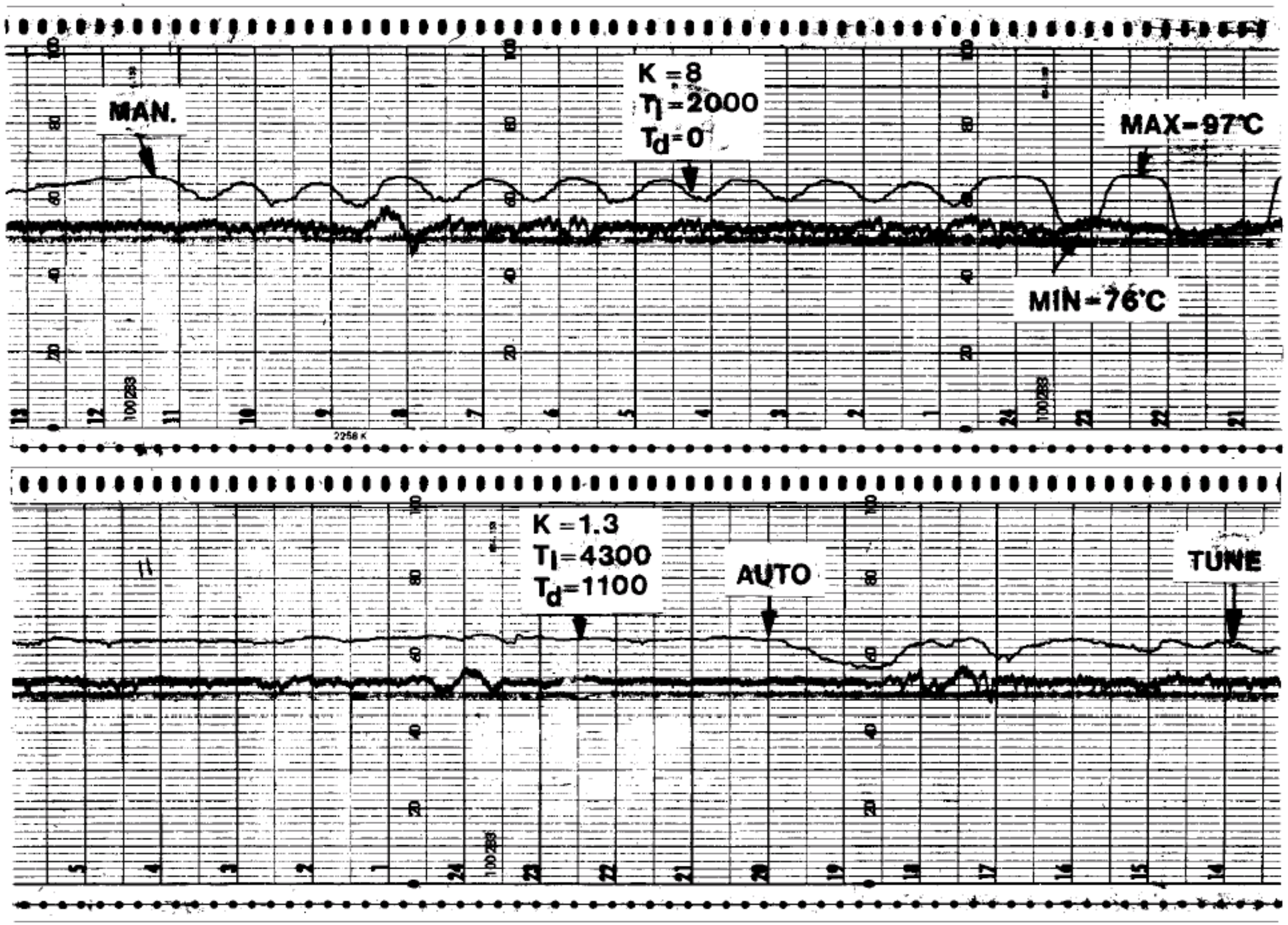






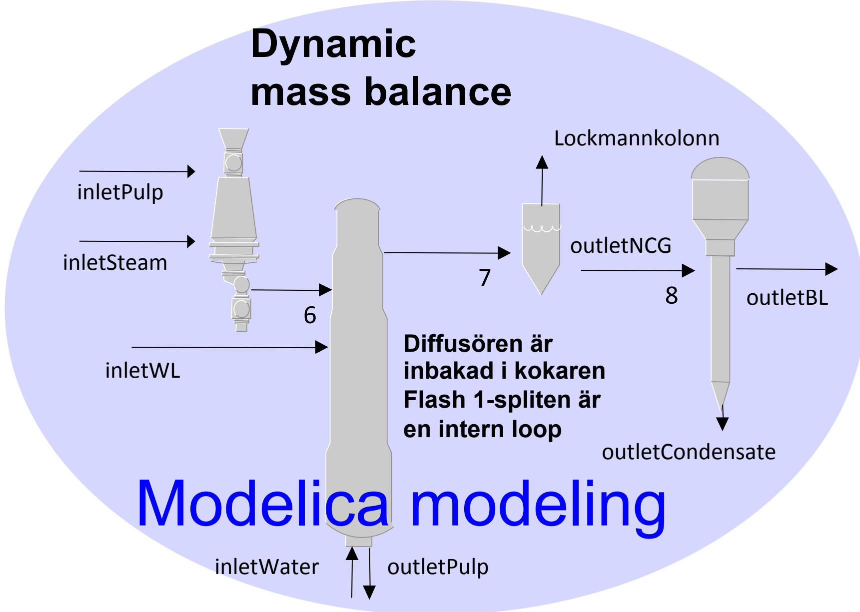
- Robust and easy to use
  - Well adapted to users
  - One-button tuning
  - Automatic generation of gain schedules + adaptation
- Many versions
  - Stand alone, DCS, PLC
- Large numbers
- Excellent industrial experience

K. J. Åström and T. Hägglund. "Automatic tuning of simple regulators with specifications on phase and amplitude margins." Automatica, **20**, pp. 645–651, 1984.

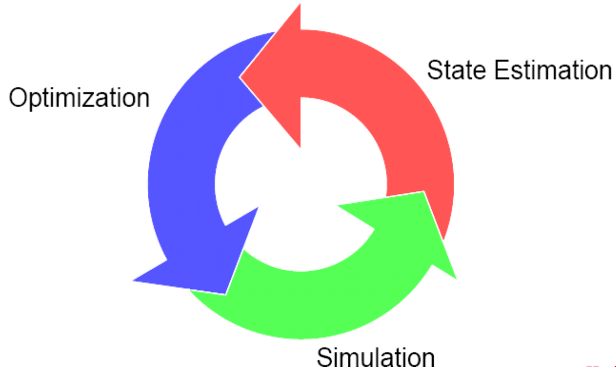


All controllers should have facilities for automatic tuning!

Mill Wide Control

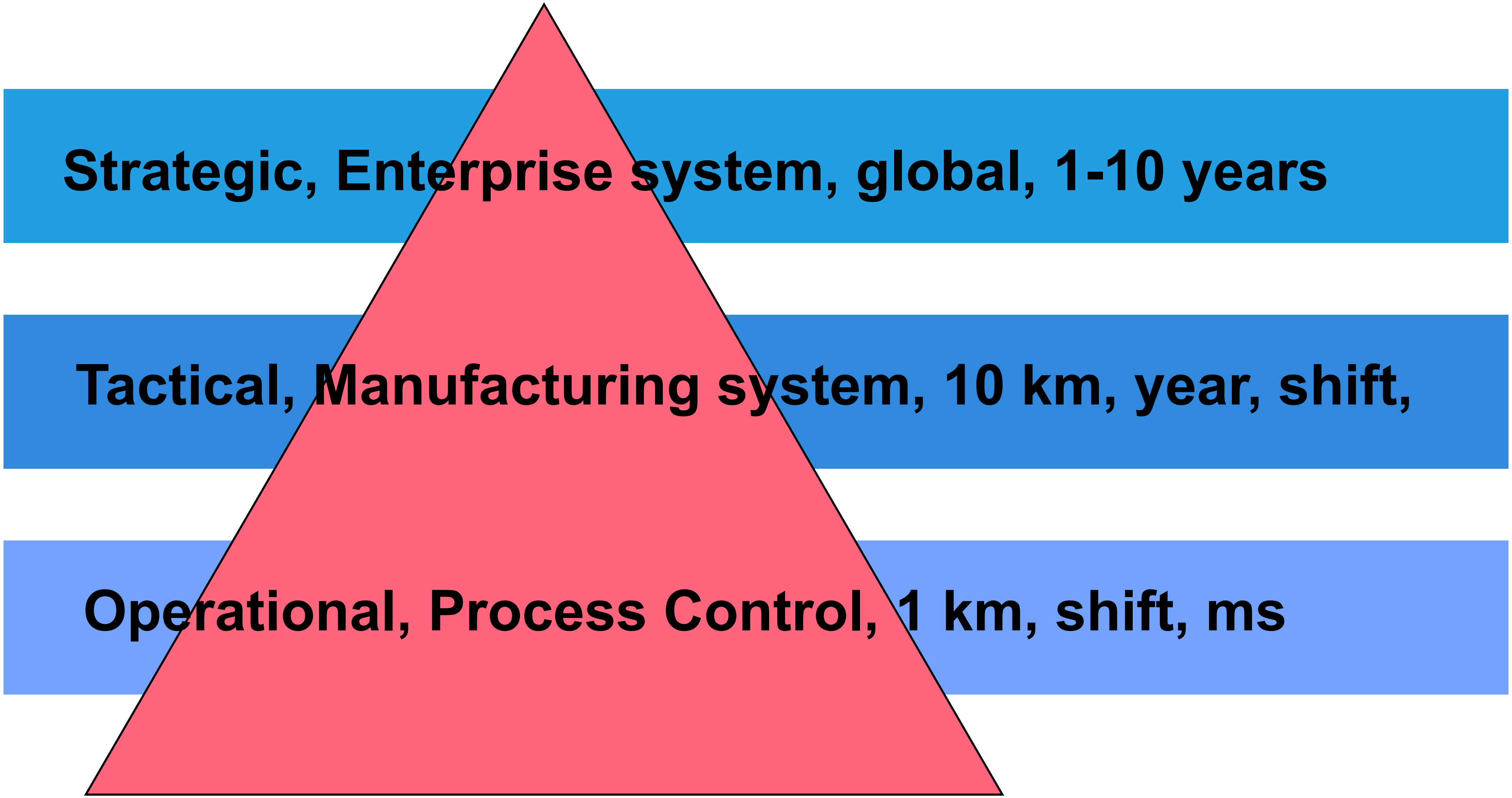


25 Production units
38 Buffer tanks
250 Streams
250 Measurements
2500 Variables



Slide from Alf Isaksson ABB

Global Enterprise Control



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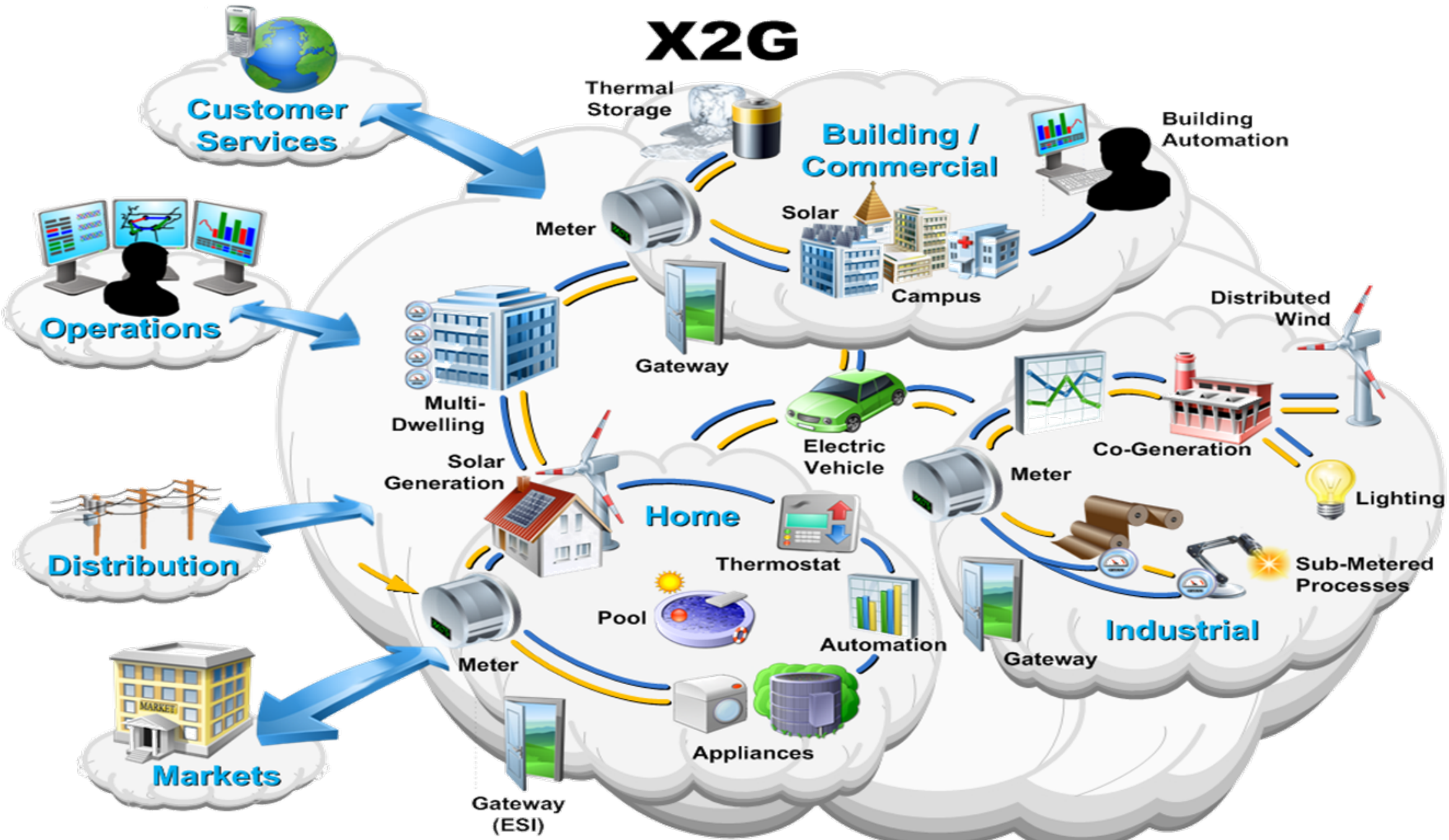
A New Era?

- Increased use in traditional fields and new emerging applications
- Drivers: Complex networked systems, physics, biology, social networks
- Autonomy: Adaptation, Learning, Cognition
- Sensor and actuator rich systems (vision)
- Provable safe design and reconfiguration
- Recover the holistic view

Smart Grids


X2G
Customer Services
Operations
Distribution
Markets
Thermal Storage
Building / Commercial
Building Automation
Meter
Solar
Campus
Gateway
Multi-Dwelling
Distributed Wind
Electric Vehicle
Co-Generation
Meter
Lighting
Solar Generation
Home
Thermostat
Pool
Automation
Sub-Metered Processes
Industrial
Gateway
Meter
Appliances
Gateway (ESI)

Mobile Phones – Billions of Loops

1980

Ericsson Hotline 900 Pocket
Price: 5000 $
Weight: 4kg resp 630 g
Talk time: 30 min
Affordable for few

2010

Vodafone150
Price: 700 rupies ~ 13 $
Weight: 60g
Talk time: 5hours
Affordable for most

10 control loops * 10^9phones/year = 10^{10} loops

Frequency control – temperature, voltage, aging, Doppler effect

Without feedback: frequency error ~ 10 parts per million

With feedback: frequency error ~ 0.01 parts per million => 1000 times improvement

Power control and gain control – components with large dynamic range are costly

Receive power range 10^{-14}W – 10^{-5}W

Transmit power range 10^{-8}W – 1W (compare lamp versus nuclear power plant)

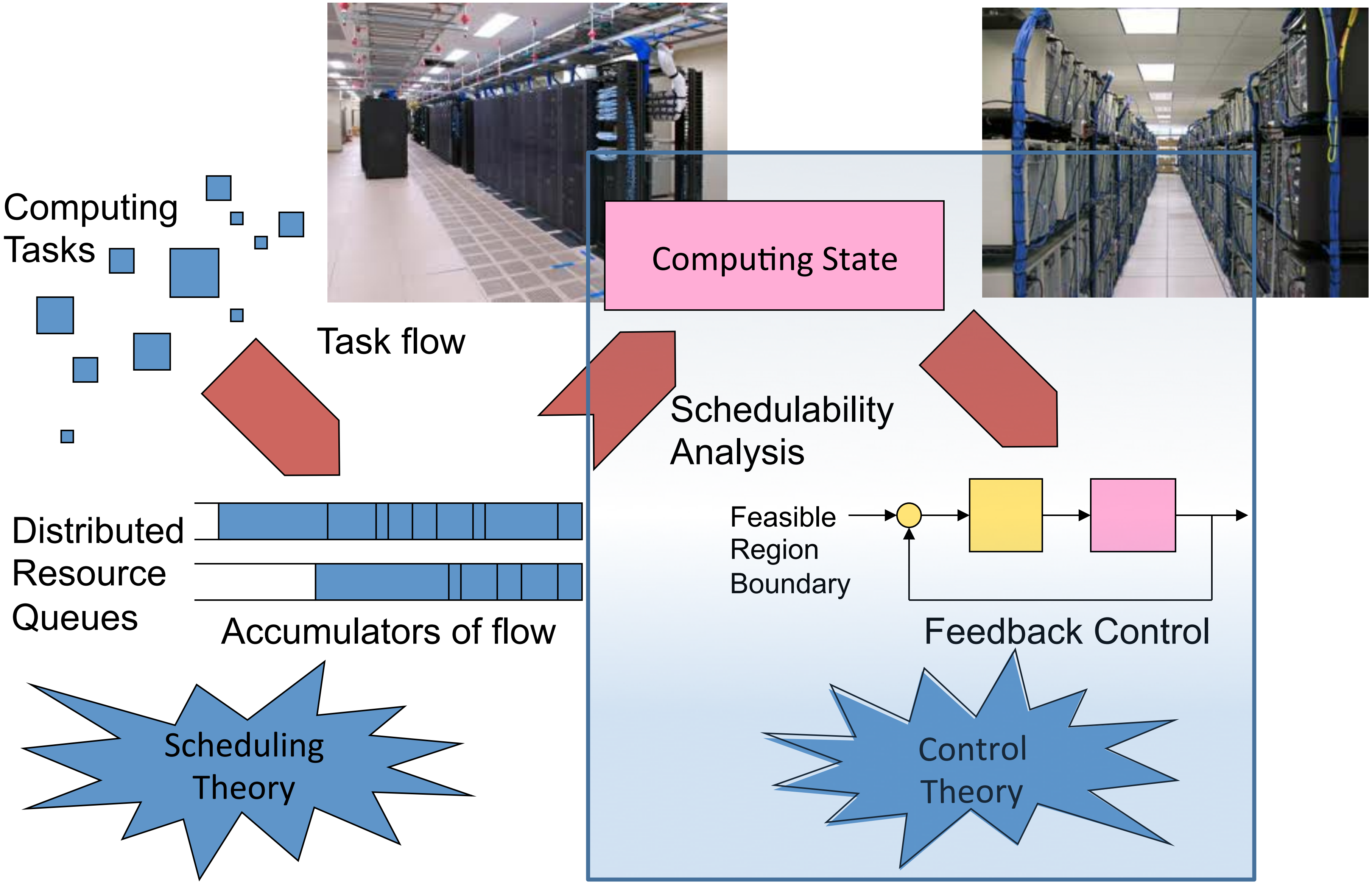
PI(D) , anti-windup, feedforward, gain scheduling

Thanks to Bo Bernhardsson

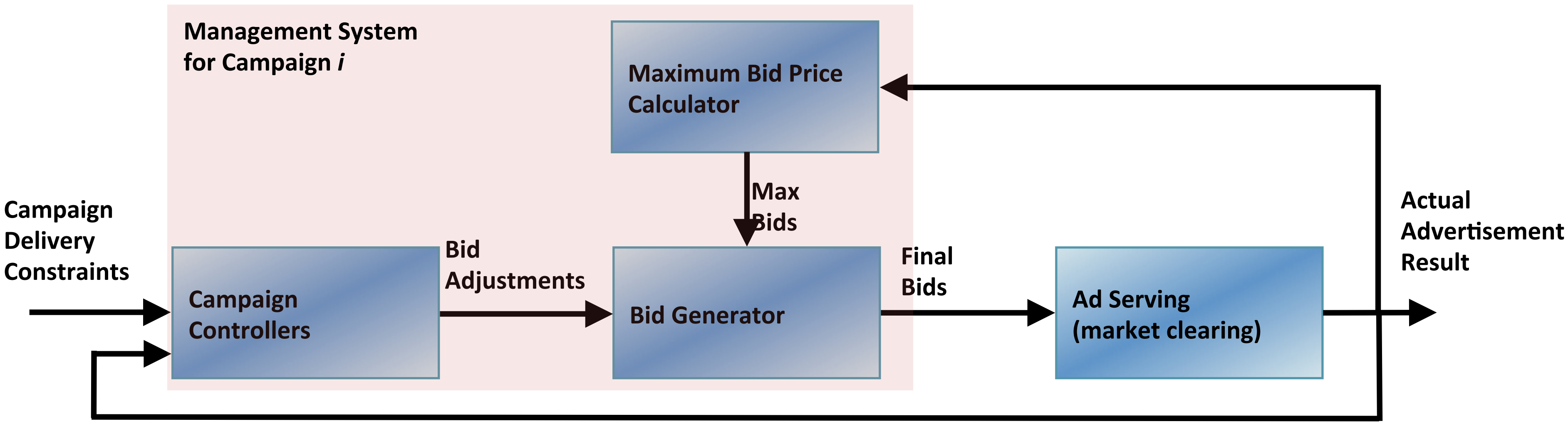
ERICSSON
TAKING YOU FORWARD

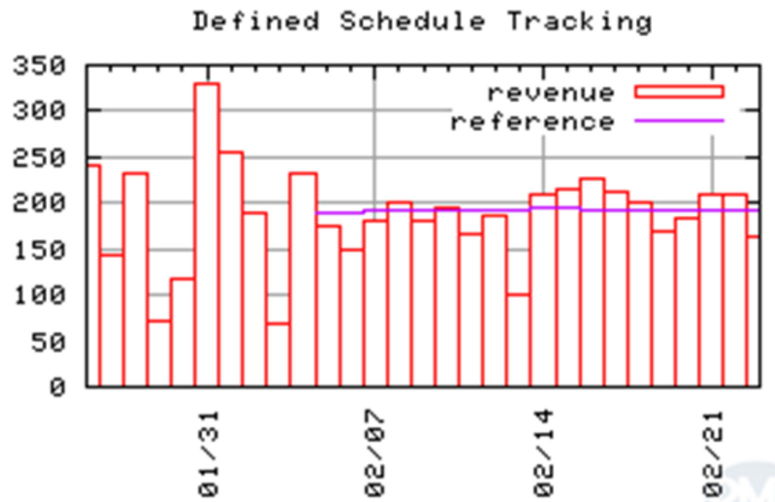
Control of Computing Systems

(Data centers, Server clusters, Data fusion)



Internet Advertisement





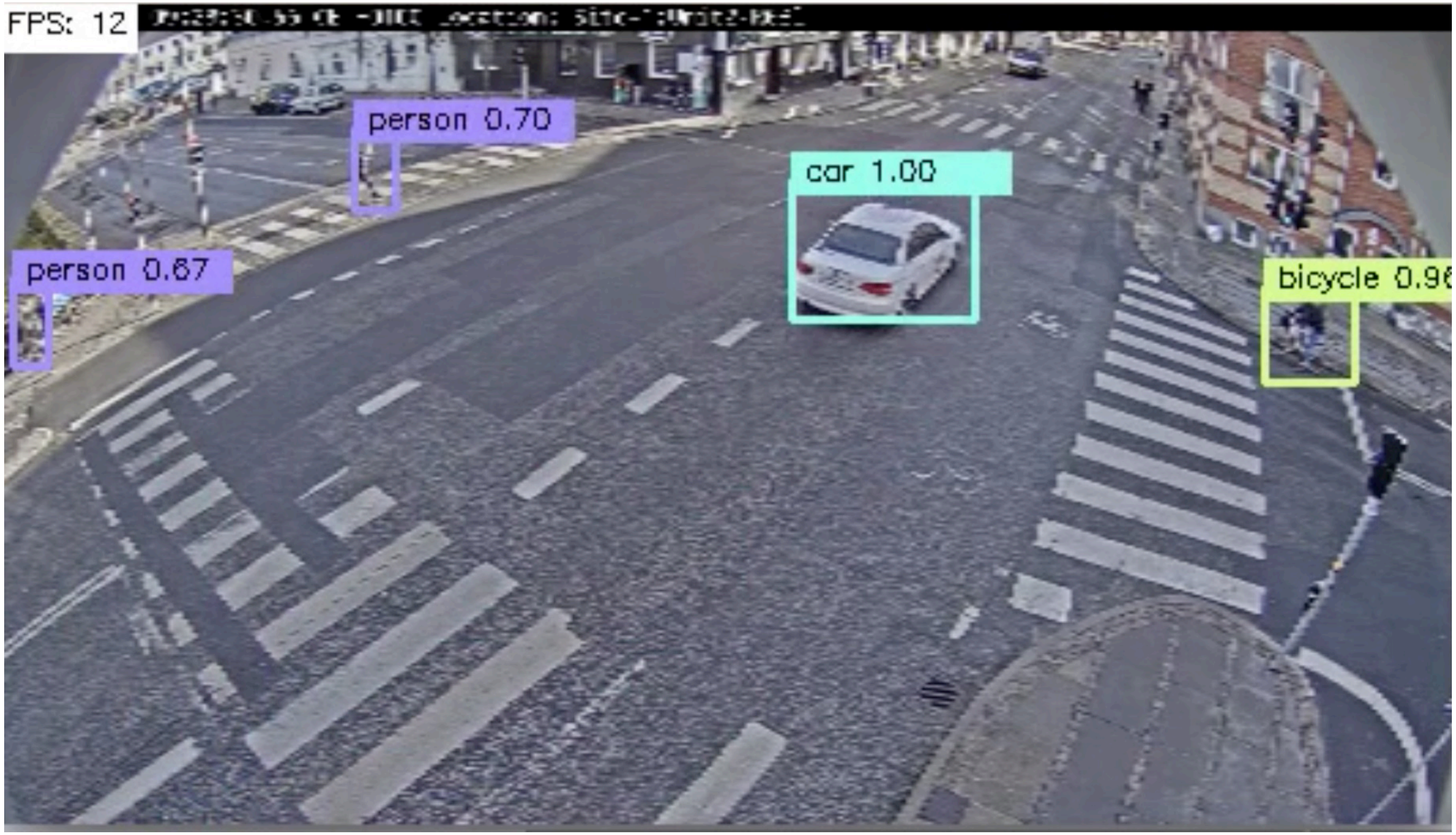
- Decentralized control
- Auction bidding

Courtesy of Niklas Karlsson

Challenges

- Complex networked systems
- Sensor and actuator rich systems
- Safe design of embedded systems
- Autonomy
- Adaptation, learning, reasoning, cognition
- High level control principles
- Biology, physics, …

Sensor-Rich Systems



Camera with deep learning algorithm can be viewed as a specialized trainable sensor

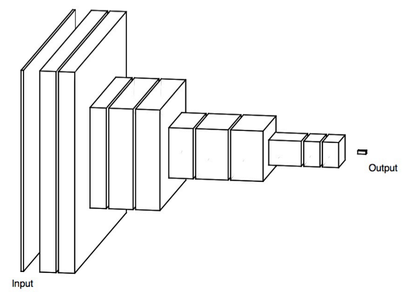
Deep Learning

- Many layers
- Convolution C

$$y(i,j,k) = w_o(k) + \sum_u \sum_v \sum_l x(i-u, j-v, l) w(u,v,l,k).$$

- Maxpooling, downsampling M
- Rectified Linear Unit ReLU

$$y(i,j,k) = \max\left(x(i,j,k), 0\right).$$



Y=S∘C∘R∘C∘M∘R∘C∘M∘R∘C∘M∘R∘C

- Softmax S

$$y(i,j,k) = \frac{e^{x(i,j,k)}}{\sum_l e^{x(i,j,l)}}$$

Autonomy

- Adaptation
- Learning
- Cognition
- Safety
- Diagnostics
- Maintenance
- Reconfiguration

- Manufacturing
- Process Control
- Distribution

Airbus to run parcel-delivery drone trial, and maybe one for flying taxis in S'pore

Airbus Helicopters signed a contract with the Civil Aviation Authority of Singapore last year to test a drone parcel-delivery service on the campus of the National University of Singapore in mid-2017.
PHOTO: ISTOCKPHOTO

By Soon Weilun
soonwl@sph.com.sg
@SoonWeilunBT

Singapore

AVIATION giant Airbus said it will reveal more details "in the coming months" about an unmanned parcel-delivery drone trial in Singapore, one that could be extended to transporting passengers too.

Its comments come a day after the city-state's Ministry of Transport told *The Business Times* that it is talking to some firms about trying out human-carrying drones as a mode of transport. No additional details were shared then.

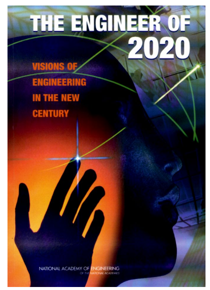
When approached by BT and asked whether it was exploring such a possibility in Singapore, Airbus said: "Airbus is heavily involved in studying the future of urban mobility with several projects underway, including the Skyways initiative in Singapore.

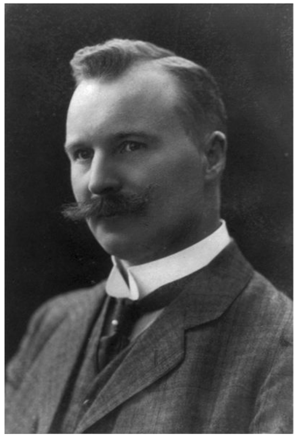
Continued on Page 2

The Systems Perspective

In the past steady increases in knowledge has spawned new microdisciplines within engineering. However, contemporary challenges – from biomedical devices to complex manufacturing designs to large systems of networked devices – increasingly require a systems perspective

NAE The Engineer of 2020





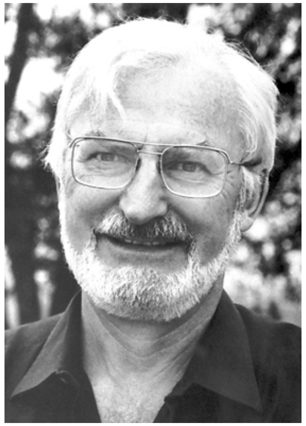
Physics

- Nobel prizes in physics with control connections

  Gustaf Dalén 1912

  Rubbia and van der Meer 1984

  Binning and Rohrer 1986



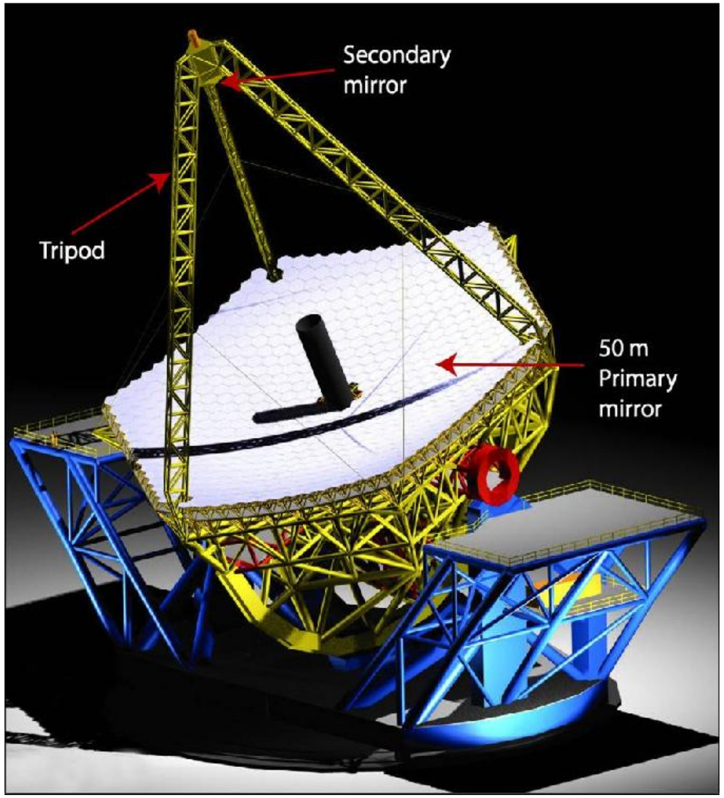
- Quantum and molecular systems
- Shear flow turbulence (gain not instability)

The 1912 Nobel in Physics

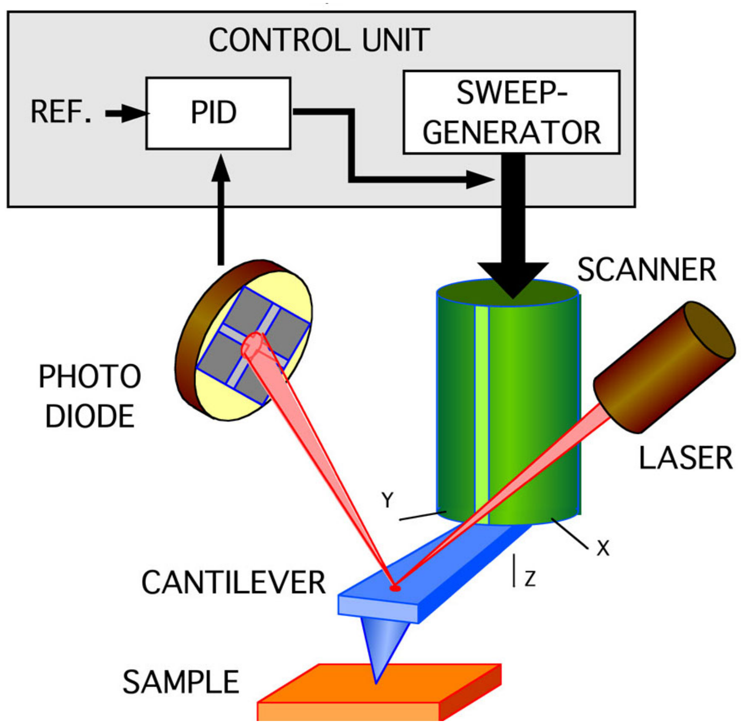
- Many strong candidates: Kammerlingh Onnes (1913), Max Planck (1918), Albert Einstein (1921), Walther Nernst (1920), Henri Poincaré (†), ...
- Unanimous physics committee, chaired by professor Gustaf Granquist Uppsala, proposed Kammerlingh Onnes
- Erik Johan Ljungberg CEO of Stora Kopparberg, member of the class for economic, statistical and social sciences nominated Dahlén: **For his invention of automatic regulators for use in conjunction with gas accumulators for illuminating lighthouses and buoys**
- Ljungberg's proposal won after intense debate with the vote 37-28

Instruments Giga to Nano

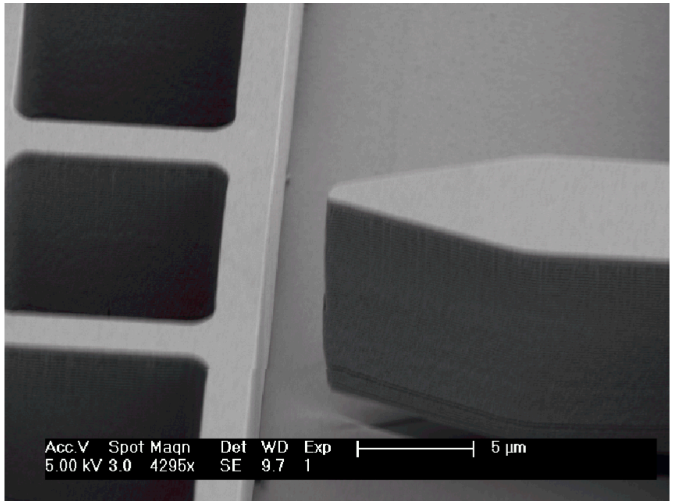
Adaptive Optics

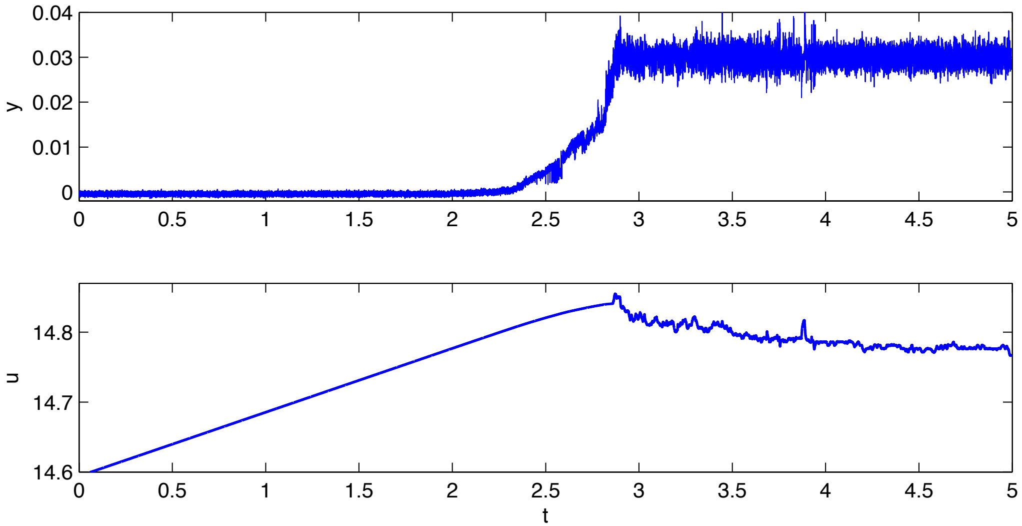


Atomic Force Microscope



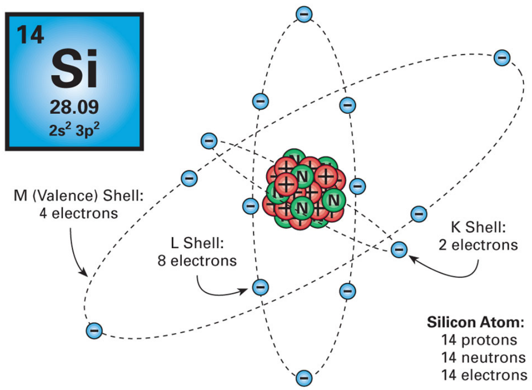
Control with Atomic Precision



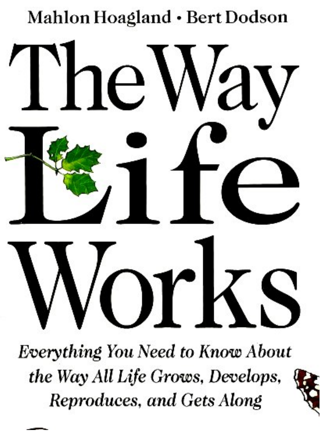


Standard deviation σ =2.3 mV = 0.16 Å = 16 pm

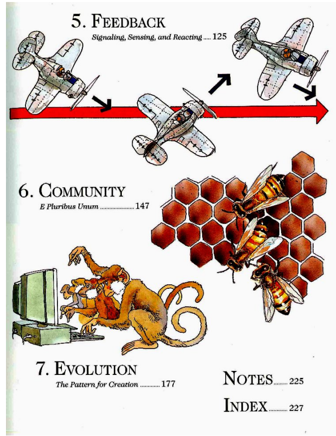
- σ Brownian motion 99.7 %
- σ Johnson-Nyquist 0.17 mV = 0.012 Å 7 %
- σ tunneling 2 %
- Radius of silicon atom 1.1 Å = 110 pm



L.A. Oropeza-Ramos, N. Kataria, C.B. Burgner, K.J. Åström, F. Brewer and K.L. Turner. Noise Analysis of a Tunneling Accelerometer base on state space stochastic theory. Hilton Head 2008.



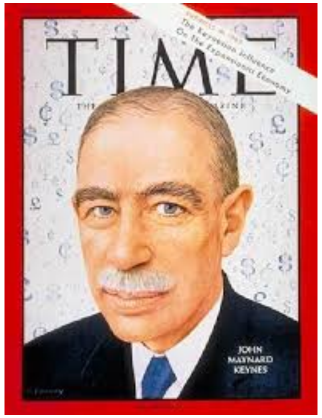
Biology



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.

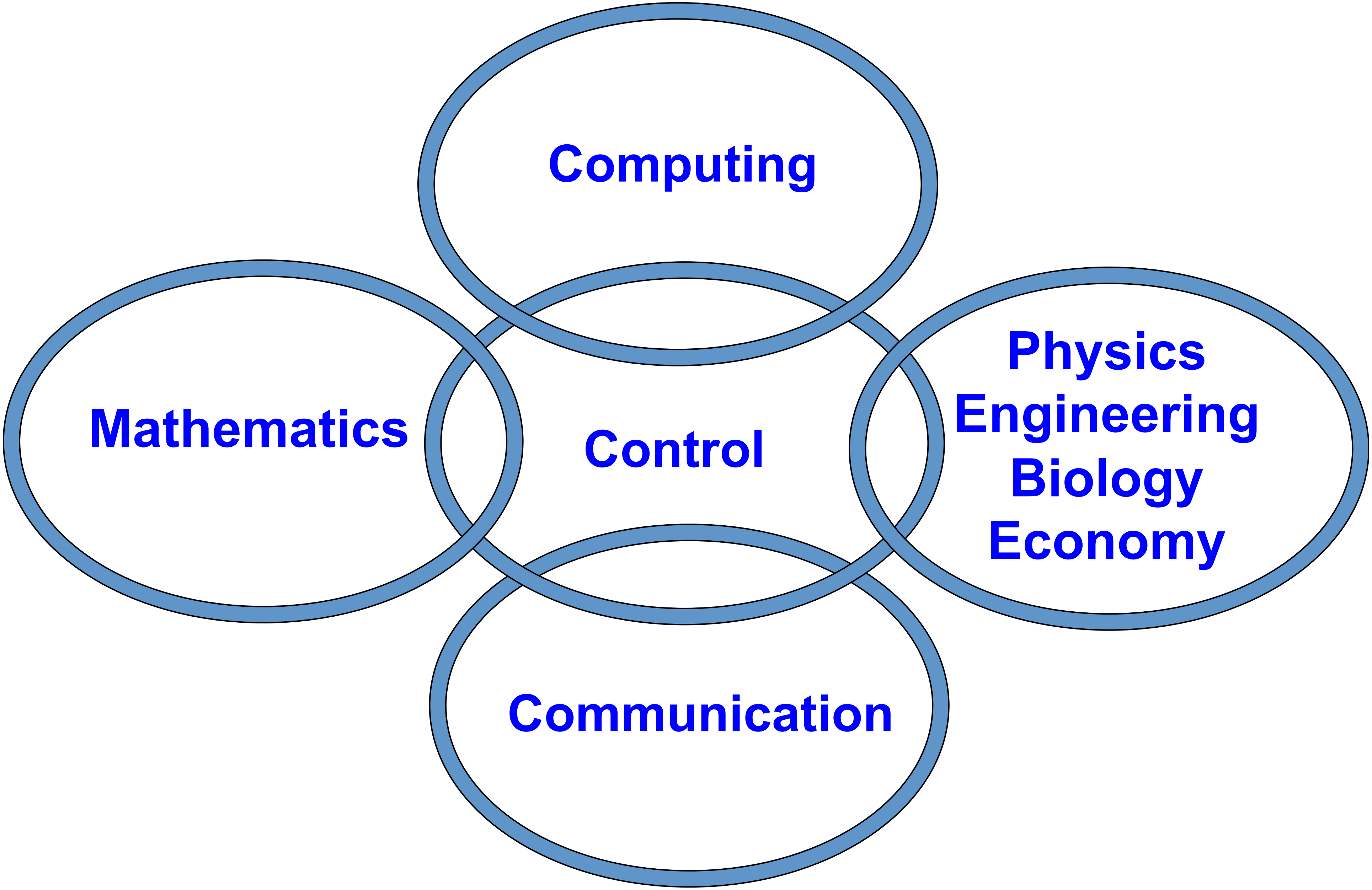
Mahlon B Hoagland and B Dodson The Way Life Works Three Rivers Press 1998



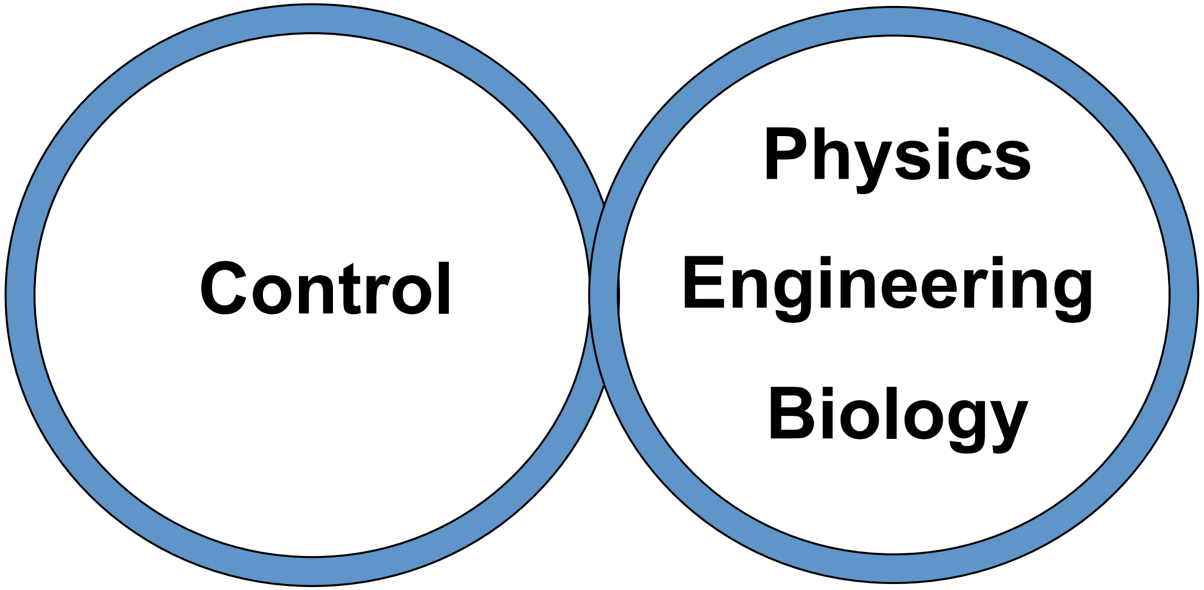
Economics

We have magneto trouble, said John Maynard Keynes at the start of the Great Depression: most of the economic engine was in good shape, but a crucial component, the financial system, wasn't working. He also said this "We have involved ourselves in a collossal muddle, having blundered in the control of a delicate machine, the working of which we do not understand" Both statements are as true now as they were then

Paul Krugman The Return of Depression Economics. Penguin 2008


Computing
Mathematics
Control
Physics
Engineering
Biology
Economy
Communication

The Physics Barrier



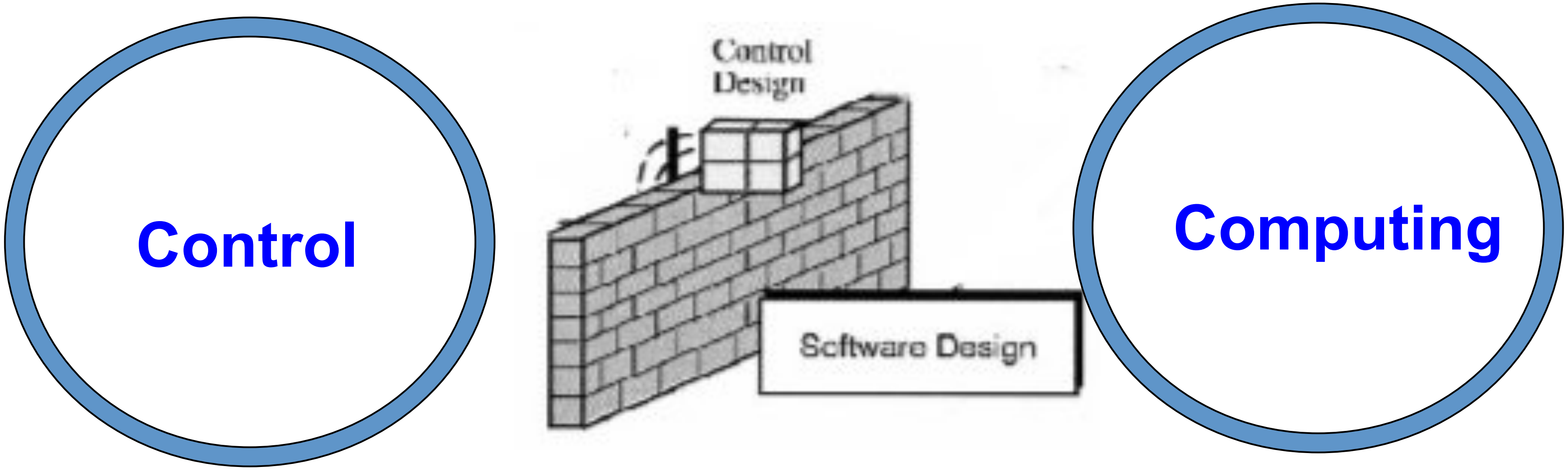
Blockdiagrams ODEs

Mass, energy, momentum

Block diagrams unsuitable for serious physical modeling

Modeling for control - Modelica

The CS Barrier

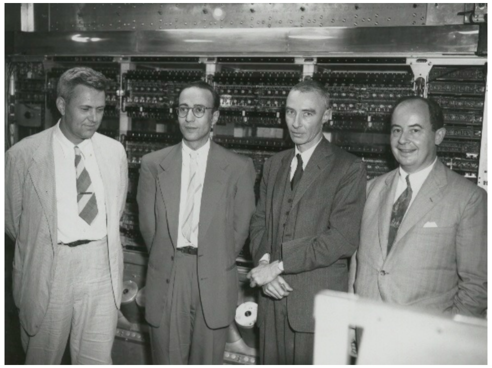


Feedback,Stability, ODE, PDE
Moderate complexity
Robustness

Logic, languages, DES,FSM
Formal methods, abstractions
Architecture

The controller

Computing



- Vannevar Bush 1927. Engineering can progress no faster than the mathematical analysis on which it is based. Formal mathematics is frequently inadequate for numerous problems, a mechanical solution offers the most promise.

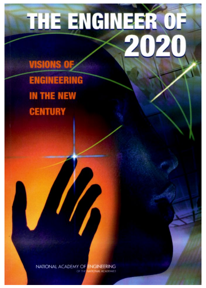
- Herman Goldstine 1962. When things change by two orders of magnitude it is revolution not evolution.

- Gordon Moore 1965: The number of transistors per square inch on integrated circuits has doubled in approximately 18 months. A revolution every 10 years!

- Strong potential, but so far algorithms and software have not delivered corresponding productivity increases!

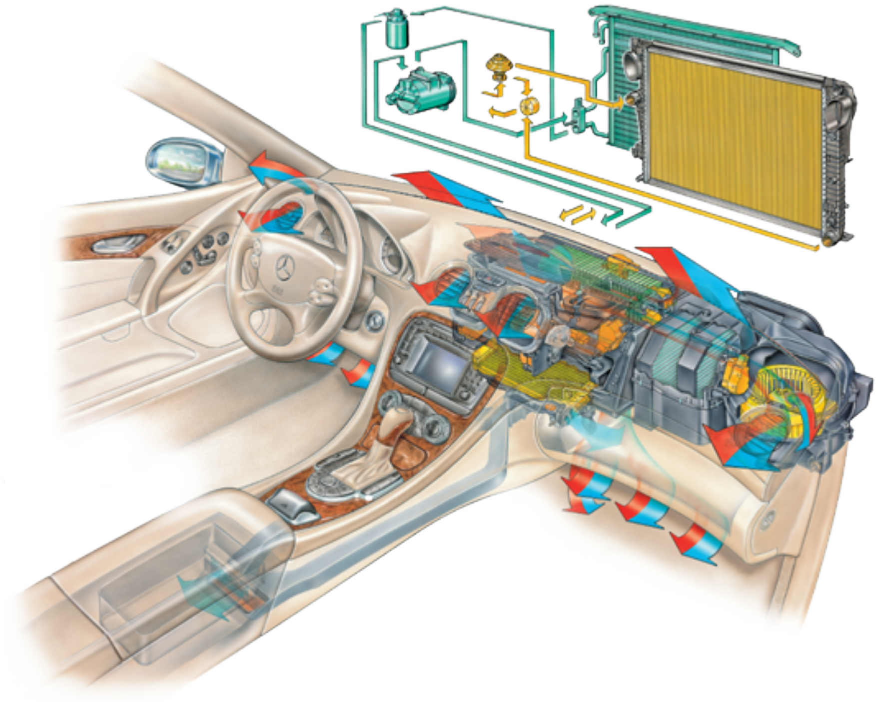
Modeling and Simulation

There will be growth in areas of simulation and modeling around the creation of new engineering “structures”. Computer-based design-build engineering ... will become the norm for most product designs, accelerating the creation of complex structures for which multiple subsystems combine to form a final product.



NAE The Engineer of 2020

Automotive Climate Control



- Audi, BMW, Daimler, Ford, Volvo, VW and their suppliers have standardized MBD based on Modelica
- Suppliers provide components and validated Modelica
- Car manufacturers evaluate complete system by simulation
- IP protected by extensive encryption
- Substantial reduction of road & climate chamber testing

Picture courtesy of Behr GmbH & Co.

Modelon

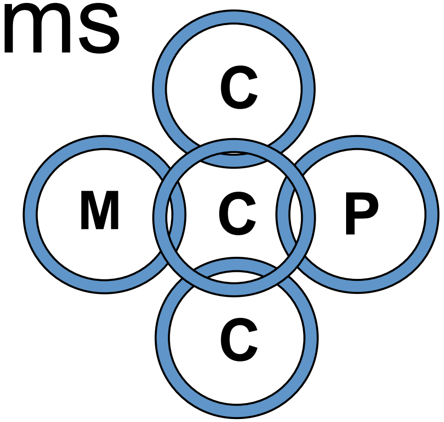
Educational Challenges

- Educating the future engineers and scientists
- Education of physicists and biologist
- The dilemma of emerging fields
- Filter out the fundamentals and exploit advances in computing
- Deep knowledge in specific areas
- Broad knowledge of neighboring fields
- Ability to communicate and to work in teams

1. Introduction
2. The Power of Feedback
3. The Field Emerges
4. The Golden Age
5. A New Era?
6. Summary

Summary

- Control is a vital dynamic field
- Networked embedded systems
- Autonomy and safety
- The educational challenge



- Continue to take care of the foundations and develop the holistic view