Control
the Hidden Technology

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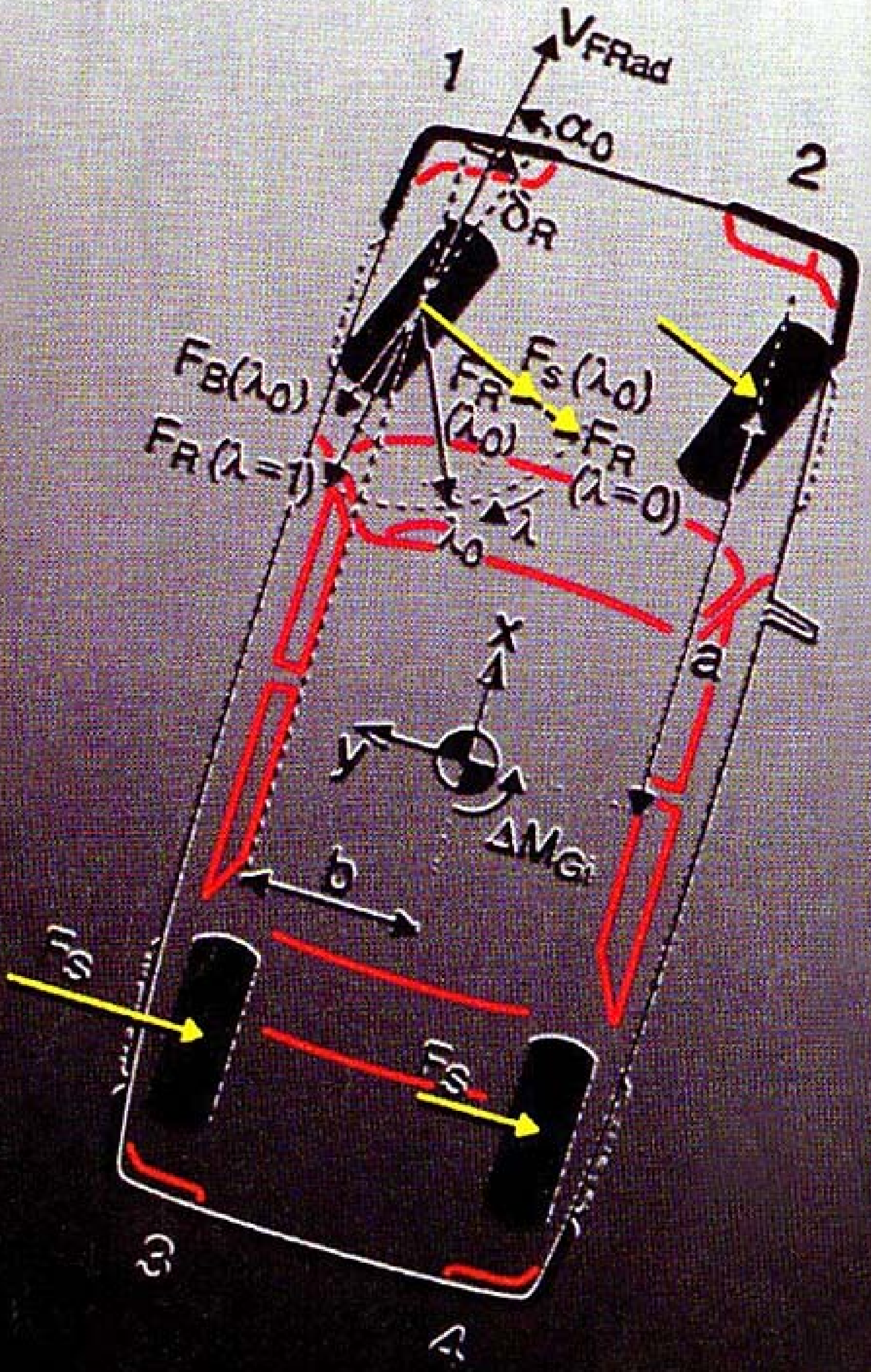


V_{FRad}
1
α_0
2
δ_R
$F_B(\lambda_0)$
$F_S(\lambda_0)$
$F_R(\lambda_0)$
$F_R(\lambda=1)$
$F_R(\lambda=0)$
λ
λ_0
x
a
y
ΔM_{Gi}
b
F_S
F_S
3
4

Electronic Stability Program (ESP) is a new safety system which guides cars through wet or icy bends with more safety….

The key is a yaw-rate sensor, which detects vehicle movement around its vertical axis, and software which recognizes critical driving conditions and responds accordingly.

The Hidden Technology

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

Easier to talk about devices than ideas
Not enough attention to popularization

A Broad Picture

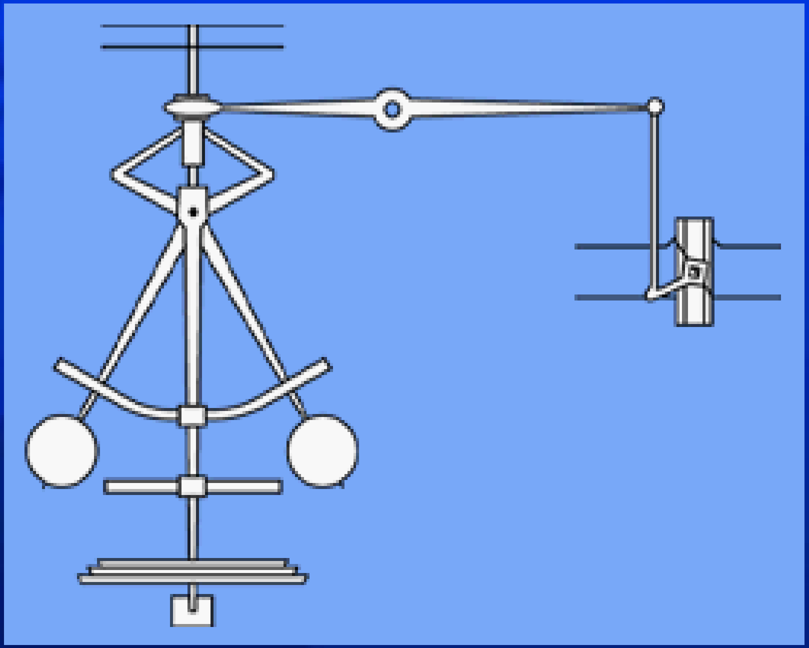
Control appeared in the industries that emerged in the 19th and 20th centuries: steam power, electric power, ships, aircrafts, chemicals, telecommunication. Control was sometimes an enabling technology (aircraft, telecom).

In the 1940s it appeared as a separate engineering discipline and it has developed rapidly ever since. Academic positioning difficult since it fits poorly into the ME, EE, ChemE framework. Today applications everywhere.

1. Introduction
2. A Brief History
3. State of the Art
4. The Future
5. Conclusions

Industrial Process Control

- The problem: Keep a machine running at constant speed in spite of disturbances
- Solution: PID control
- Side effect: Standards for control (PID) and communication



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

Flight Control

The Wright Brothers	1903
Sperry's Autopilot	1912
Robert E. Lee	1947
V1 and V2 (A4)	1942
Sputnik	1957
Apollo	1969
Mars Pathfinder	1997
UAVs	2000

Flight Control

- Problem 1: How to fly?
- Solution: Build maneuverable but unstable aircraft stabilize with manual control
- Problem 2: Stabilization
- Solution: Feedback

Telecommunications

Telephone Calls Over Long Distances

The problem: Build a good amplifier from bad components

Solution: The negative feedback amplifier. Black 1928.

Side effect: Stability theory and systems theory from the input-output view

The Magic of Feedback

- Make precise systems from imprecise components
- Keep variables constant
- Stabilize unstable system
- Reduce effects of disturbances and component variations
- New degrees of freedom for designers
- Main drawback - Danger of Instability

Theory

Stability Theory

- Maxwell Routh 1887
- Stodola Hurwitz 1895
- Lyapunov 1892
- Nyquist 1932

Design and limitations

- Bode 1940

The Scene of 1940

Widespread use of control in many fields

- Power generation and distribution
- Process control
- Autopilots for ships and aircrafts
- Telecommunications

The similarities were not recognized

Stability Theory

A Discipline Emerges

Industrial Process Control

Telecommunications

Flight Control

Mathematics

→

Principles

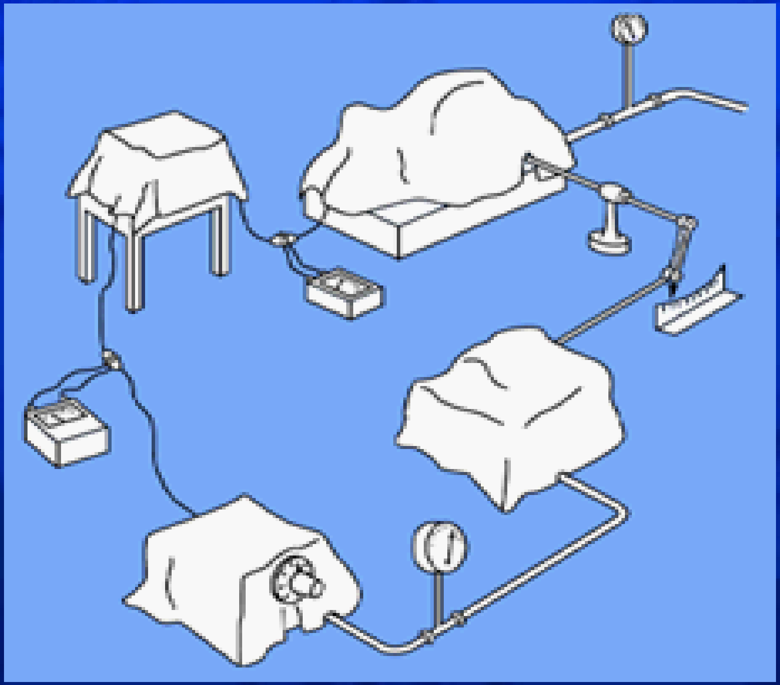
Theory

Design

Methodology

Applications

The Black Box Concept



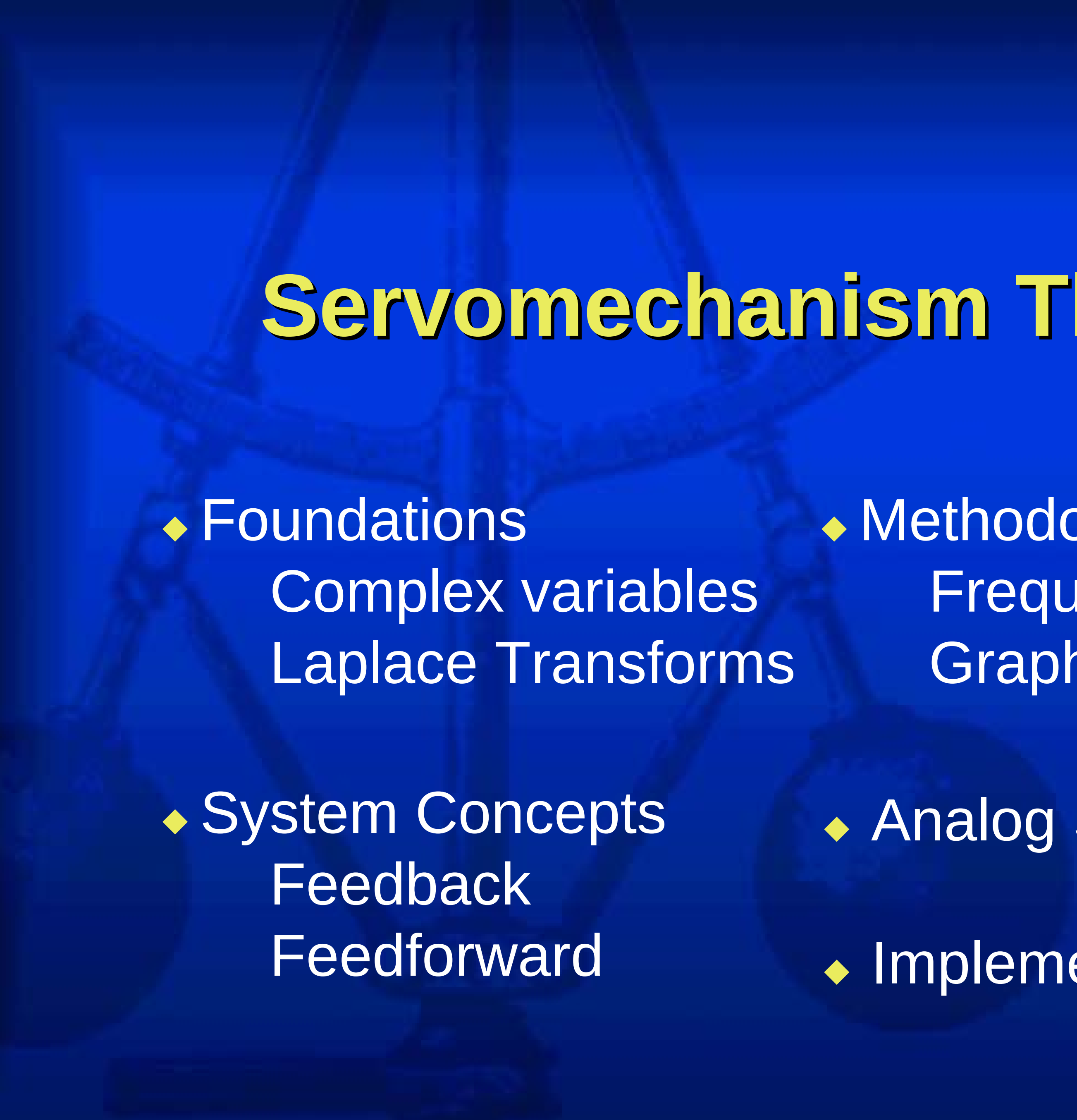
Input

Output

Abstraction

Information hiding

Transfer functions



Servomechanism Theory

- Foundations
  - Complex variables
  - Laplace Transforms
- Methodology Design
  - Frequency Response
  - Graphical Methods
- System Concepts
  - Feedback
  - Feedforward
- Analog Simulation
- Implementation

Theory of Servomechanisms

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

Consequences

Education

Application

Industrialization

Organisation

Journals

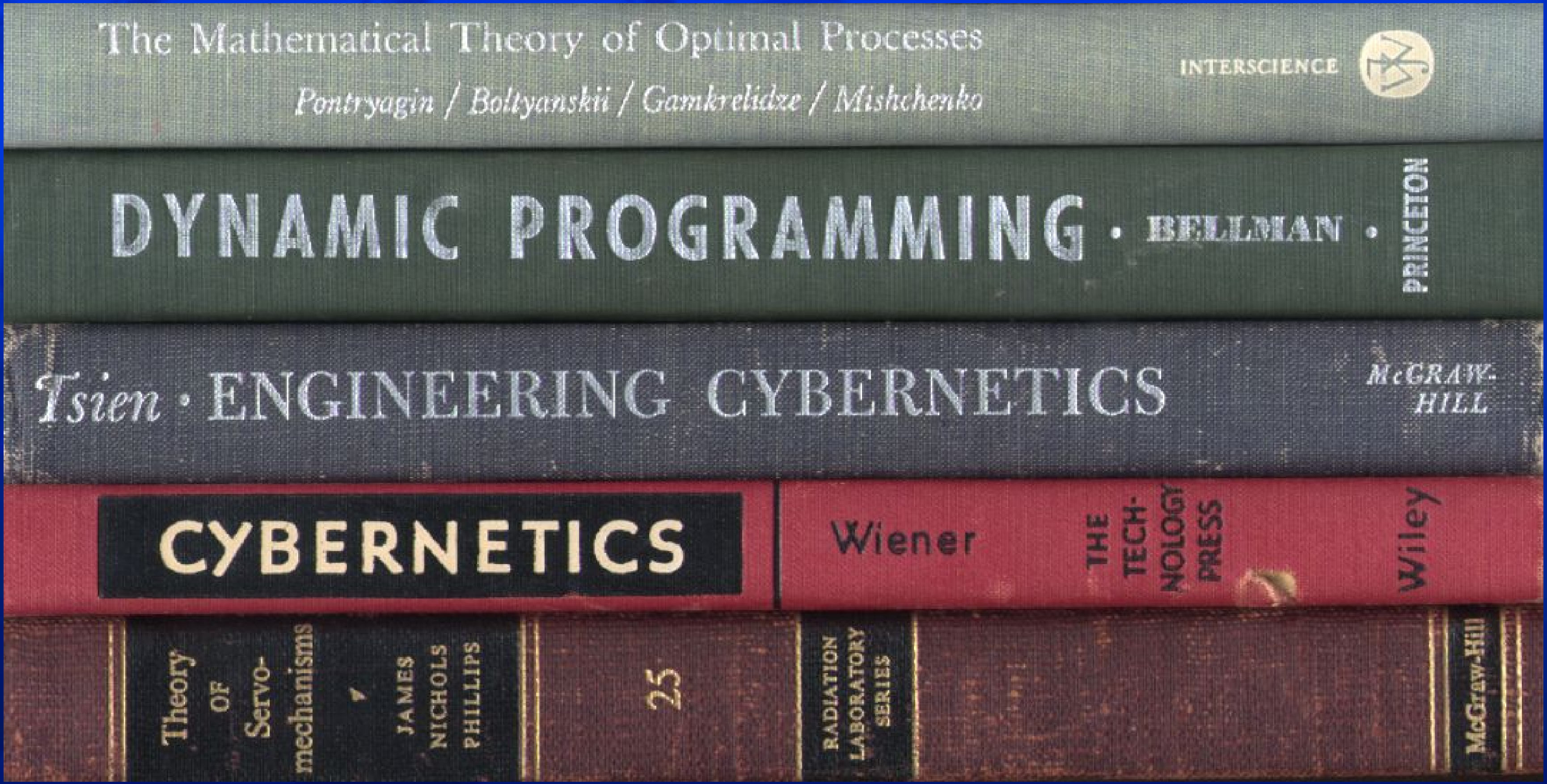
Conferences

The Second Wave

- Driving Forces
  - Space race
  - Mathematics
  - Computers
- A New Paradigm
  - State Space
- Rapid Expansion
  - Subspecialities

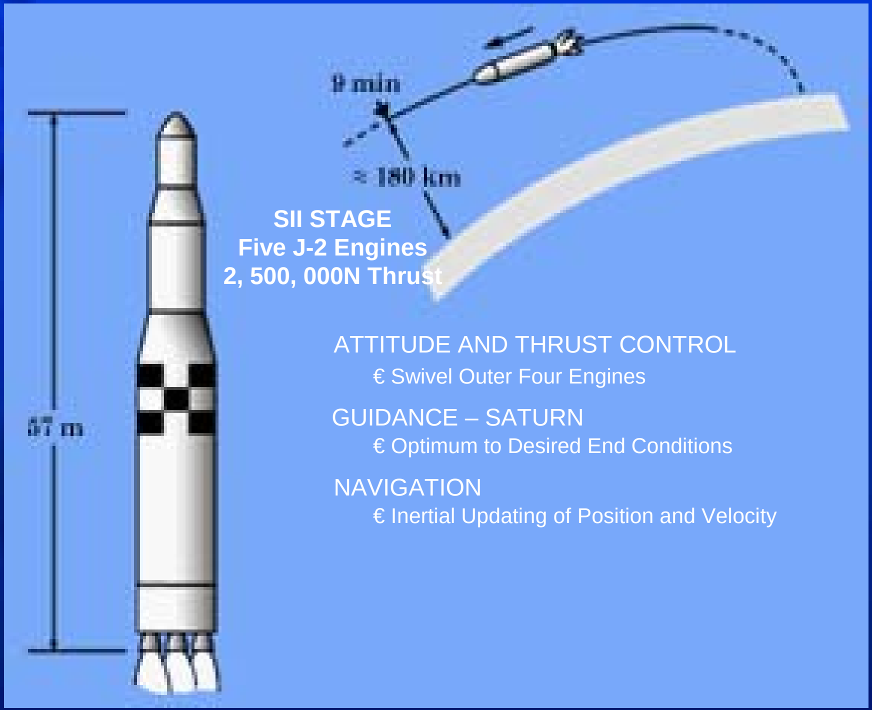
- Optimal Control
- Nonlinear Control
- Computer Control
- Stochastic Control
- Robust Control
- System Identification
- Adaptive Control
- CACE

Inspiration



Optimal Control

Euler	1707–1783
Lagrange	1736–1813
Pontryagin	1908-1988
Hamilton	1805–1865
Jacobi	1804–1851
Bellman	1925-1984



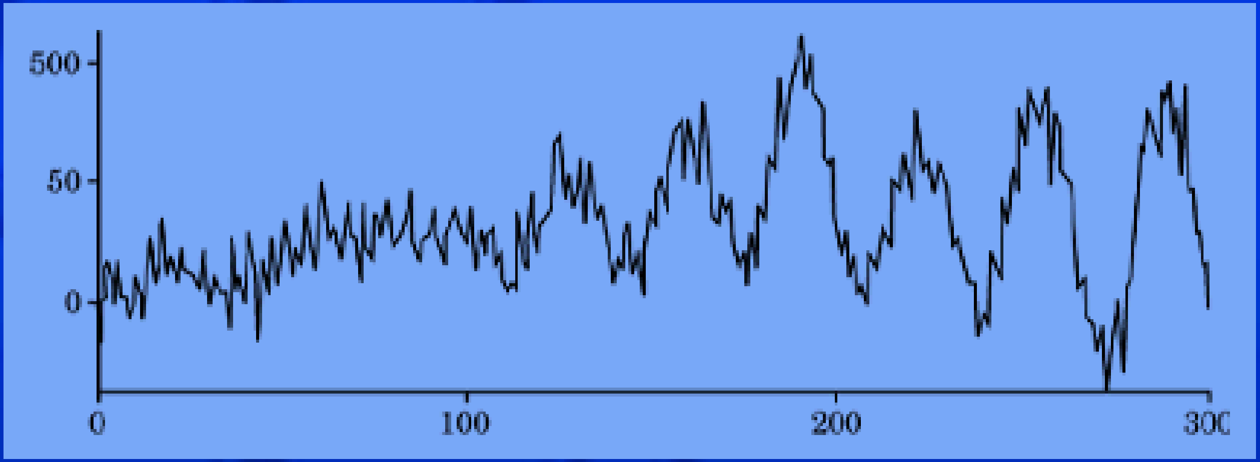
SII STAGE
Five J-2 Engines
2, 500, 000N Thrust

ATTITUDE AND THRUST CONTROL
€ Swivel Outer Four Engines

GUIDANCE – SATURN
€ Optimum to Desired End Conditions

NAVIGATION
€ Inertial Updating of Position and Velocity

Kalman Filtering



Gauss	1810 least squares
Wold	1935 innovations
Kolmogorov	1941 discrete time
Wiener	1941 spectral factorization
Kalman	1961 recursive equations

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Current Status

A well established body of ideas, concepts, theory and design methods.

Wide and growing application areas

Still developing rapidly

Control a Commodity

The MathWorks NATIONAL INSTRUMENTS dSPACE

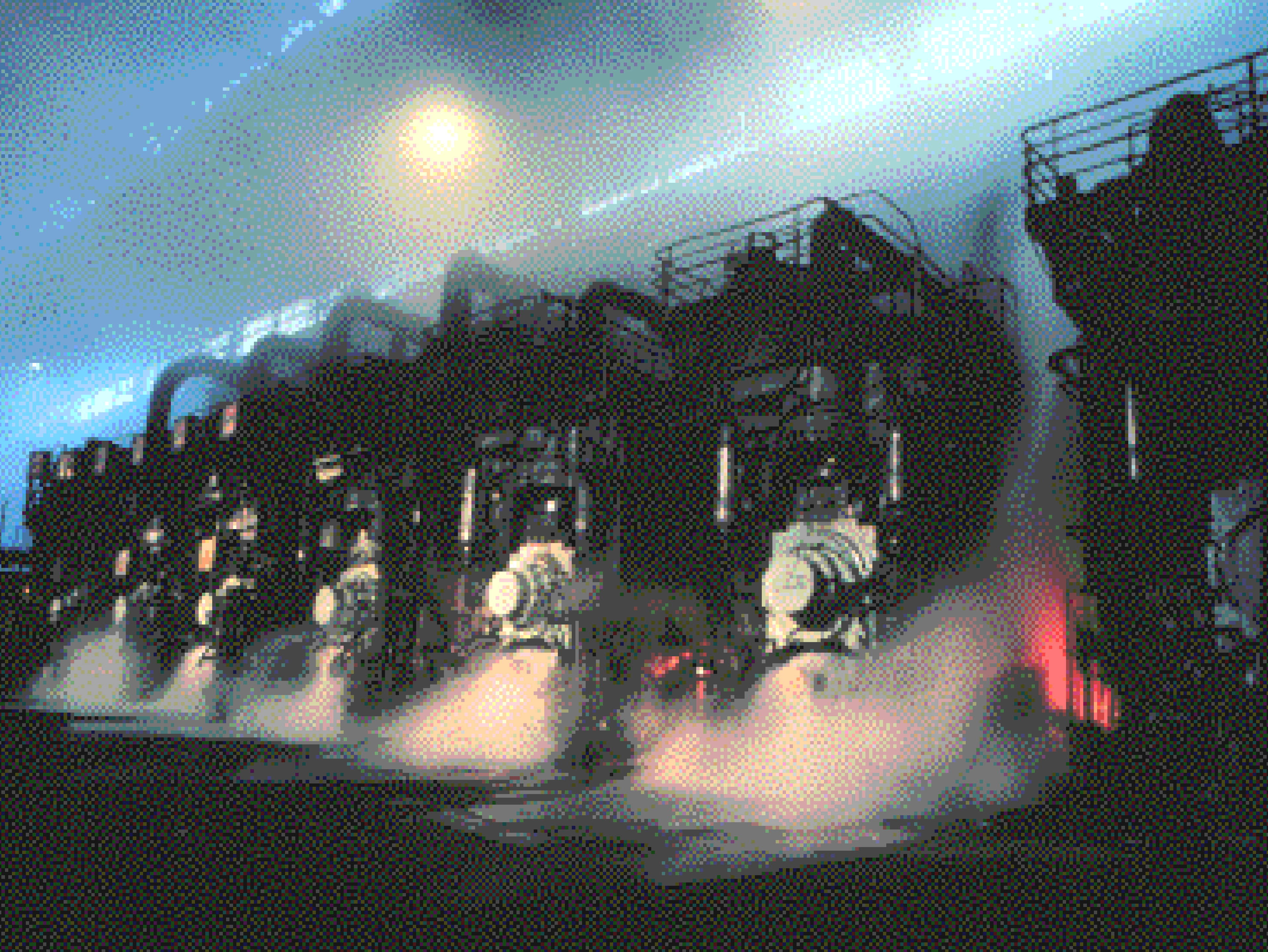
- ➢ Sensors, actuators, process interfaces
- ➢ Computers, signal processors, FPGA
- ➢ Tools for modeling, analysis, simulation and design
- ➢ Operating systems, automatic code generation

Perhaps Most Important

A good group of very talented and creative young researchers.

Applications

- Energy generation
- Energy transmission
- Process control
- Discrete manufacturing
- Communication
- Transportation
- Buildings
- Entertainment
- Instrumentation
- Mechatronics
- Materials
- Physics
- Biology
- Economics



Unmanned Air Vehicles

Challenge: Replacing the Pilot with Software

Relative Level of Autonomy

1

.5

Lightning Bug

- Target Drone
- C-130 Launched
- Operator Controlled
- Limited Autopilot

Tomahak

- Autopilot
- Tgt Recognition
- Multi Targeting
- Launch & Forget

Predator

- Autopilot
- Piloted T-O & Landing
- Racetrack
- Surveillance
- Route Replanning

UCAV

- T.O & Landing
- Navigation
- ESM Search
- RADAR Pointing/ Cueing/Transmission
- SEAD
- Air-to-Ground
- In-flight Retargeting
- Collaborative AOA Measurement

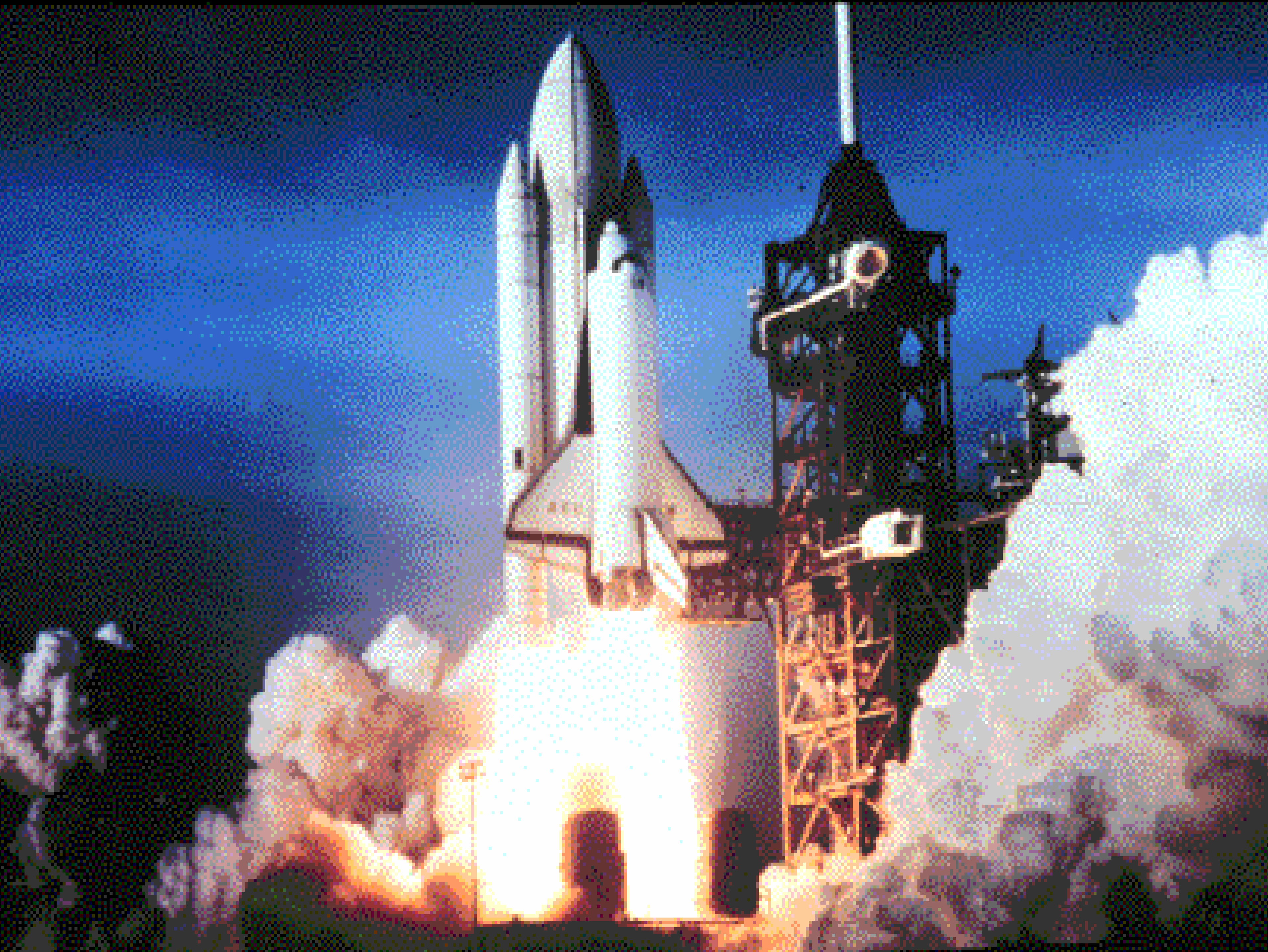
UASV

Autonomous
- Evasive Maneuvers
- Extreme Performance
- T.O & Landing
- Navigation
- Multi-ship Trajectories (TF/TA)
- Inter-Ship Collaboration
- Information Mining
- Sensor Control
- ATR
- Weapon Delivery
  - A/G & A/A
- BDA
- Manned A/C Augmentation
- In-flight Retargeting
- N on N Engagement

1960s **1980s** **2000** **2010** **2015-20**

Time →

Siva Banda U.S. Air Force Research Lab



Consumer Electronics

A Dilemma

Automatic control is a collection of ideas, concepts and theories with very wide applications areas. How to cope with:

- Coupling to hardware
- Coupling to industries
- Specific domain knowledge
- Academic positioning

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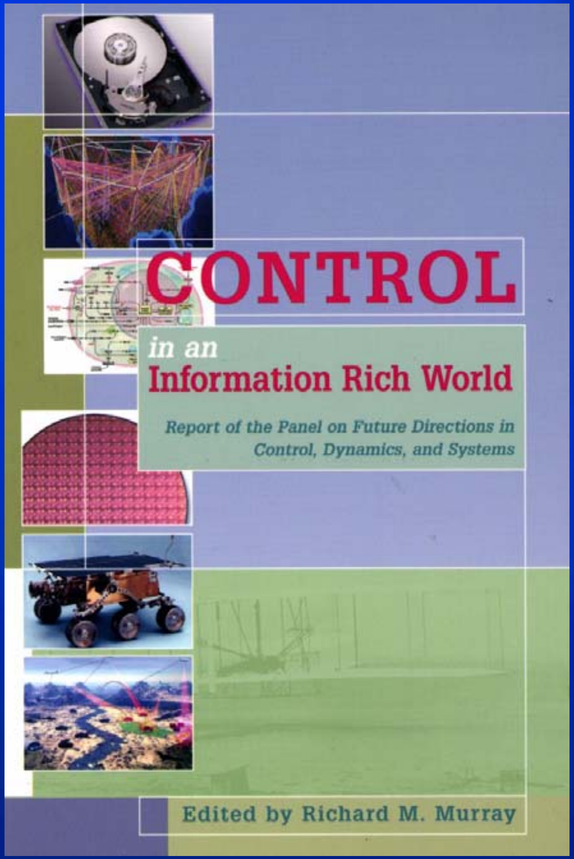

CONTROL

in an

Information Rich World

Report of the Panel on Future Directions in Control, Dynamics, and Systems

Edited by Richard M. Murray

The Future of Control

- **Natural science**
  - Devices and ideas in physics, quantum systems.
  - Strong systems orientation in biology
  - Many previous attempts. Will it work this time?
- **Increased use in engineering**
  - Control of/over communications networks
  - Autonomous systems
  - Learning and reasoning

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

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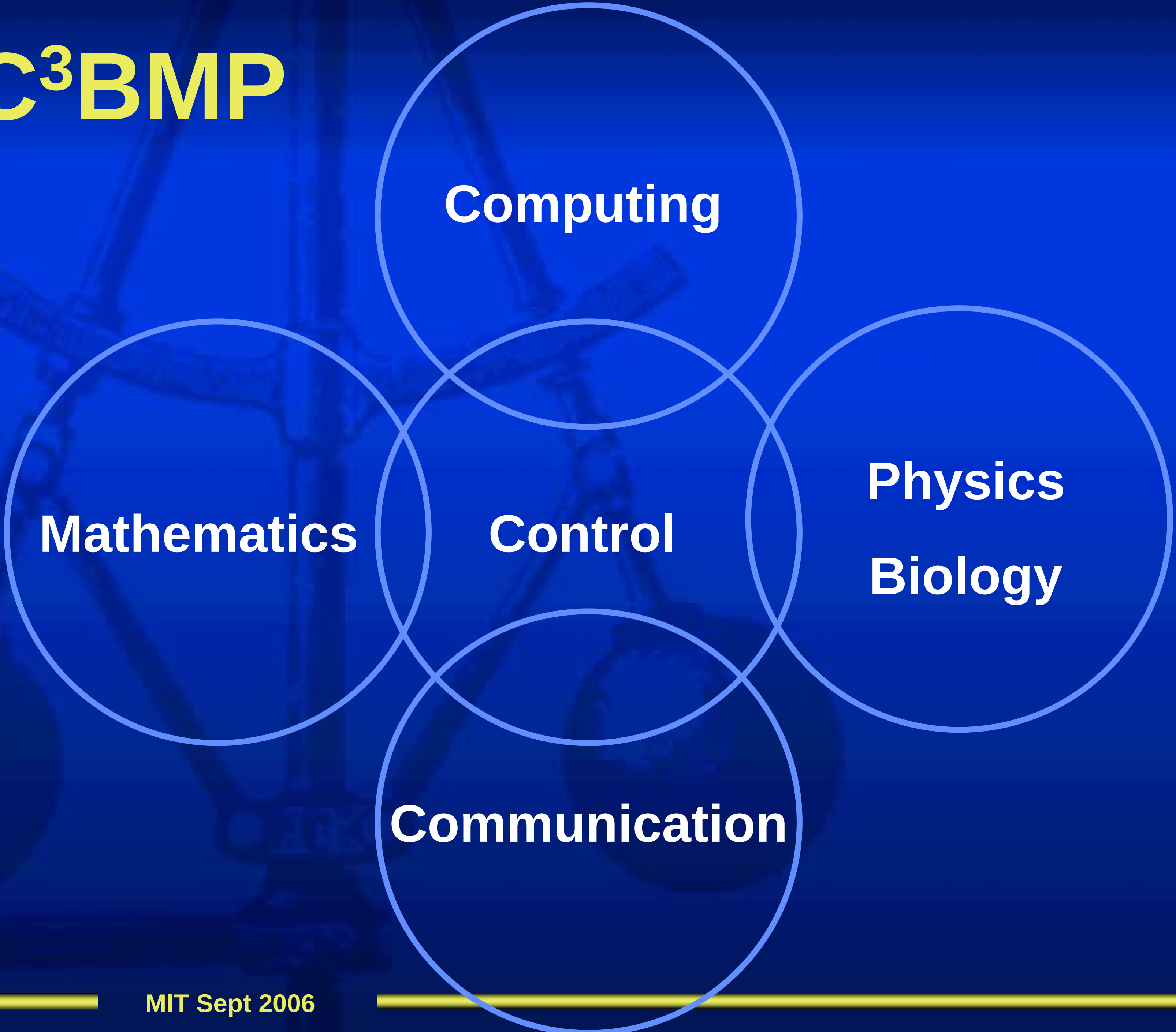
C^{3}BMP



Computing

Mathematics

Control

Physics

Biology

Communication

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

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Natural and Engineering Sciences

Understand Nature vs Man-made Systems

Equally Challenging

Extensive use of Mathematics

Design and Operation of Systems

Physical Laws vs System Principles

Isolation vs Interaction

Reductionism vs Systems

Theoretical Physics vs System Theory

The Physics Barrier

Control

Physics

Blockdiagrams ODEs

Mass, energy, momentum

Block diagrams unsuitable for serious physical modeling

Physics

- Devices and ideas
- Particle Accelerators
    - The 1984 Nobel Prize Van Der Meer
- Adaptive Optics
- Atomic Force Microscope
- Quantum and Molecular Systems
- Turbulence

A Phycicist View

The obvious places to learn about control theory – introductory engineering textbooks ... - are not very satisfactory places for a phycisist to start. They are long - 800 pages is typical - with the relevant information often scattered in different sections. ... They often cloak concepts familiar to the physicist inunfamiliar language and notation. ... The main alternative, more mathematical texts, ..., are terse but assume that the reader already has an intuitive understanding of the subject.   *John Beckhoefer Rev. Mod. Phys. July 2005*

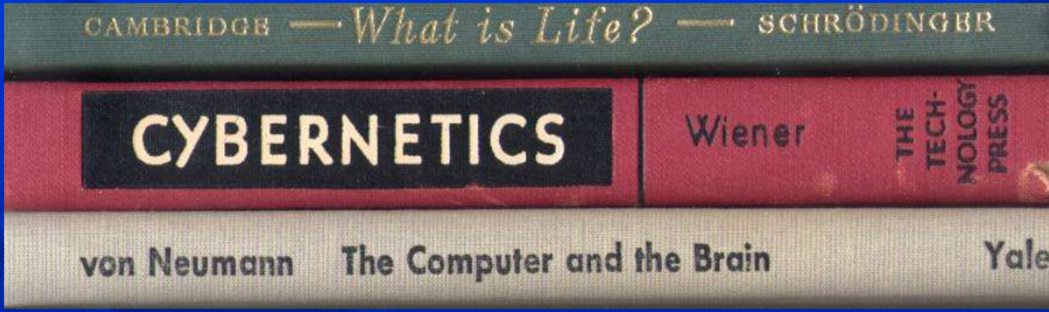
Biology

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

Biology

A long tradition - will it fly this time around?



- Schrödinger 1944
- Wiener 1948
- von Neumann 1958
- Bellman Mathematical Biosciences
- Understanding dynamics and control crucial
- What is new?

Systems Biology

Leading biologists have recognized that new systems-level knowledge is urgently required in order to conceptualize an organize the revolutionary developments taking place in the biological sciences, and new academic departments and educational programs are being established at major universities, particularly in Europe and in the United States

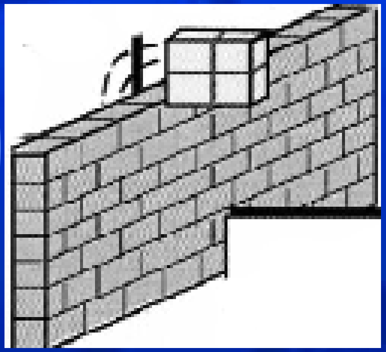
Eduardo Sontag 2006

Charles Darwin

It is not the strongest of the species that survive, nor the most intelligent, it is the one that is most adaptable to change.

The Computing Barrier

Control



Computing

Feedback,Stability, ODE, PDE
Moderate complexity
Robustness

Logic, languages, DES,FSM
High complexity, abstractions
Architecture

Networked embedded systems

Control and 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 10 months.
- Software has unfortunately not kept up!

Control and Computing

- Software issues increasingly important
- Object oriented modeling
- Feedback scheduling
- Control of servers and nets
- Vision Feedback and haptics
- High level control principles
- Learning systems

Embedded Computing

- It has been predicted that by the year 2010 about 90% of all program code will be implemented for embedded systems.
- Embedded systems have sensing and/or actuation
- Compelling reason to combine control and computing

Automotive

Engine control

Power trains

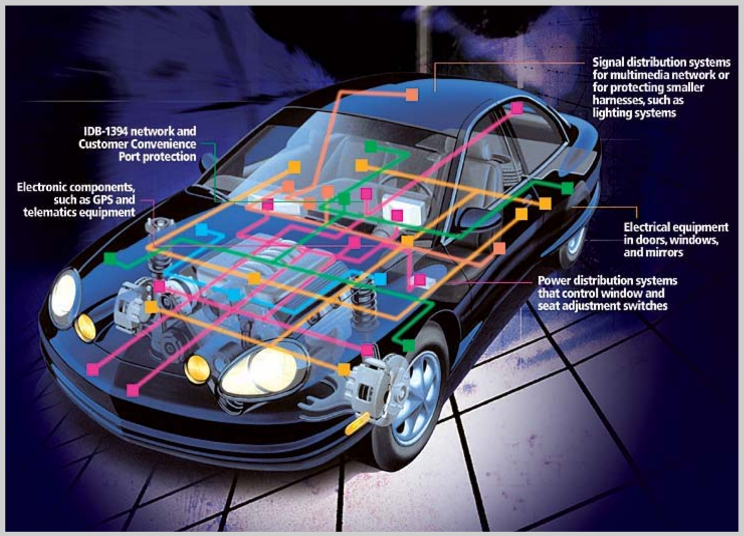
Cruise control

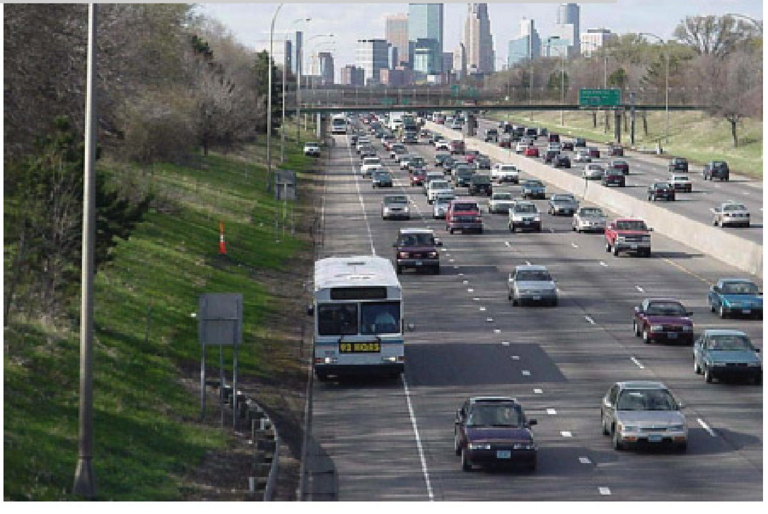
Adaptive cruise control

Traction control

Lane guidance assistance

Platooning

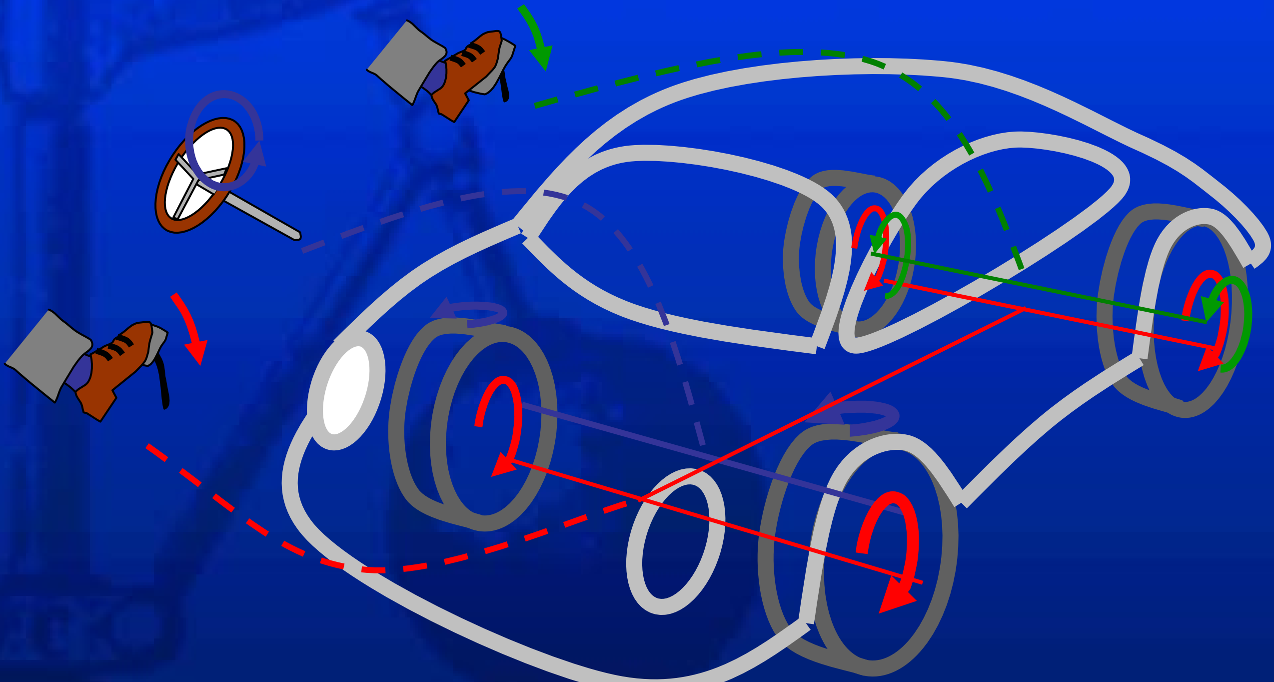




Automotive

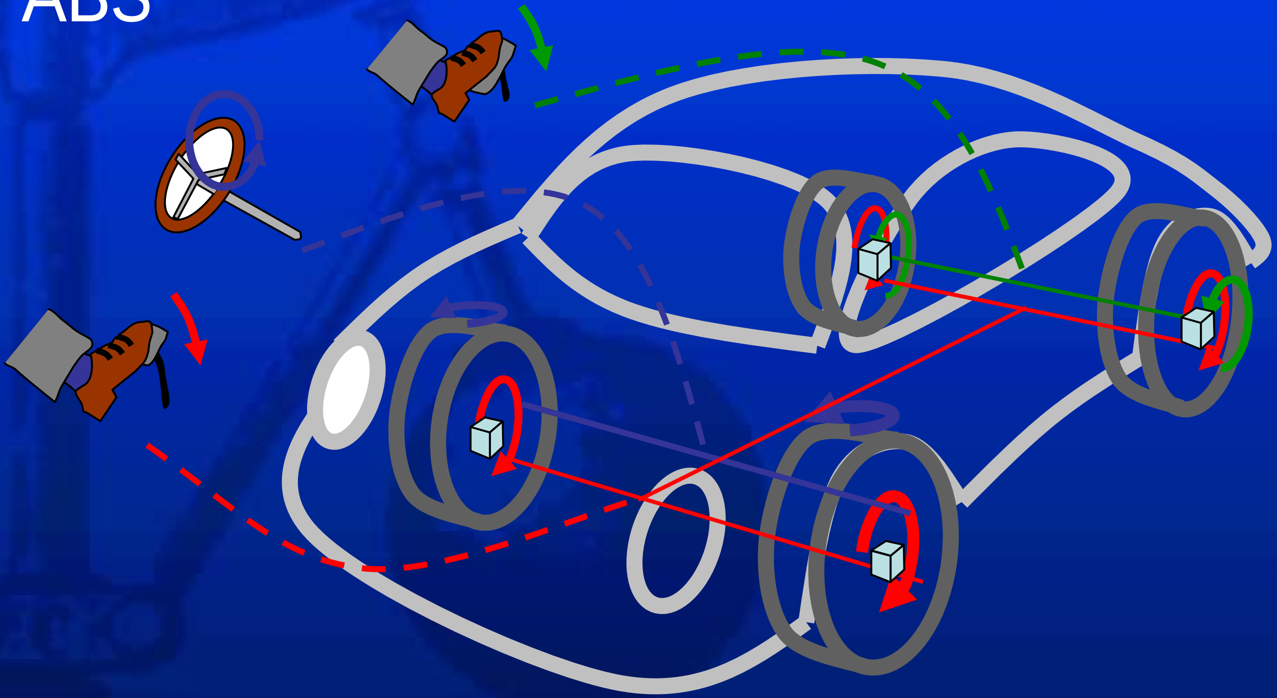
- Strongly enhanced performance
- Strong technology driver
- Large numbers (microcontroller)
- Low costs
- Safe design and operation of networked embedded systems

Automotive

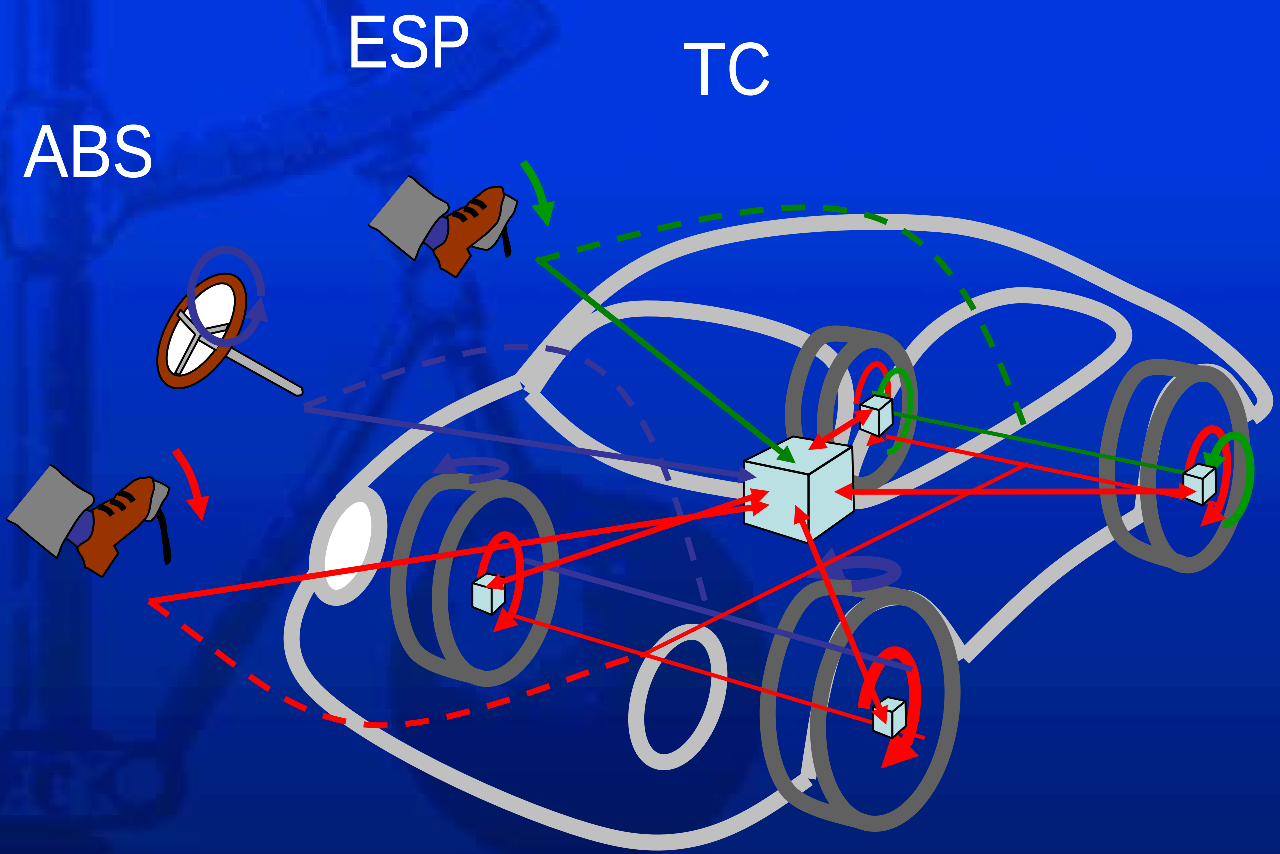


Automotive

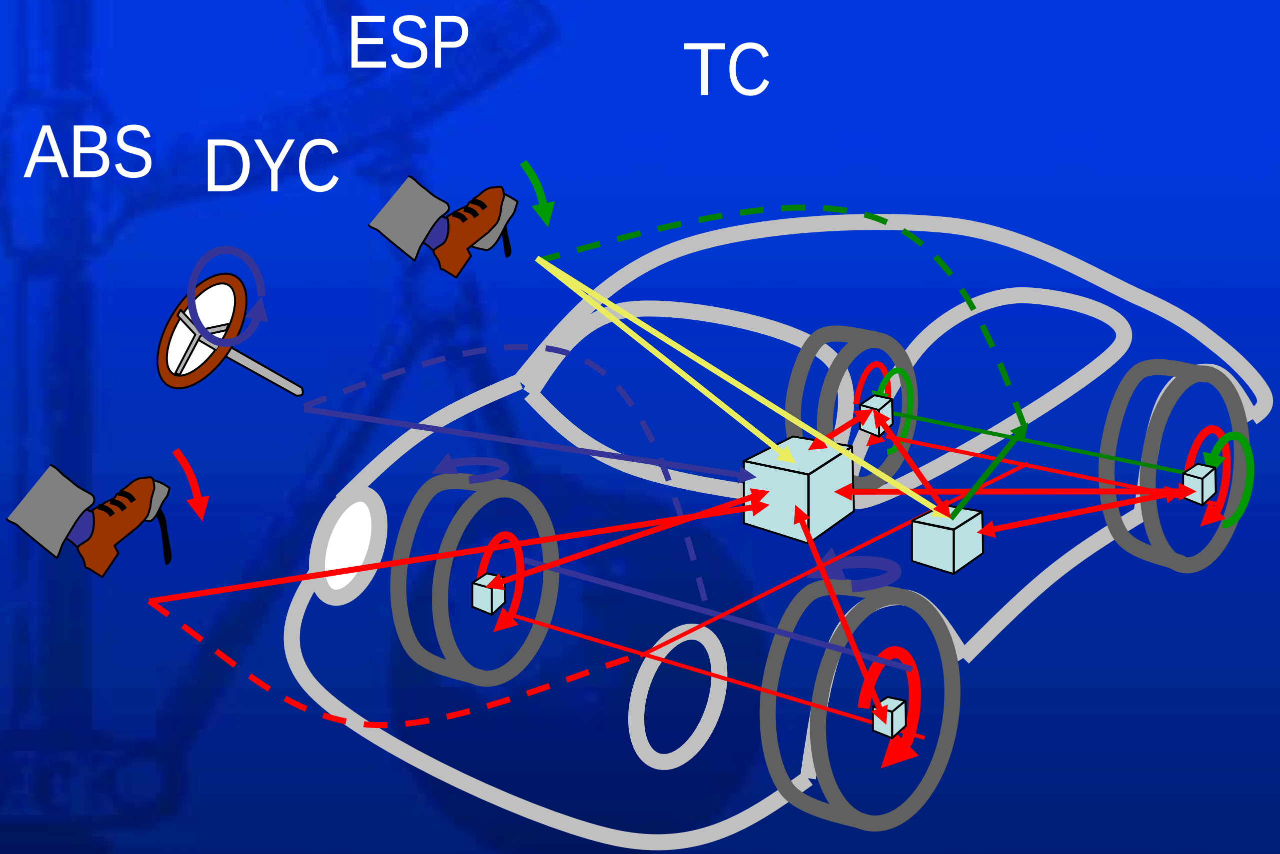
ABS



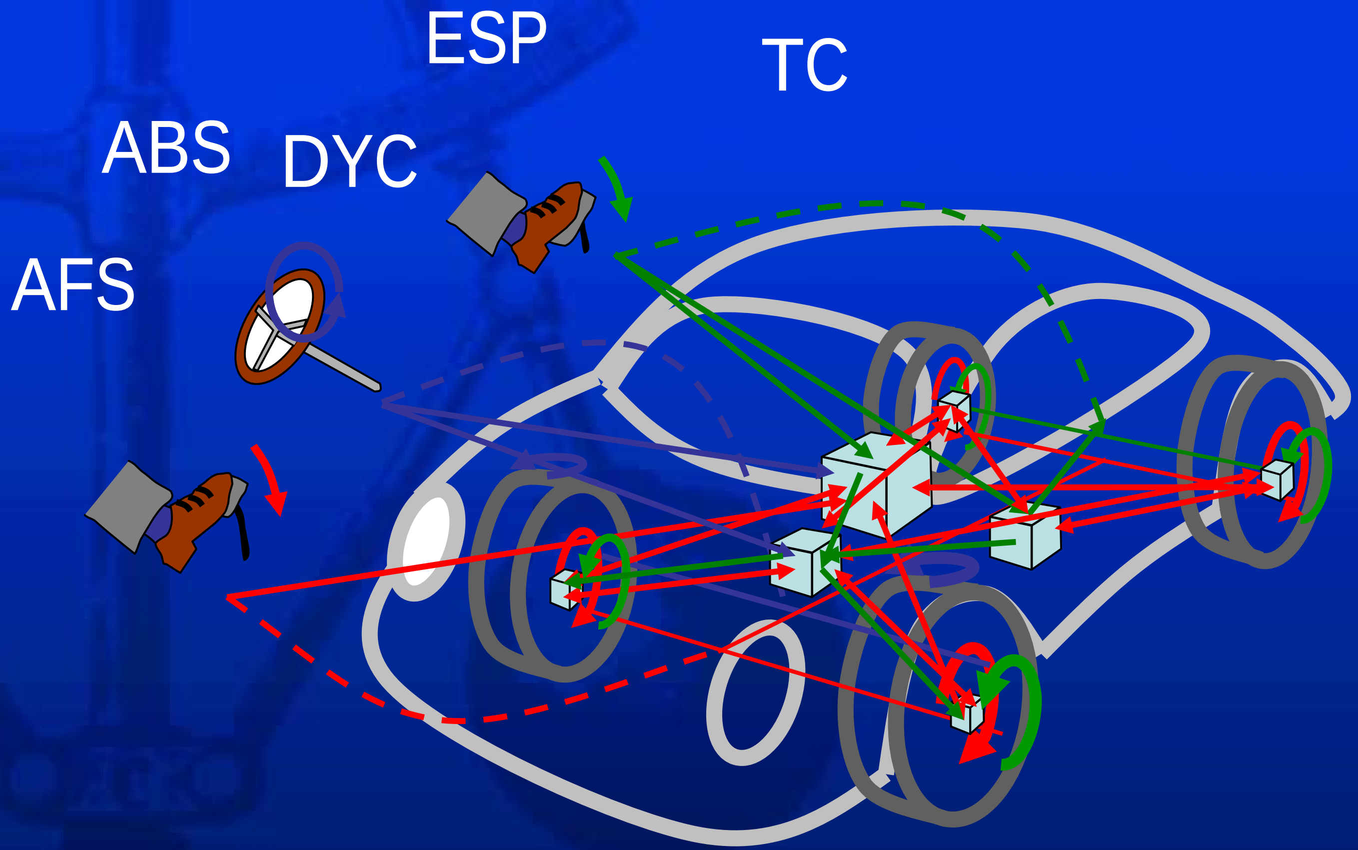
Automotive



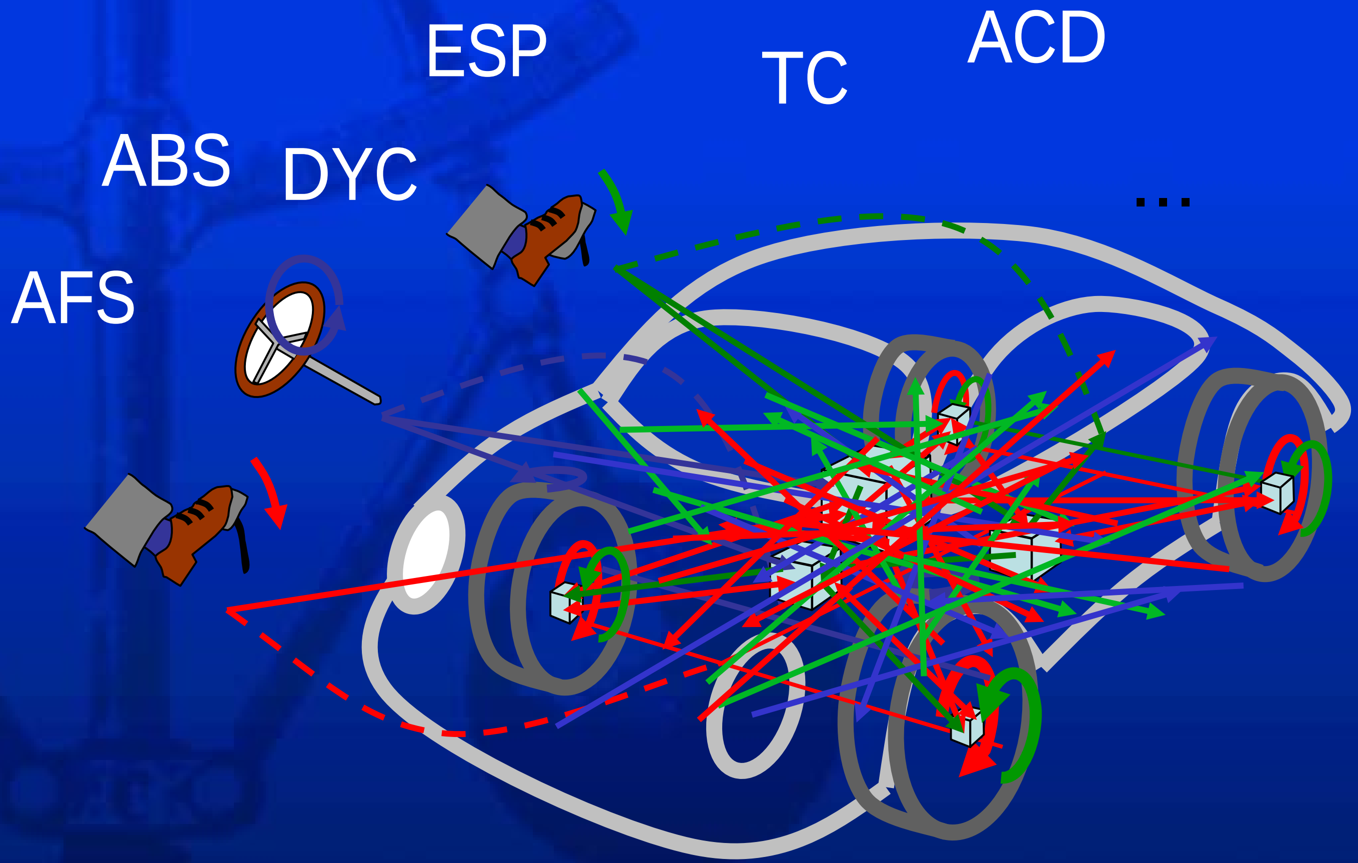
Automotive



Automotive

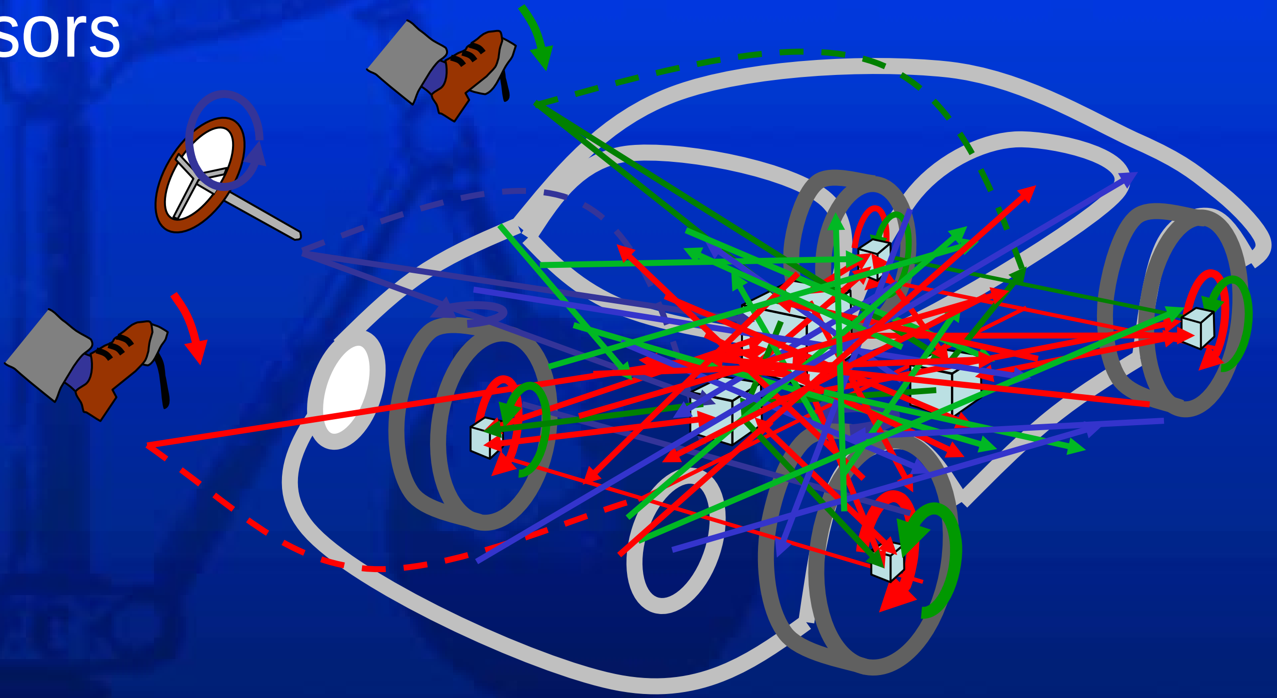


Automotive

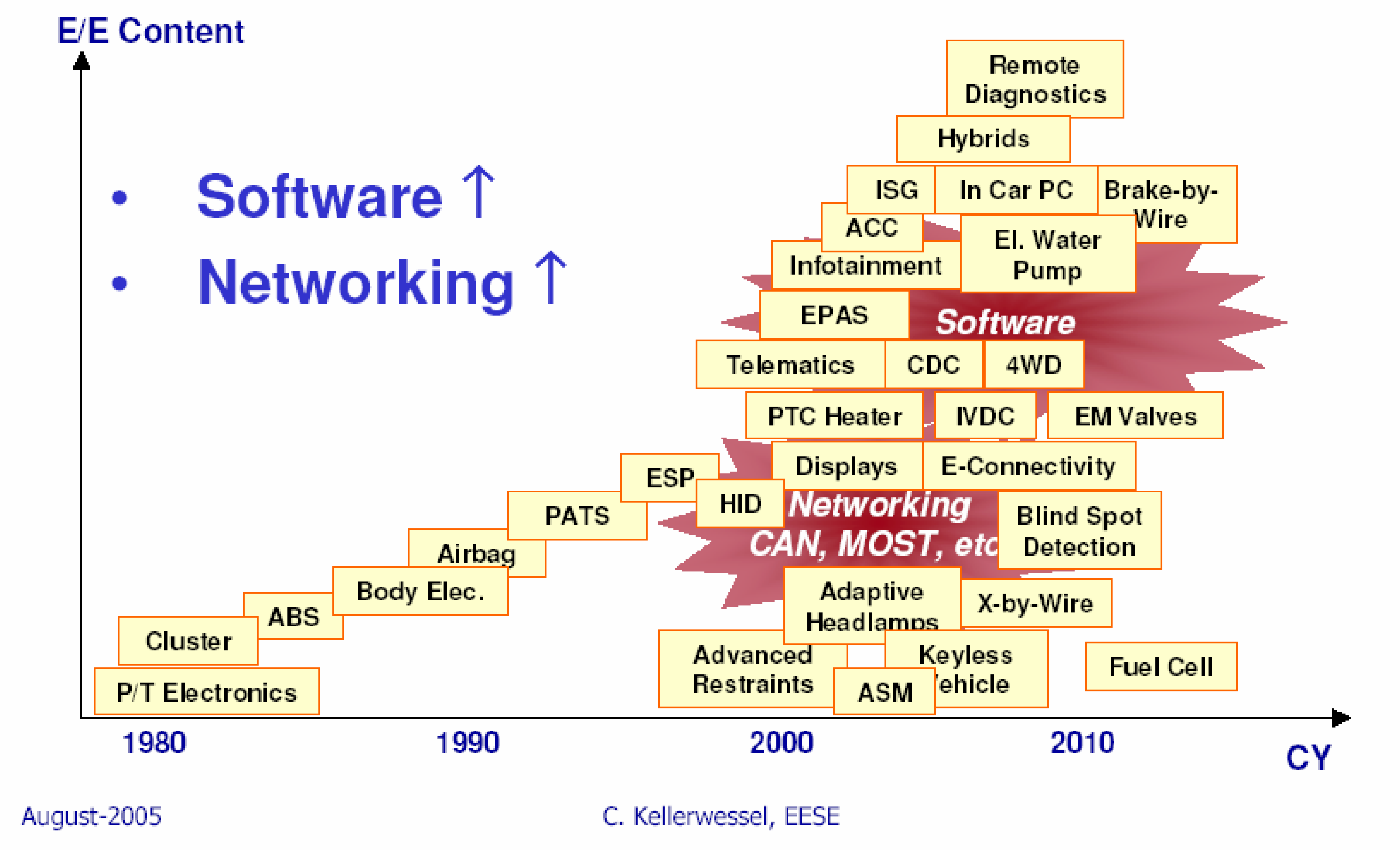


Automotive

Industry structure
Common sensors
Interaction
Safe design



Dramatic Increase of Complexity



August-2005

C. Kellerwessel, EESE

Safe Design

- Much more than automatic code generation
- System architecture
- Integration of subsystems
- Modification, upgrade
- Formal specification, design, verification, validation

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Conclusions

- An exciting field
- Use of feedback often revolutionary
- Rapid growth of applications
- Streamline available knowledge
- Education is a key issue
- Many new challenging problems

Entering the Third Phase?

- Drivers: embedded system, networks, biology, physics, ...
- Autonomy, distribution
- Exploding applications
- Hardware and software platforms
- Will the holistic view be recovered?

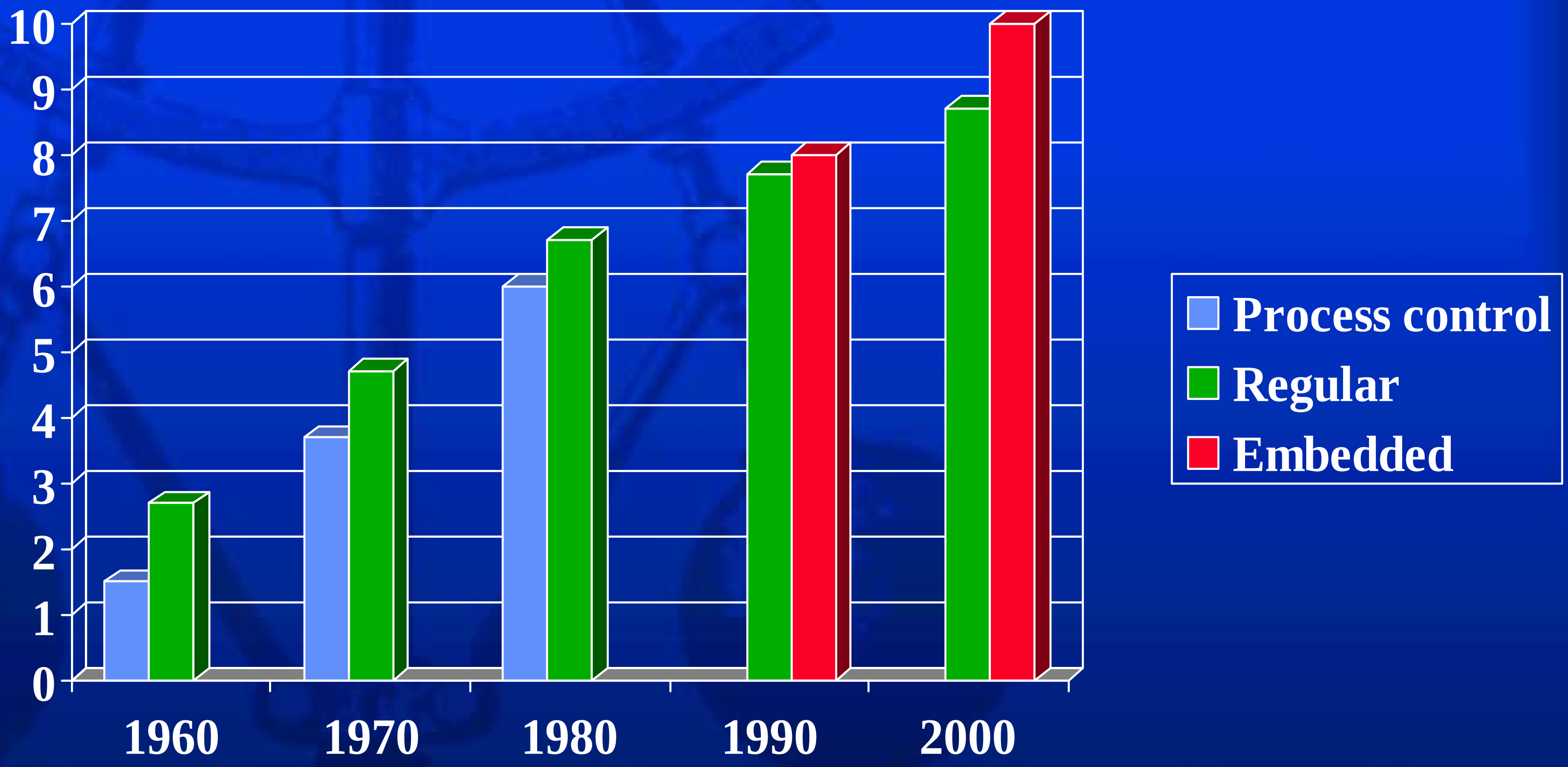
Examples of New Problems

- Sensor-rich control
- Actuation-rich control
- High level control principles
- Architecture and design of embedded systems

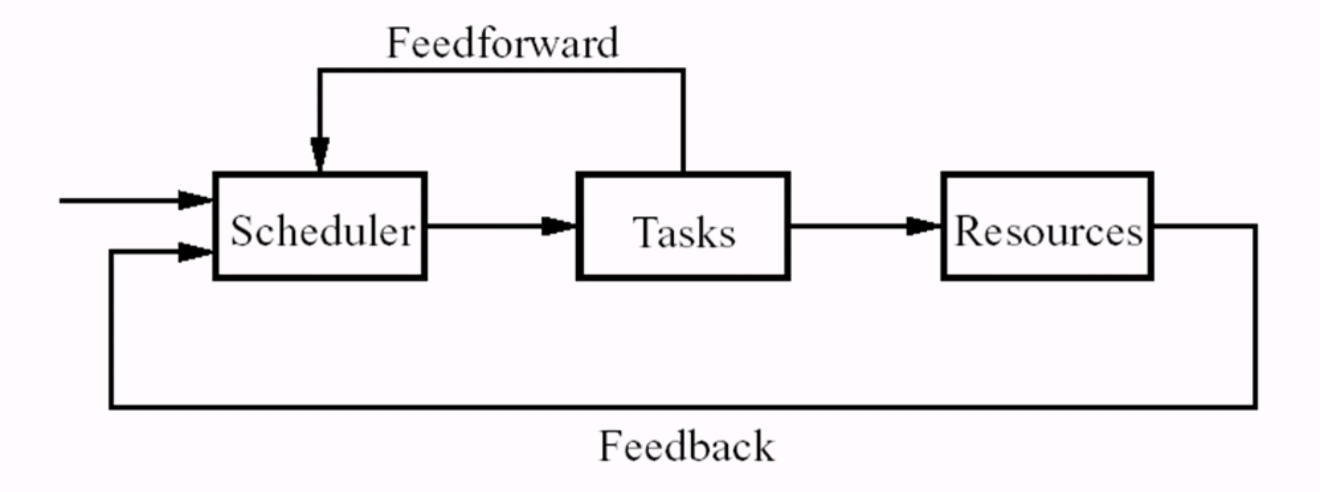
Recipe for Success

- Good ideas and demanding problems
- Solid theory
- Good engineering
- Examples
  - Servomechanisms, Optimal control
  - Robust control, Computer control

Computing and Control



Feedback Scheduling



- Adjust sampling period of controllers
- Adjust priorities
- Adjust dead-lines

Modelica (www.modelica.org)

- Mimics how an engineer builds a real system
- Object oriented, component-based, multi-domain
- Efficient engineering through reuse
- Model libraries (free and commercial)
- Simulator Dymola (Dynasim)
- Extensive symbolic manipulation, automatic inversion, ...
- Efficient real-time code
- Syntax and semantics formally defined

Dynasim

Modeling and Simulation

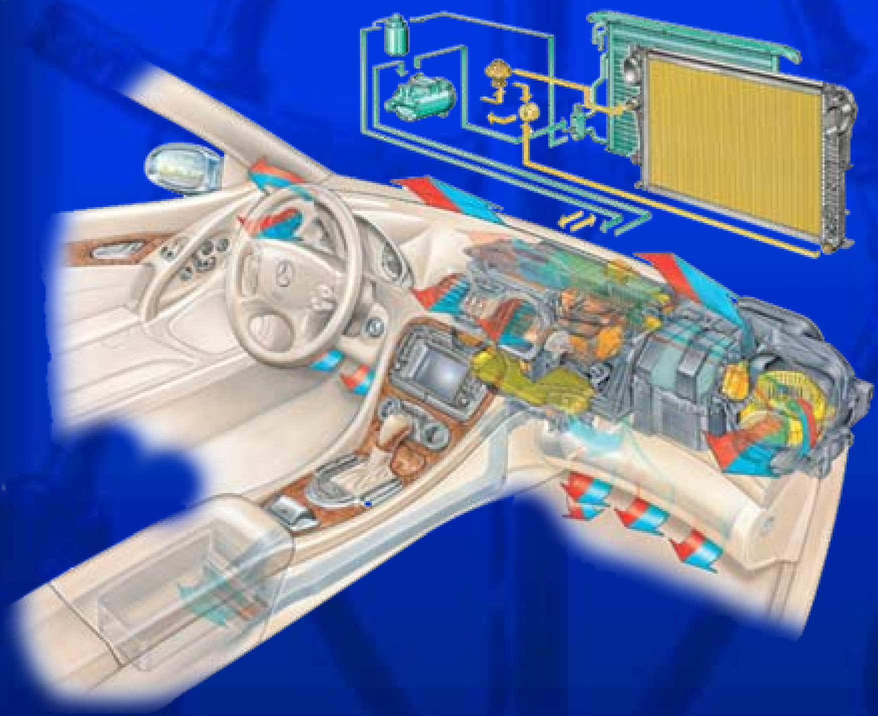
There will be growth in areas of simulation and modeling around the creation of new engineering “structures”. Computer-based design-build engineering ... will become the norm for most product designs, accelerating the creation of complex structures for which multiple subsystems combine to form a final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

NAE The Engineer of 2020

Modelica (www.modelica.org)

- Block diagrams and ODEs not suited for physical modeling – the control/physics barrier
- Behavior based (declarative) modeling is a good alternative
- European activity based on industry/university collaboration
- Groups with broad competence and experience

Automotive Climate Control



- *Audi, BMW, DaimlerCrysler, Volkswagen and their suppliers have standardized on Modelica*
- *Suppliers provide components and validated Modelica models based on the AirConditioning library from Modelon*
- *Car manufacturers evaluate complete system by simulation*
- *IP protected by extensive encryption*

Picture courtesy of Behr GmbH & Co.

Modelon

Computing Control and Communication