MIT Symposium
2040 Visions of Process Systems Engineering

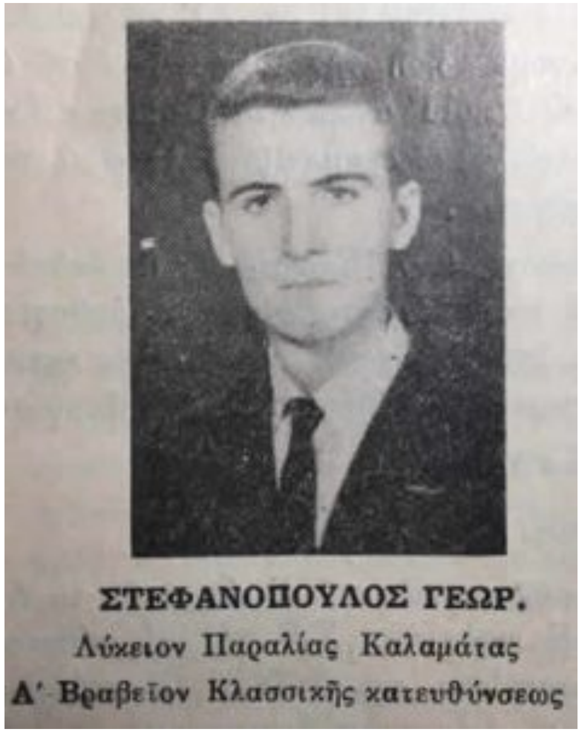
George's Impact

Manfred Morari
Electrical & Systems Engineering
University of Pennsylvania

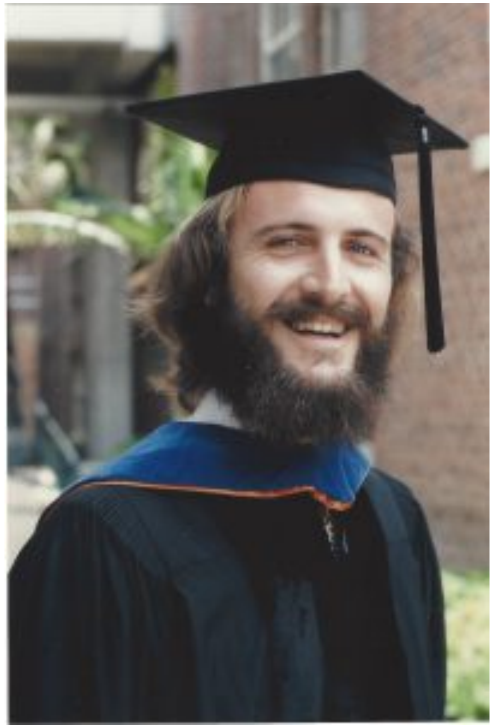
June 1, 2017

Penn
University of Pennsylvania

George’s Formative Years



1965



1974

1977

MIT Symposium
2040 Visions of Process Systems Engineering

George's Impact

Manfred Morari
Electrical & Systems Engineering
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June 1, 2017

Penn
UNIVERSITY of PENNSYLVANIA

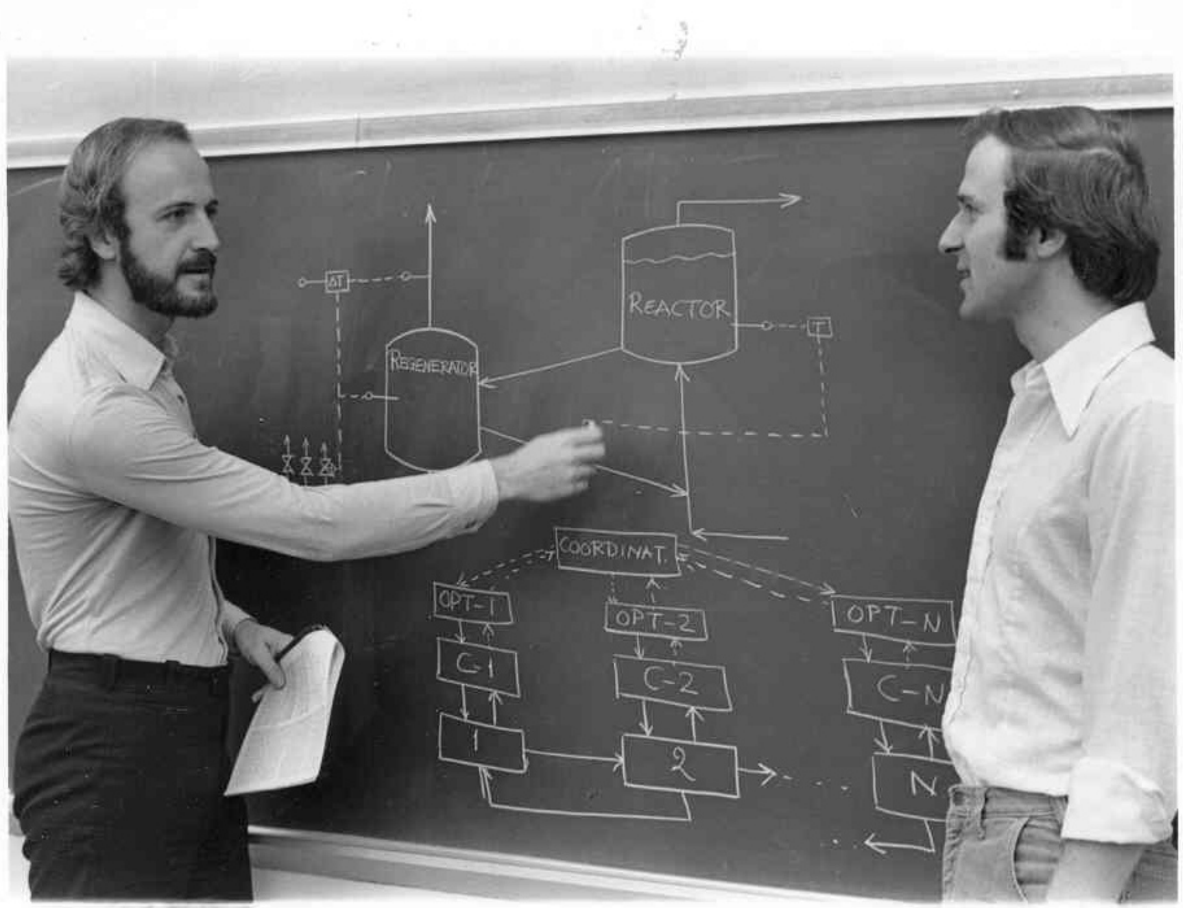
Outline

- My Time with George at U of MN
- Past Attempts to Predict the Future
- Predicting the Future

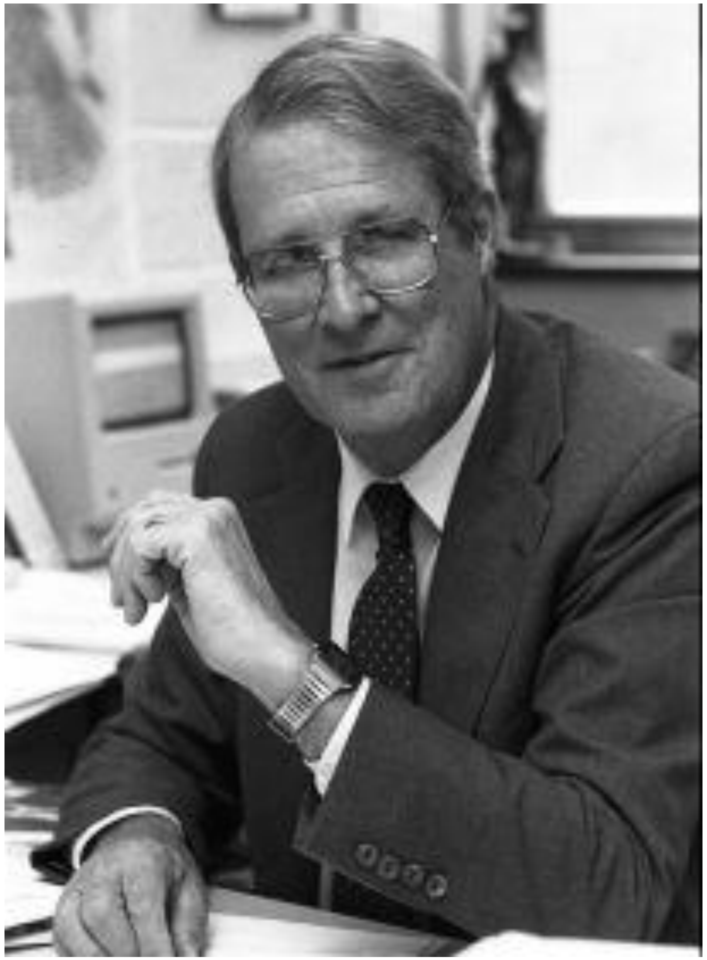
Outline

- **My Time with George at U of MN**
- Past Attempts to Predict the Future
- Predicting the Future

My advisors at the U of Minnesota 1975-77

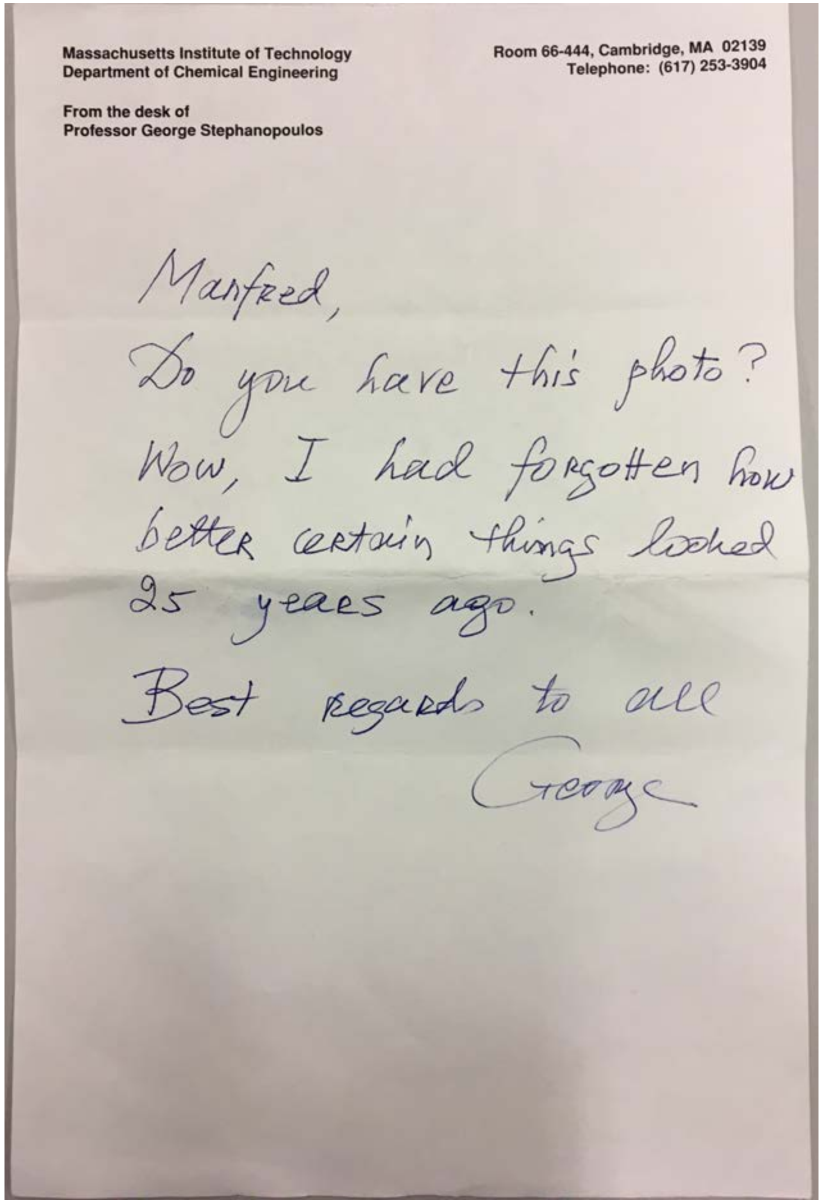


George Stephanopoulos



Rutherford "Gus" Aris 1929-2005

Accompanying Note ~ 1995



Massachusetts Institute of Technology
Department of Chemical Engineering

Room 66-444, Cambridge, MA 02139
Telephone: (617) 253-3904

From the desk of
Professor George Stephanopoulos

Manfred,

Do you have this photo?
Wow, I had forgotten how
better certain things looked
25 years ago.

Best regards to all

George

Technology: Digital Control Computer

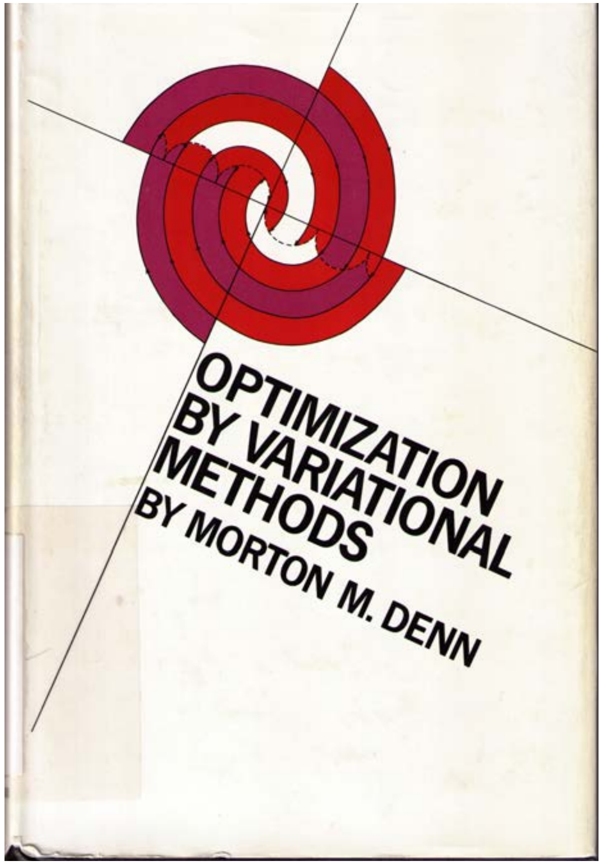
IBM 1800 (introduced 1964)

[wikipedia]

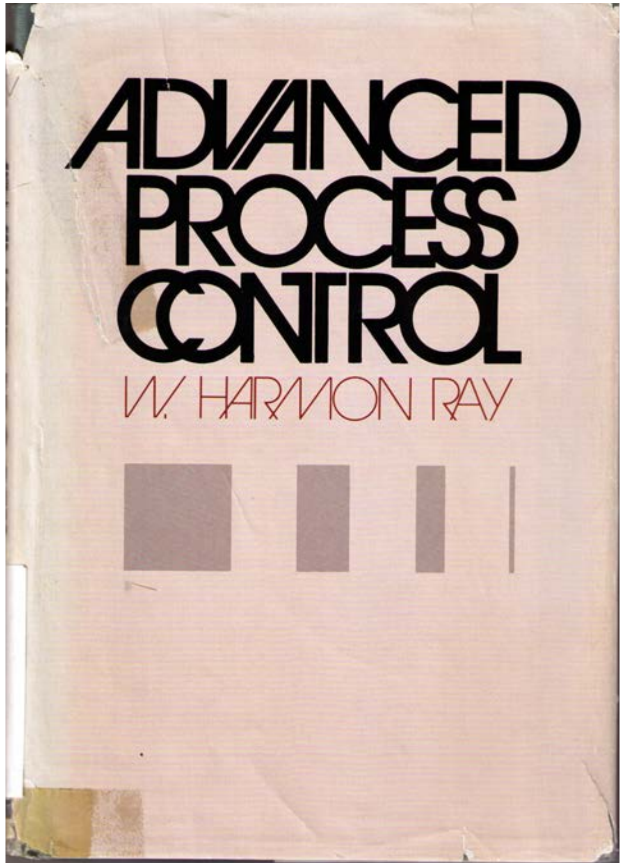
Computer Control ~1968
Standard Oil of California

Courtesy: Chevron

Advanced Process Control Textbooks with Origins at U of Minnesota



1969



1981

Critique of (Process) Control

1973

Critique of Chemical Process Control Theory

A. S. FOSS
Department of Chemical Engineering
University of California, Berkeley, California 94720

1976

Advanced Control Practice in the Chemical Process Industry: A View from Industry

WOOYOUNG LEE
and
VERN W. WEEKMAN, JR.
Mobil Research and Development Corporation
Research Department
Paulsboro, New Jersey 08066

1976

Design Concepts for Process Control

A. Kestenbaum,[1] R. Shinnar,*[1] and F. E. Thau[2]
Departments of Chemical Engineering and Electrical Engineering,
New York, New York 10031

1975

Superiority of Transfer Function Over State-Variable Methods in Linear Time-Invariant Feedback System Design

ISAAC M. HOROWITZ, FELLOW, IEEE, AND URI SHAKED

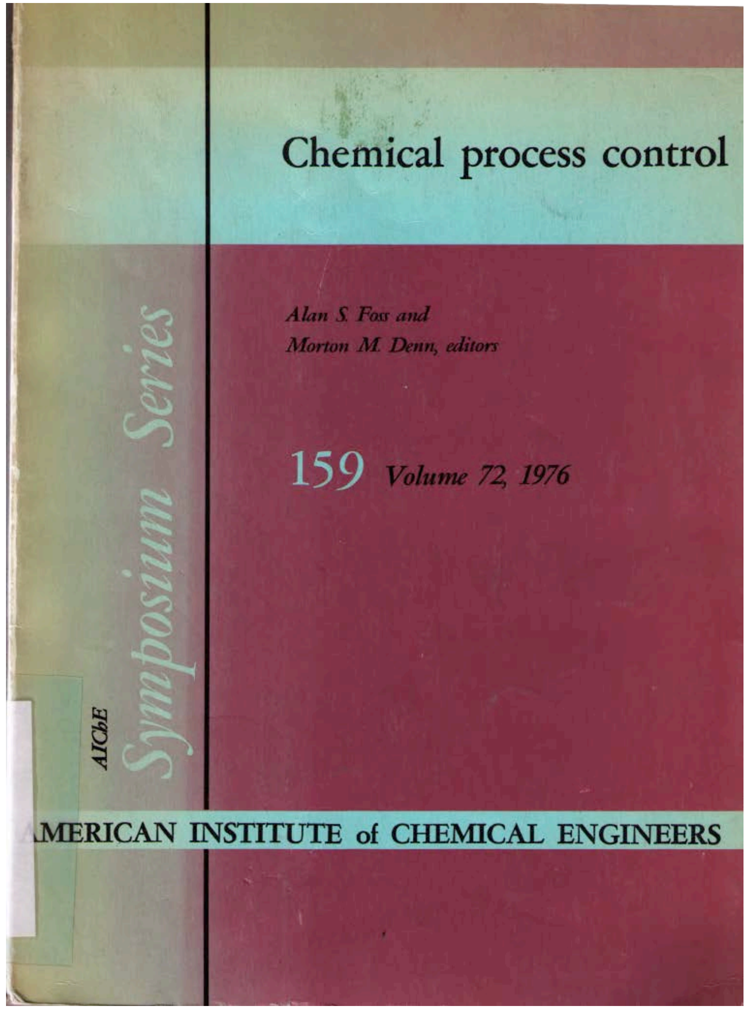
Theory-Practice Gap

Main theme of CPC I in 1976

Explosive development of theory had taken place

- Industry did not understand theory
- Academia had no clue about real controller design

Exceptions: Åström, Gilles, Balchen,…



George’s Research Theme in the 1970s

“The research community is studying the wrong problems”

Importance of Timing and a Good Start

If you are to do important work then you must work on the right problem at the right time and in the right way. Without any one of the three, you may do good work but you will almost certainly miss real greatness.

An important aspect of any problem is that you have a good attack, a good starting place, some reasonable idea of how to begin.

A Stroke of Genius: Striving for Greatness in All You Do
R. W. Hamming October 1993

Socratic Method: Learning by Debate

Success is a journey, not a destination.
The doing is often more important than the outcome.

Arthur Ashe

Major Themes of George's Research Program in the 1970s

"The research community is studying the wrong problem"

- Architectures
  - Control Structure
  - Decomposition for optimization
- Design for Control

Decomposition

Studies in the Synthesis of Control Structures for Chemical Processes

Part I: Formulation of the Problem. Process Decomposition and the Classification of the Control Tasks. Analysis of the Optimizing Control Structures.

MANFRED MORARI
YAMAN ARKUN
GEORGE STEPHANOPOULOS

Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minn. 55455

March, 1980 **AIChE Journal (Vol. 26, No. 2)**

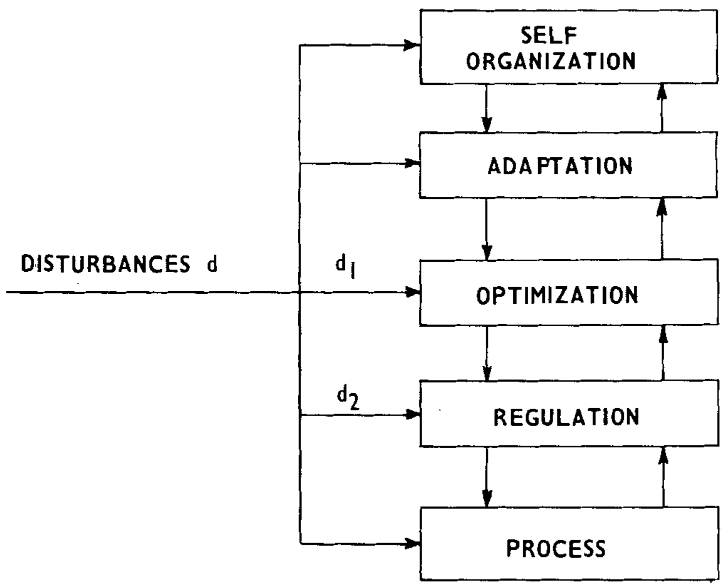


Figure 1. Multilayer decomposition of the control tasks.

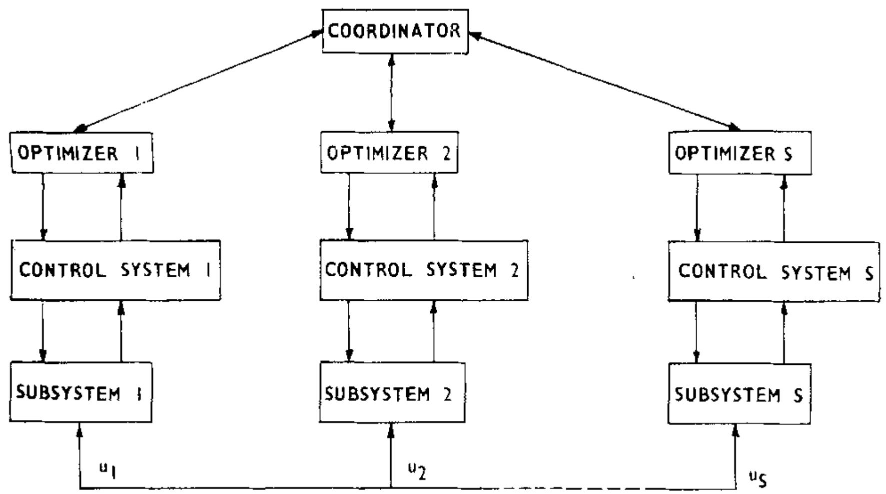
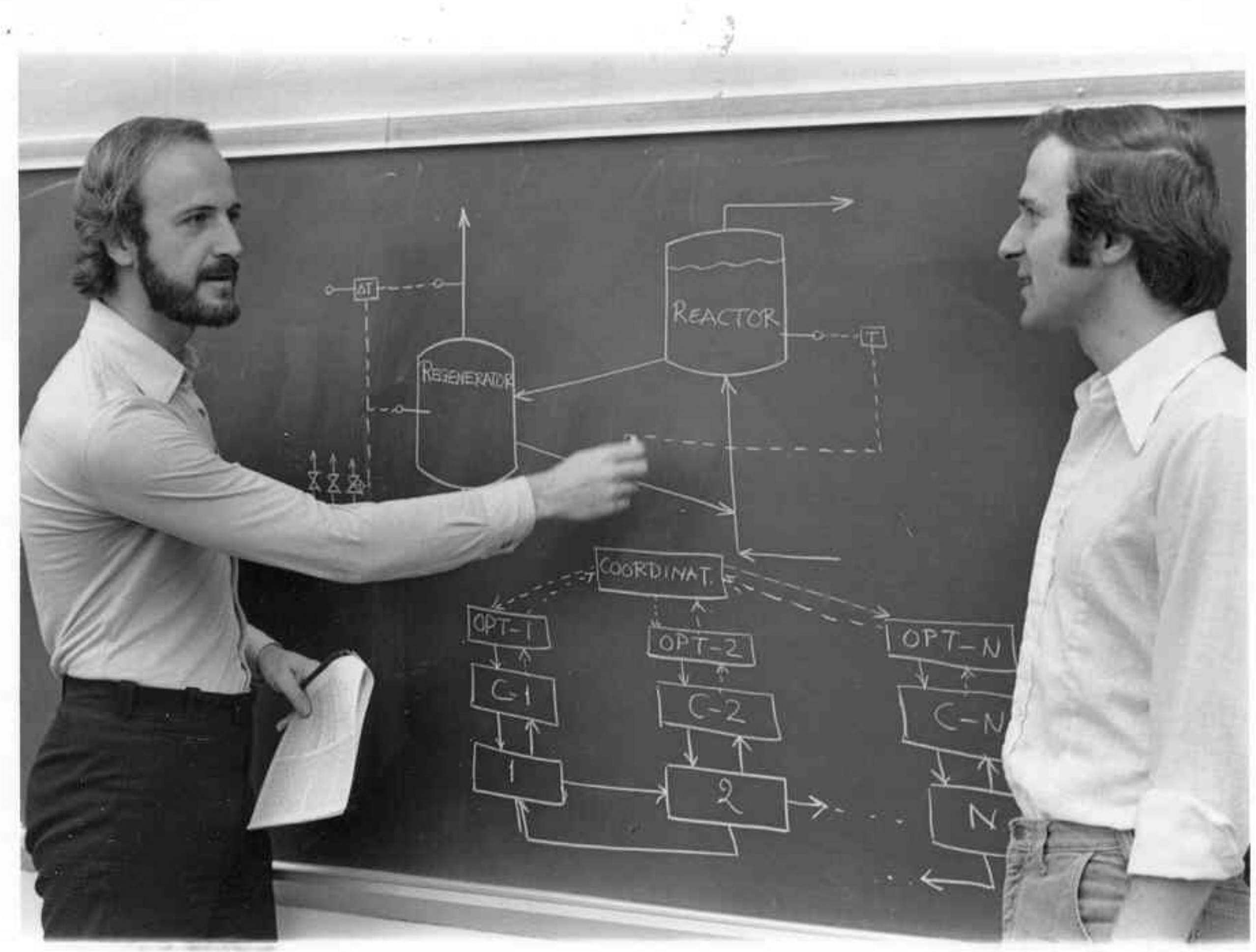


Figure 2. Multiechelon decomposition of the control tasks.

George Arguing about Decomposition



George's Dissertation with Art Westerberg

JOURNAL OF OPTIMIZATION THEORY AND APPLICATIONS: Vol. 15, No. 3, 1975

The Use of Hestenes' Method of Multipliers to Resolve Dual Gaps in Engineering System Optimization[1]

G. STEPHANOPOULOS[2] AND A. W. WESTERBERG[3]

- Lagrangian decomposition
- Method to resolve the dual gap destroying the separability of separable systems

Literature from the 1970s

Decomposition and Optimization

Current revival because

- Suitable hardware has become available
- Problems have become too large, e.g. machine learning

Control Structures

Part II: Structural Aspects and the Synthesis of Alternative Feasible Control Schemes

MANFRED MORARI
and
GEORGE STEPHANOPOULOS
Department of Chemical Engineering
and Materials Science
University of Minnesota
Minneapolis, Minn. 55455

March, 1980
AIChE Journal (Vol. 26, No. 2)

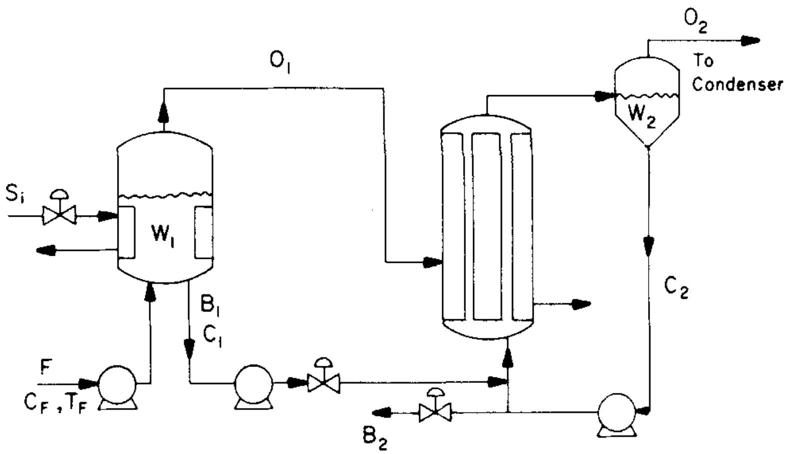


Figure 1. The double effect evaporator.

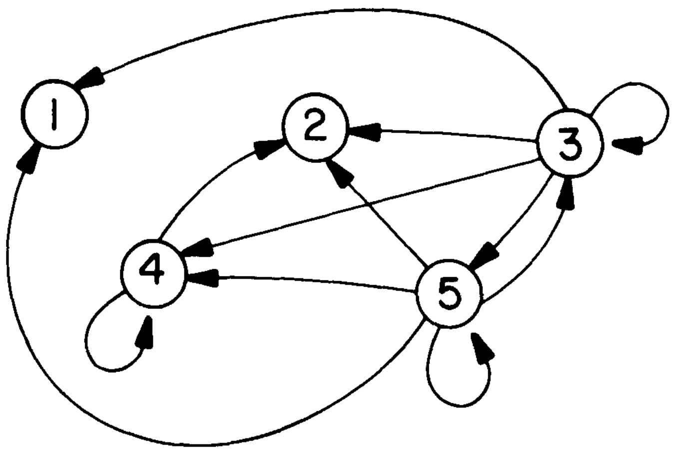


Figure 2. The digraph for the double effect evaporator.

Control Structures

PERGAMON

Automatica 37 (2001) 487–510

automatica

www.elsevier.com/locate/automatica

Survey Paper

A review of methods for input/output selection☆

Marc van de Wal[a,1], Bram de Jager[b,*]

ELSEVIER

Available online at www.sciencedirect.com

SCIENCE DIRECT®

Computers and Chemical Engineering 28 (2004) 219–234

Computers & Chemical Engineering

www.elsevier.com/locate/compchemeng

Control structure design for complete chemical plants☆

Sigurd Skogestad *

Department of Chemical Engineering, Norwegian University of Science and Technology (NTNU), 7491 Trondheim, Norway

Major Themes of George's Research Program in the 1970s

"The Research Community is studying the wrong problem"

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  - Control Structure
  - Decomposition for optimization
- Design for Control

Design for Control

Process Lags in Automatic-Control Circuits

By J. G. ZIEGLER[1] and N. B. NICHOLS,[2] ROCHESTER, N. Y.

TRANSACTIONS OF THE A.S.M.E. JULY, 1943

Methods are given for quantitative determination of time lags in automatically controlled processes. The area under recovery curves is taken as a direct measure of process difficulty, and this area is shown to vary as the second power of the time lag. A "recovery-factor" term, part of a complete expression for controllability, is introduced which makes possible a classification of processes in dimensions of the process itself, regardless of controller or valve mechanism used. Values of this recovery factor from various industrial applications are given in tabular form.

Design for Control

THE CHEMICAL ENGINEER, MAY, 1966 CE97

A PRACTICAL PROBLEM IN DYNAMIC HEAT TRANSFER

By J. S. ANDERSON, B.Sc.*

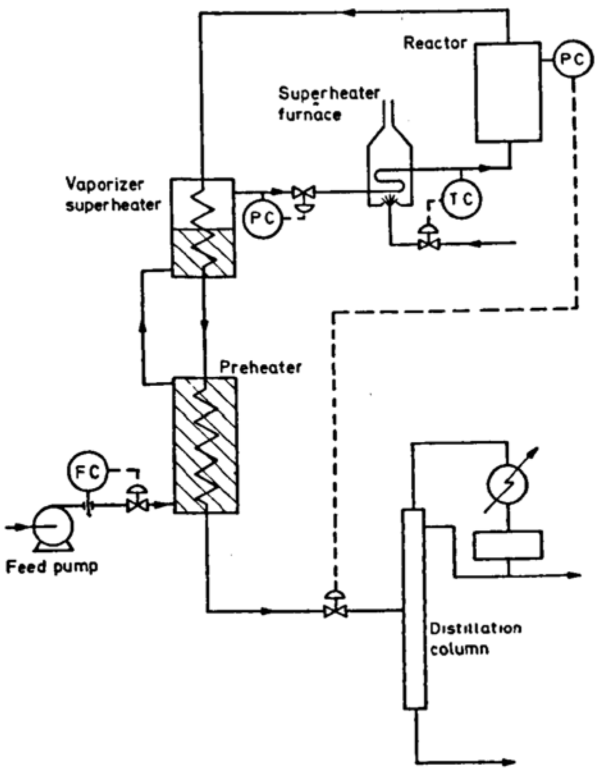


Fig. 1.—*Heat exchange system as originally designed*

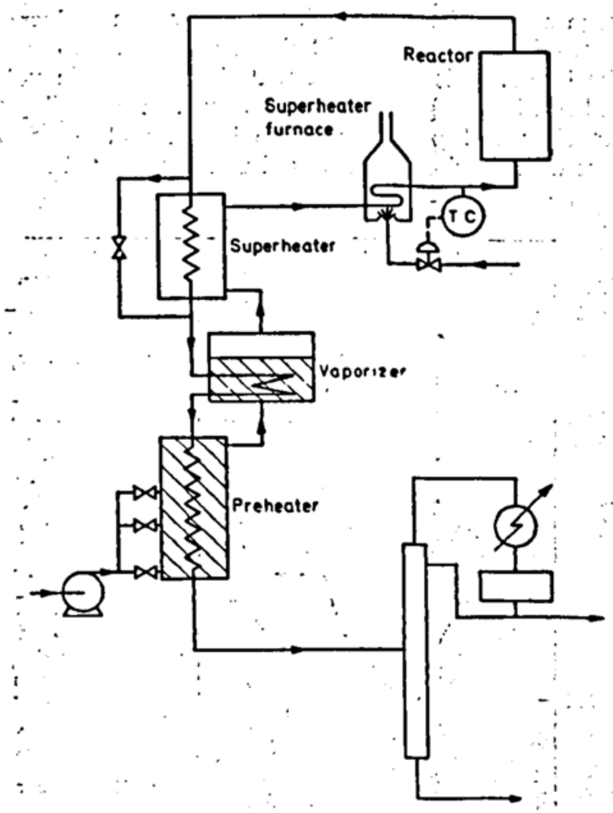


Fig. 8.—*New design of heat exchangers*

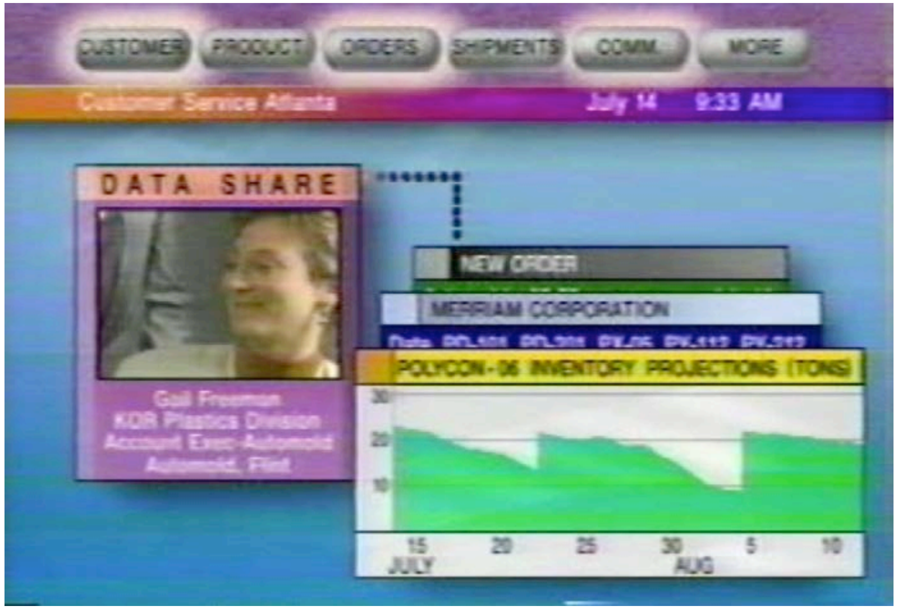
Design for Control

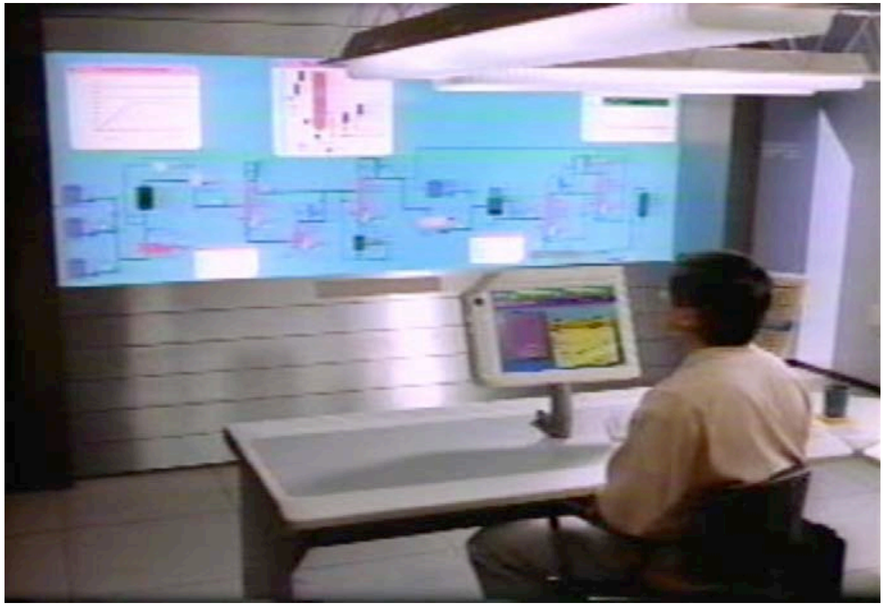
Outline

- My Time with George at U of MN
- **Past Attempts to Predict the Future**
- Predicting the Future

Predicting the future in 1990
Digital Equipment Corp. (DEC) and DuPont

Voice Control
Finger Print ID
Video Phone
Operator Screen





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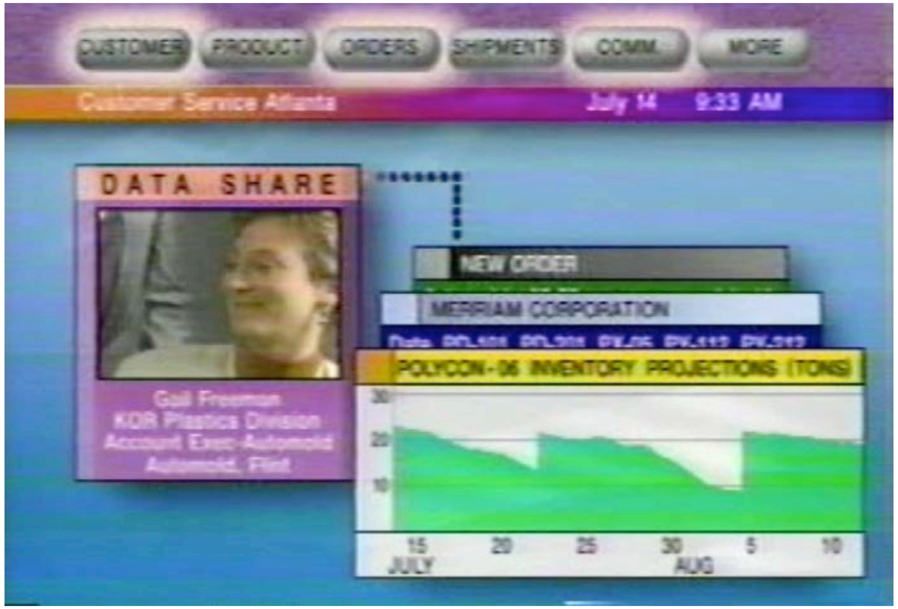

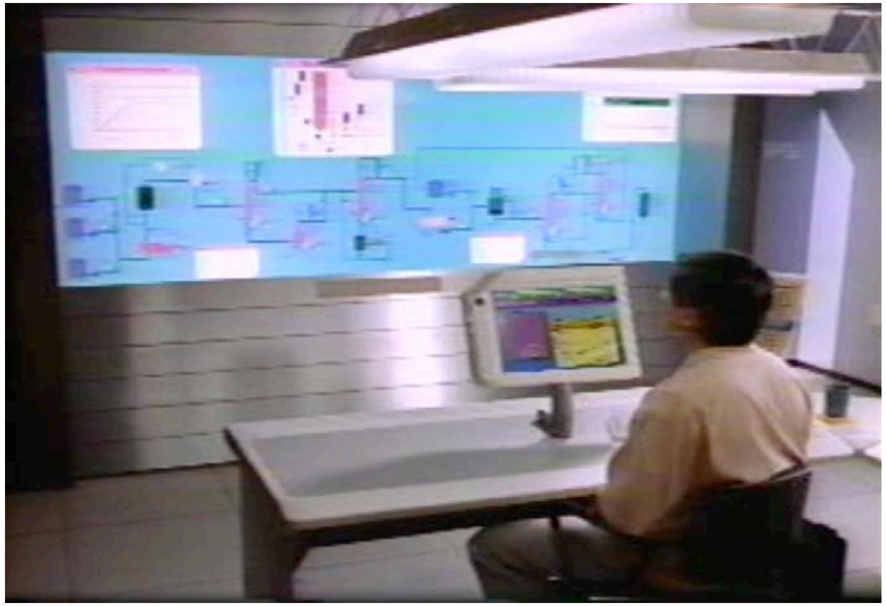

Outline

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- **Predicting the Future**

Status Assessment and Trends

- Interest in control is at an all-time high

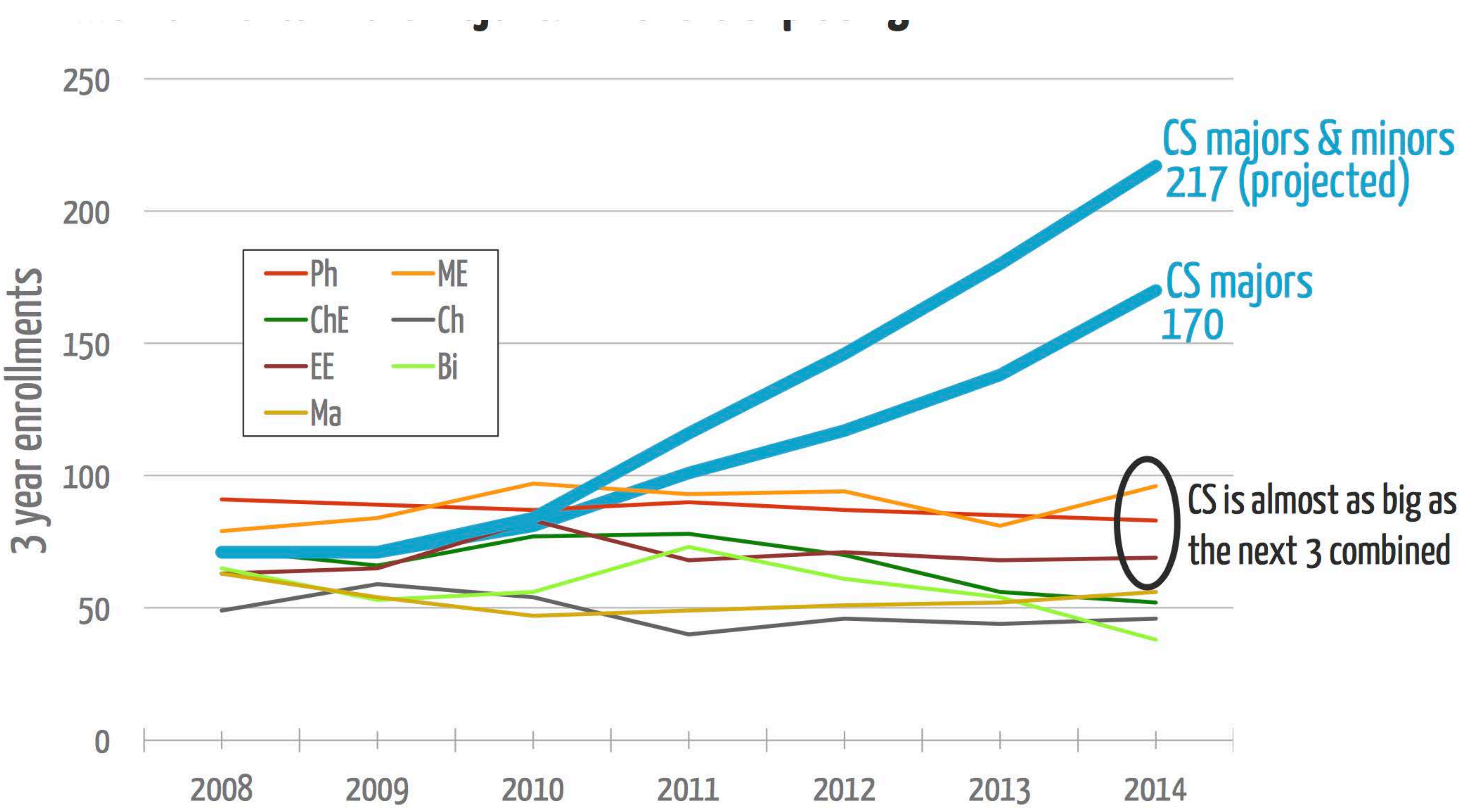
Graduate Course Enrollments ETH

	2008	2009	2010	2015/16
MPC	32	44	67	149
Linear Systems	34	42	59	63
Dynamic Programming	72	101	140	218

Status Assessment and Trends

- Interest in control is at an all-time high
- Interest in computer science is at an all-time high

CS Majors at Caltech



Status Assessment and Trends

- Interest in control is at an all-time high
- Interest in computer science is at an all-time high
- Interest in traditional positions in “hot” areas is low

Raff D'Andrea
PhD students & Post-Docs since moving to ETH

Federico Augugliaro	startup
Mark Muller	assistant professor (Berkeley)
Philipp Reist	startup
Luca Gherardi	startup
Gajamohan Mohanarajah	startup (founder)
Markus Waibel	startup (founder)
Markus Hehn	startup (founder)
Sergei Lupashin	startup (founder)
Raymond Oung	startup
Sebastian Trimpe	group leader (Max Planck)
Angela Schoellig	assistant professor (U. of Toronto)
Michael Sherback	startup
Frederic Bourgault	startup
Guillaume Ducard	assistant professor (U. of Nice)
Oliver Purwin	startup

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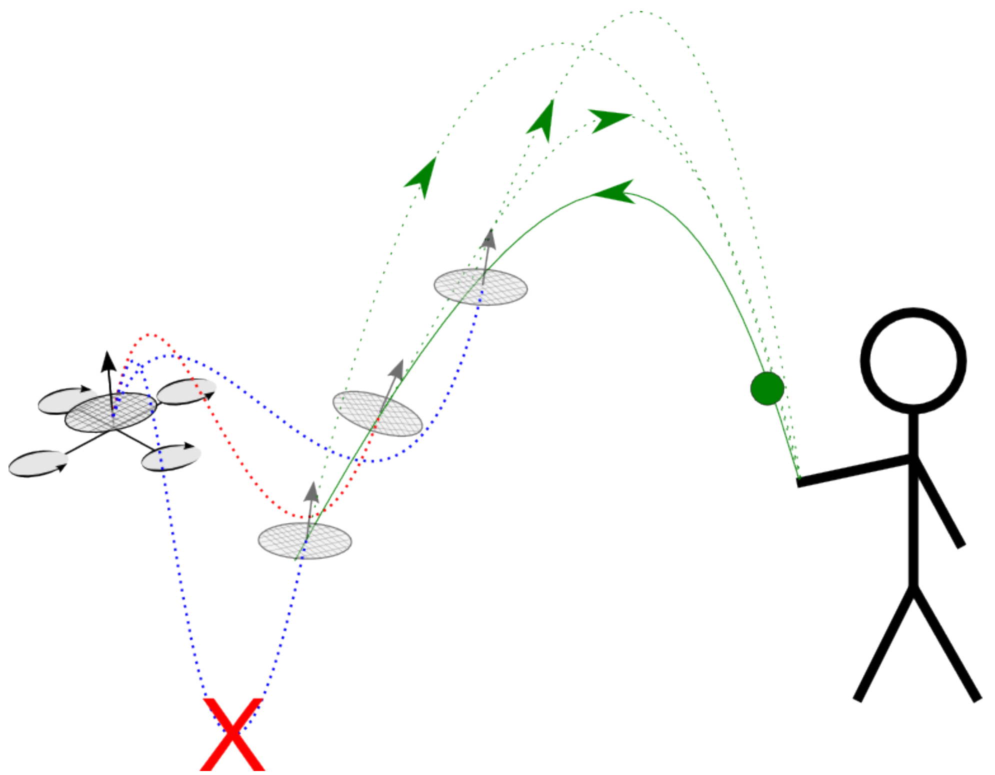
American Control Conference 2017

- 65 / 900 papers on MPC

Example problem

Mark W. Mueller
PhD Thesis, ETH
(w/ Raff D'Andrea)

- Hit back a thrown ball
- Implicit feedback law updated at 20ms
  - Try 10'000 trajectories
    - Sample different ways to hit the ball
  - Apply first 20ms of the best one



Evaluation

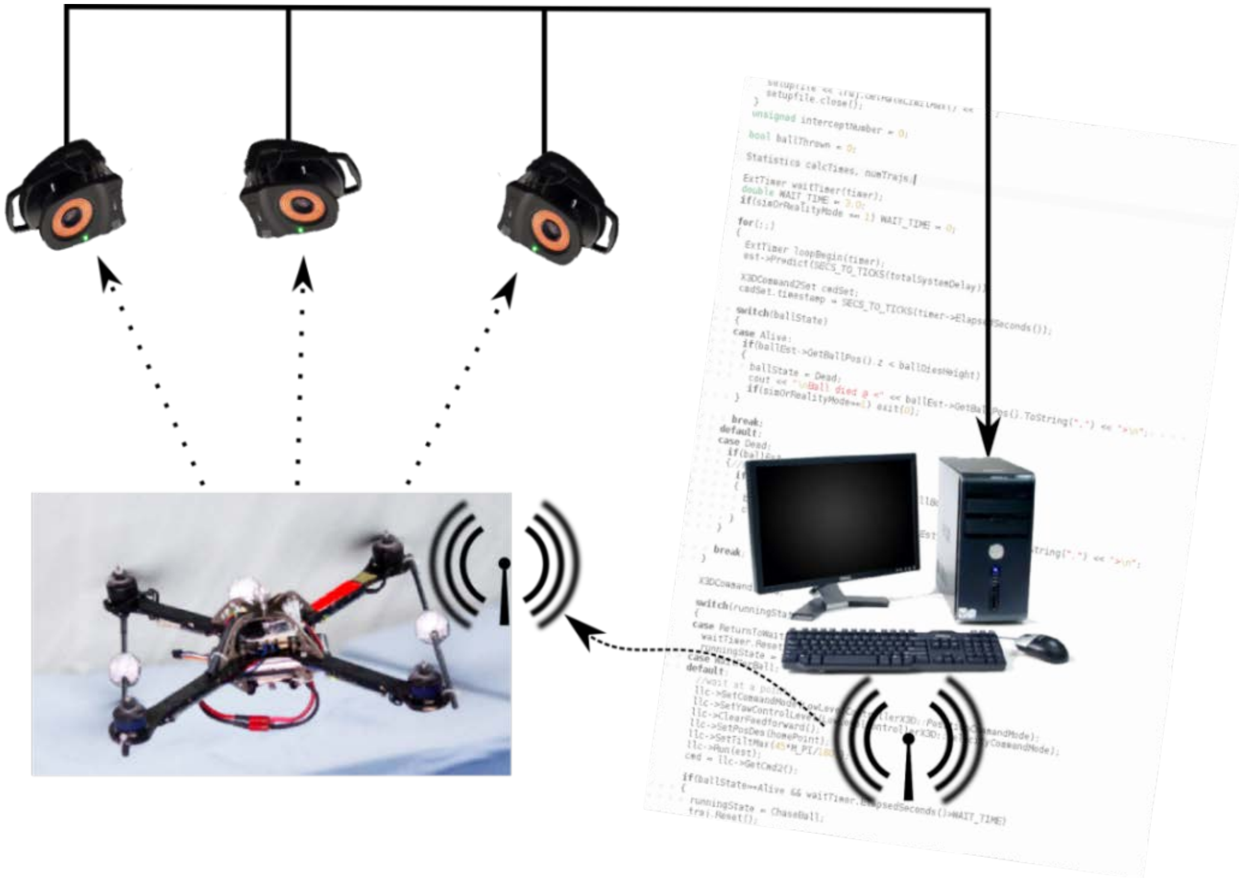
- Algorithm evaluated in the Flying Machine Arena

- System limits

$$c_{\min} = 5\mathrm{m/s}^2$$

$$c_{\max} = 20\mathrm{m/s}^2$$

$$\omega_{\max} = 25\mathrm{rad/s}$$



Rapid trajectory generation for quadrocopters

IDSC

ETH zürich

MPC@MHz

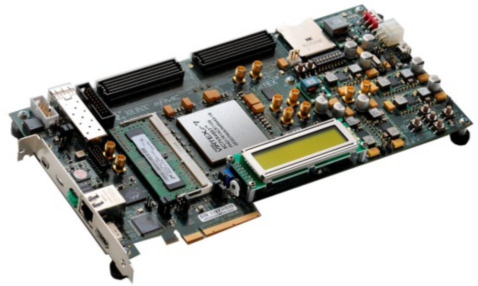
Jerez, Goulart, Richter, Constatinides, Kerrigan, Morari, IEEE TAC 2014

Motivation

Prove feasibility of online optimization@MHz sampling rate

Setup

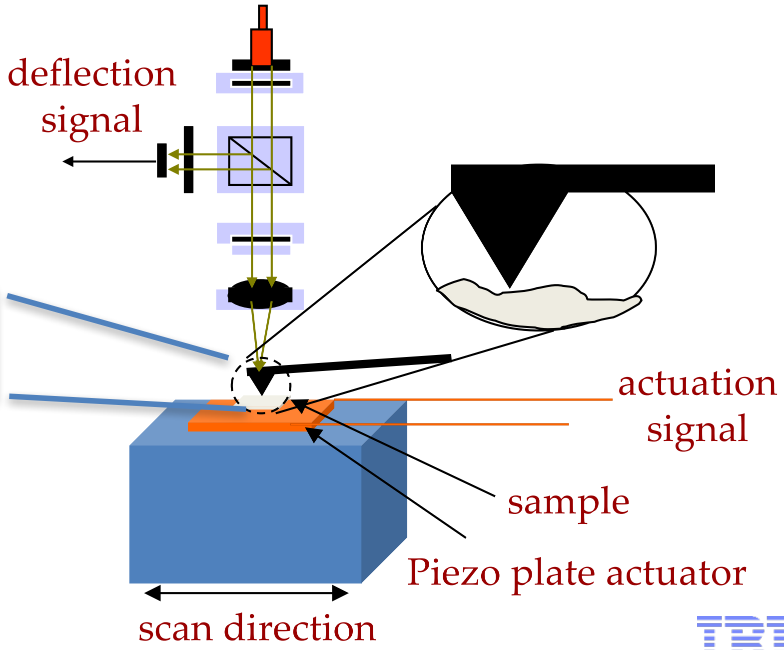
- Algorithms: first-order methods (FGM, ADMM)
- Implementation: hand-crafted fixed-point VHDL design on high-end FPGA (Xilinx Vertex 7)



Case study

Control of Piezo-electric plate actuator
in high-speed AFM (provided by IBM Zurich)

Objective: Maintain constant loading force



Status Assessment and Trends

- Interest in control is at an all-time high
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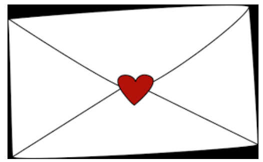
- Interest in predictive control is at an all-time high
- Trends in software and hardware
  - Optimization software
  - Data and Connectivity
  - Validation and Verification

Speedup of software for MIPs

Calculations



Improvement in MIP Software from 1988-2017

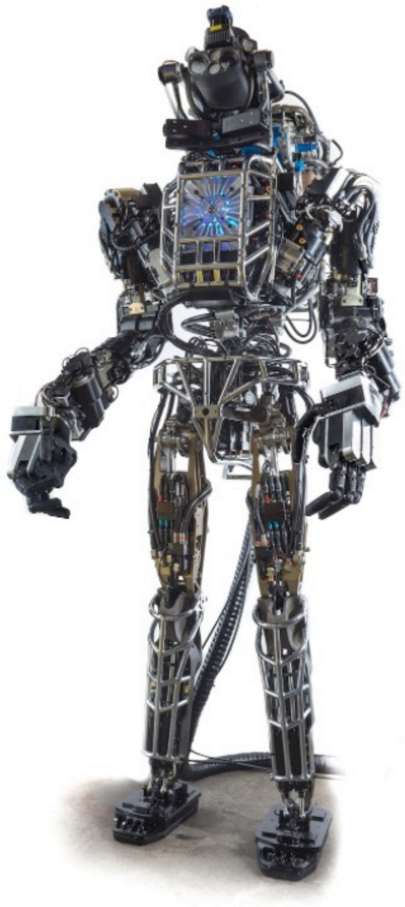
- Algorithms: 147650x
- Machines: 17120x

  http://preshing.com/20120208/a-look-back-at-single-threaded-cpu-performance/
- NET: (Algorithm $\times$ Machine): 2,527,768,000x

What Does This "Mean"?

- A "typical" MILP that would have taken 124 years to solve in 1988 will solve in 1 second now.
- This is amazing, but your mileage may vary

Control and Optimization



Convex and Combinatorial Optimization for Dynamic Robots in the Real World

Russ Tedrake

russt@mit.edu
groups.csail.mit.edu/locomotion

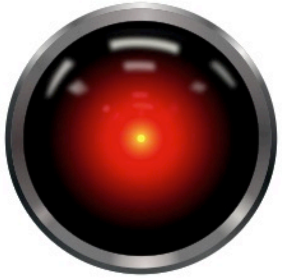
TOYOTA RESEARCH INSTITUTE · Massachusetts Institute of Technology · MIT EECS · MIT MECHE · AEROASTRO · CSAIL

Control and Optimization

MIT's approach to the DARPA Robotics Challenge

Rules allowed a human operator, but with a degraded network connection

Teleoperation

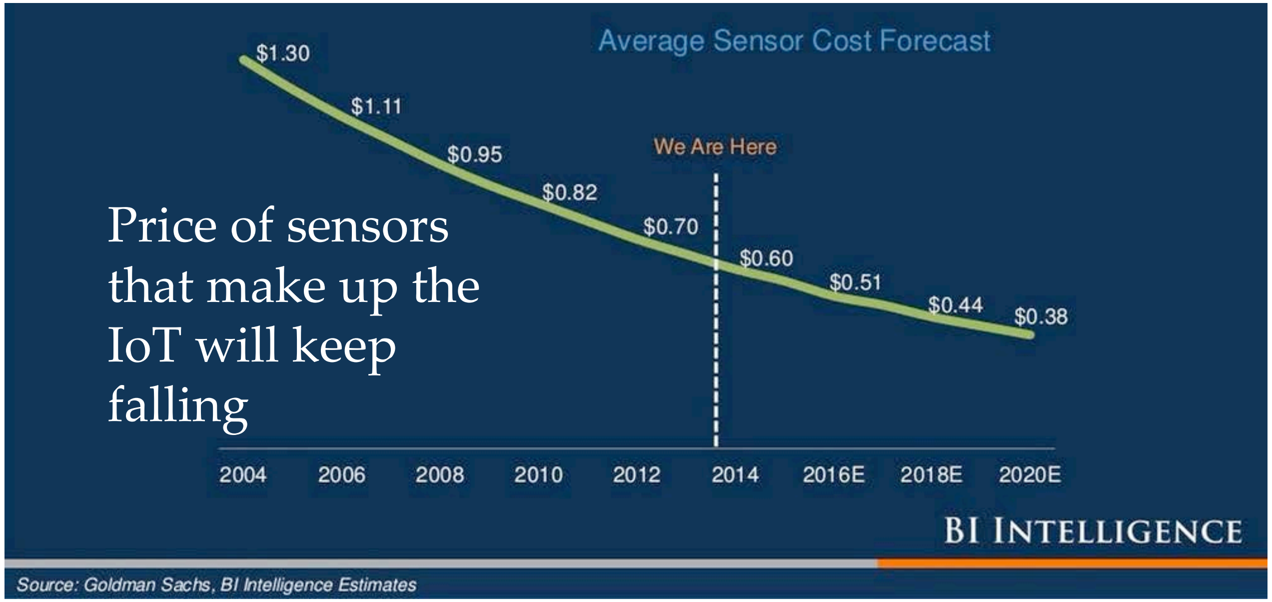


Complete
Autonomy

Our approach:

- Focus on autonomy.
  - Human operator provides high-level ``clicks'' to seed (nearly) autonomous algorithms
- Almost everything the robot does is formulated as an **optimization**
  - For me personally, a triumph for optimization-based synthesis

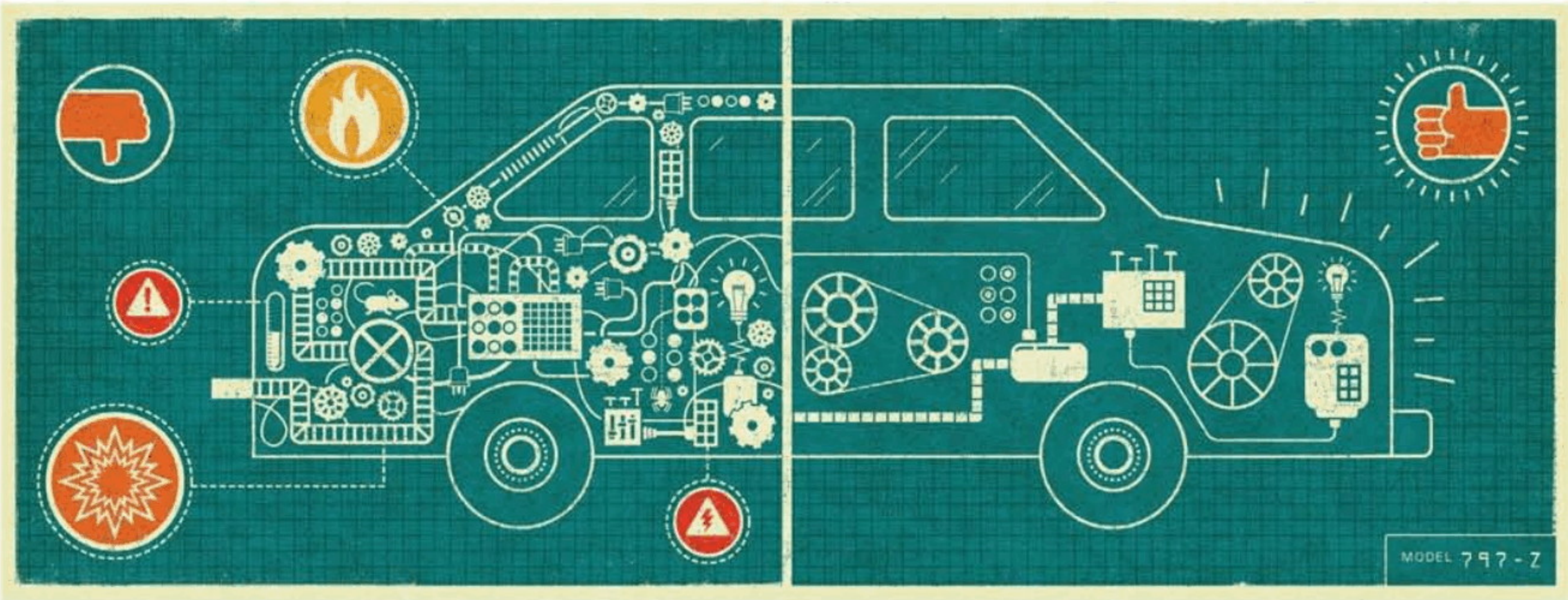
Abundance of Data and Connectivity
The New Opportunity



- 2020: 50 billion devices connected to the internet
- 2020: 800 million smart meters deployed

=> 1 million smart meters generate 1.3 TB data over 90 days.

Harvard Business Review



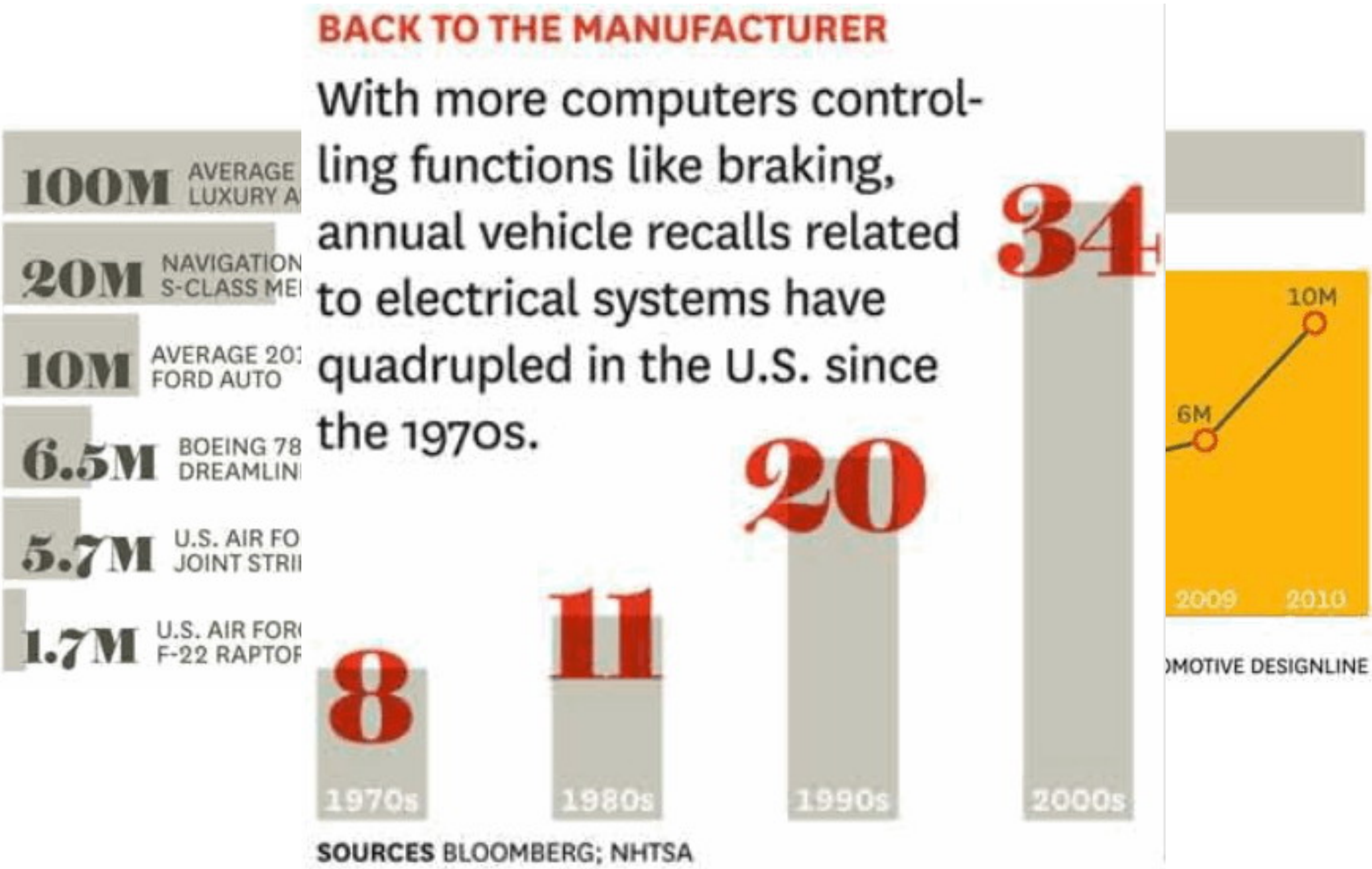
FIRST

Why Dinosaurs Will Keep Ruling the Auto Industry

Get ready for the complexity revolution. *by John Paul MacDuffie and Takahiro Fujimoto*

June 2010

Harvard Business Review



Formal Verification of Embedded Software in Model Based Design

- Model checking of safety properties for Simulink Models
- Avionics distributed control system complexity:
  - 10K-250K simulink blocks
  - 40k-150K binary raw variables
  - Hundred to few thousand bin's after *simplification/abstraction*
- Automotive single controller complexity:
  - 5K-80K simulink blocks
  - Few thousand bin's after *simplification/abstraction*
- FormalSpecsVerifier tool environment (NuSMV)

Source: Alberto Ferrari

Advanced Laboratory on Embedded Systems S.r.l.

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Dear George:

Thank you!

Happy Birthday!

Happy Retirement!