# EC/ME/SE 501 – Dynamic System Theory

## Finite Dimensional Linear Systems

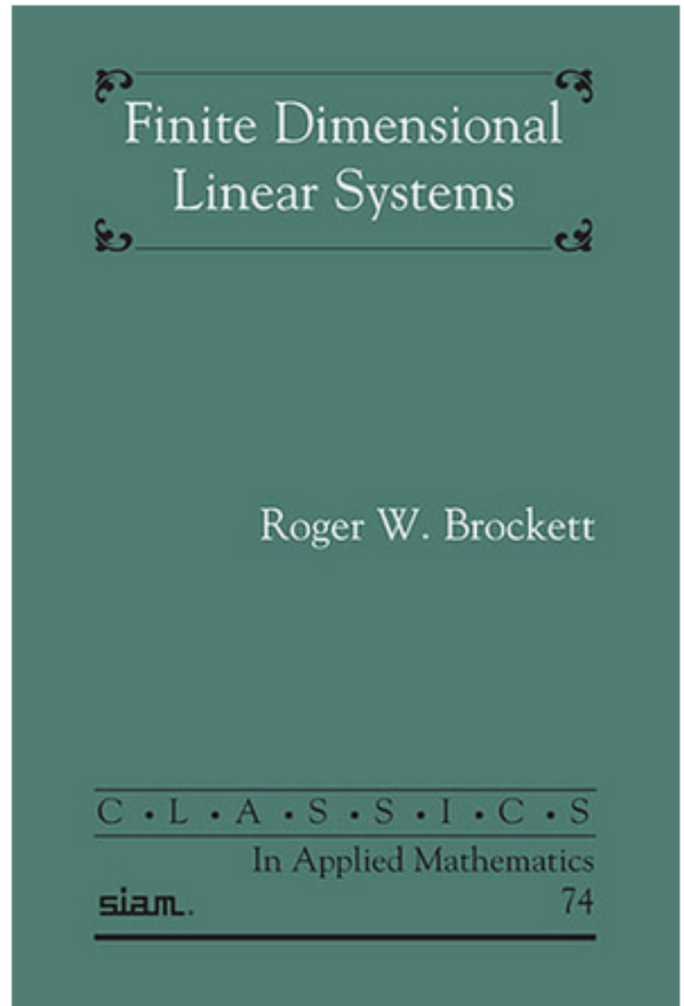
siam

C L A S S I C S

In Applied Mathematics

Roger W. Brockett

Society for Industrial and Applied Mathematics, 2015 / xvi + 244 pages
ISBN 978-1-611973-87-7.

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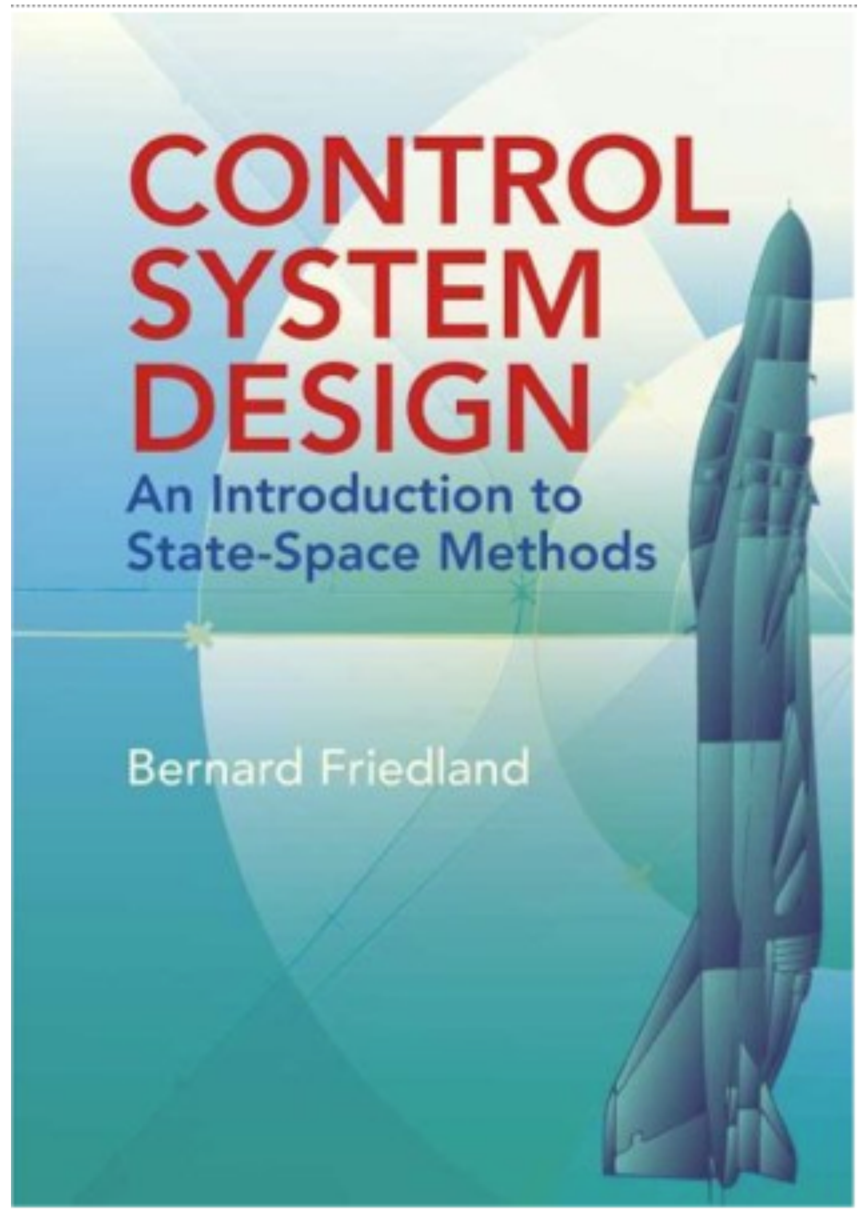
# EC/ME/SE 501 – Dynamic System Theory

## Control System Design: An Introduction to State-Space Methods (Dover Books on Engineering)

Bernard Friedland

Dover Publications (March 24, 2005), 528 pages
ISBN-10: 0486442780, ISBN-13: 978-0486442785

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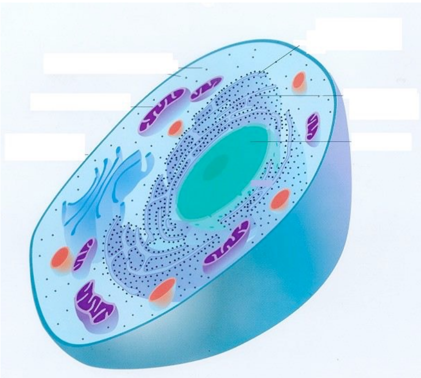
# Control Theory, Networks, and Life Itself



John Baillieul
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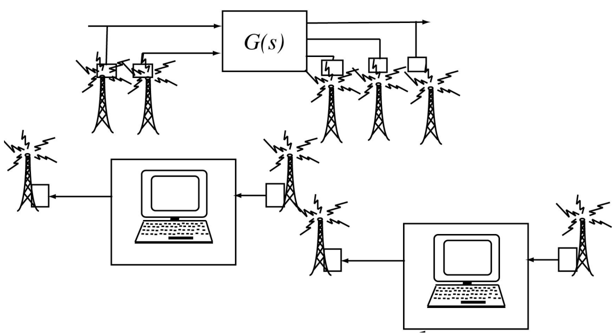
http://www.bu.edu/systems



Boston University
ME 501 First Lecture

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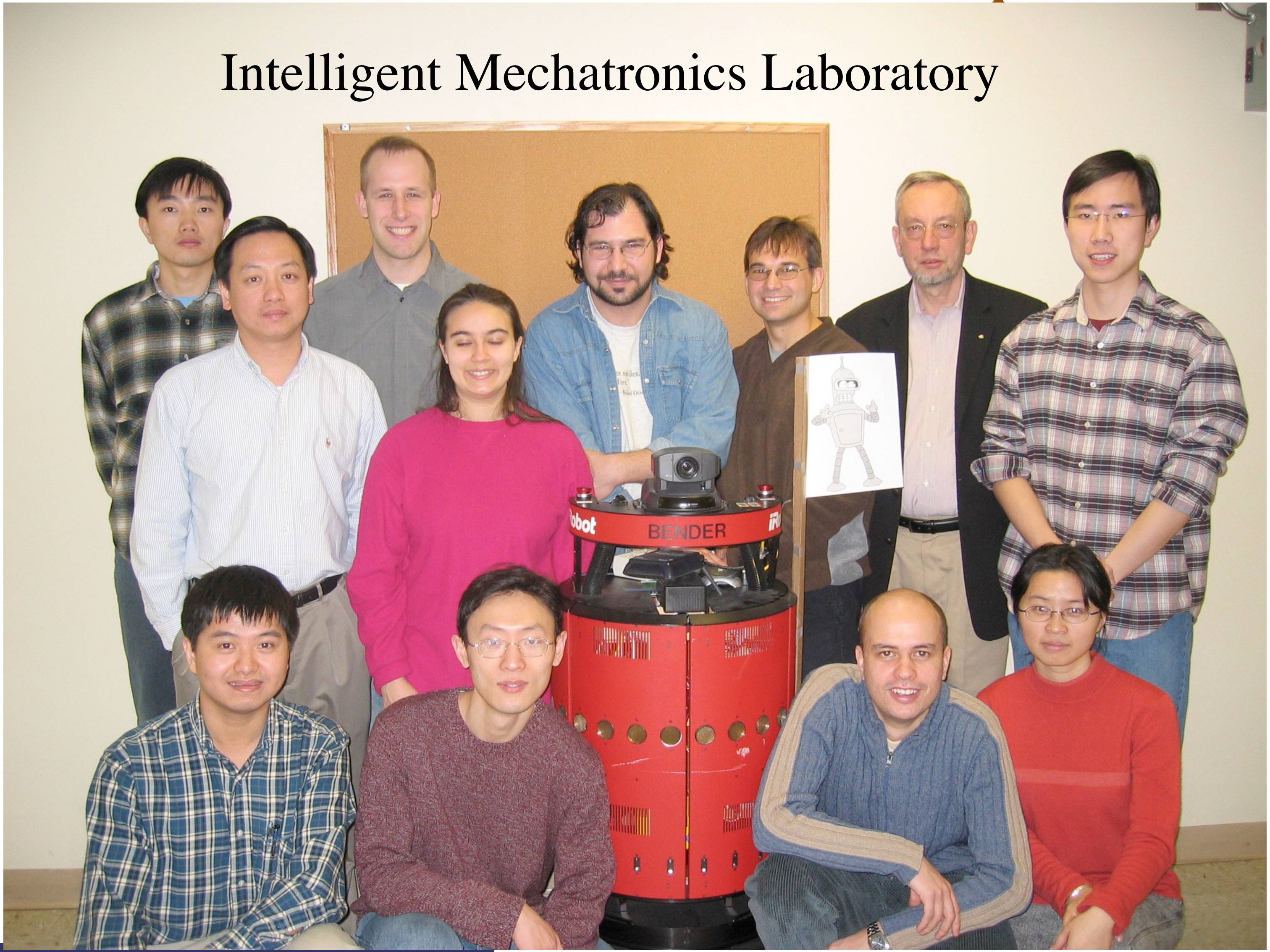
# John Baillieul's Research Group

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# John Baillieul's Hiking Friends

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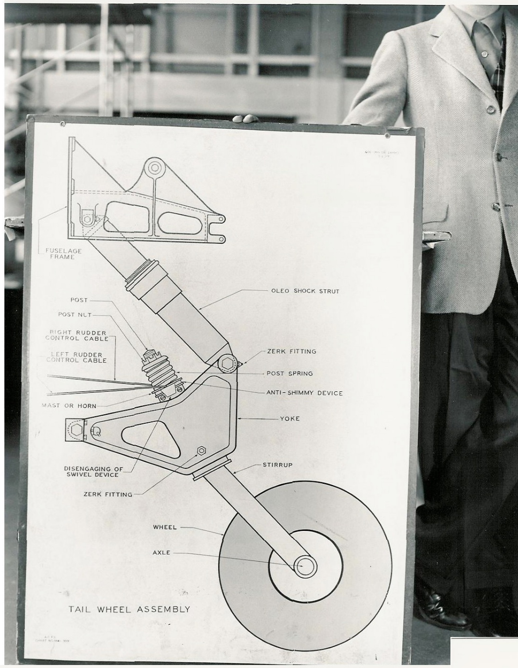
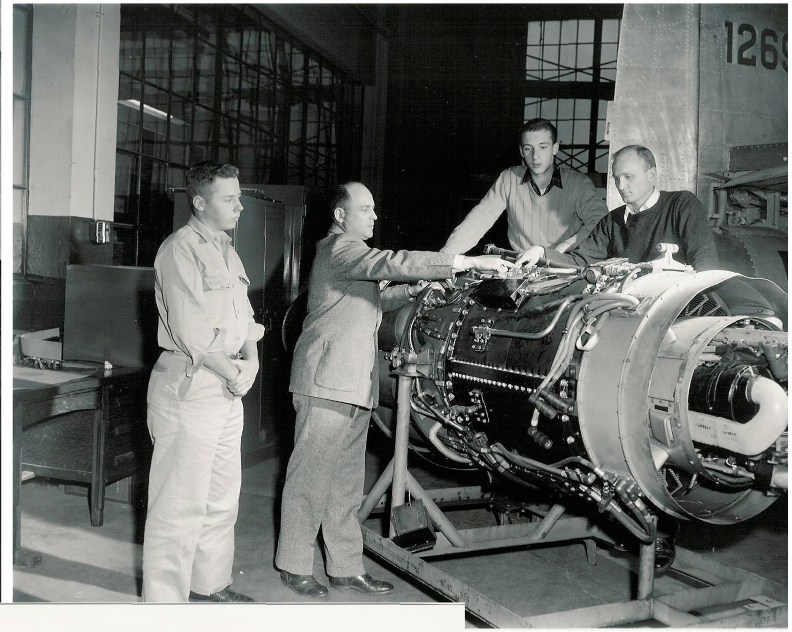
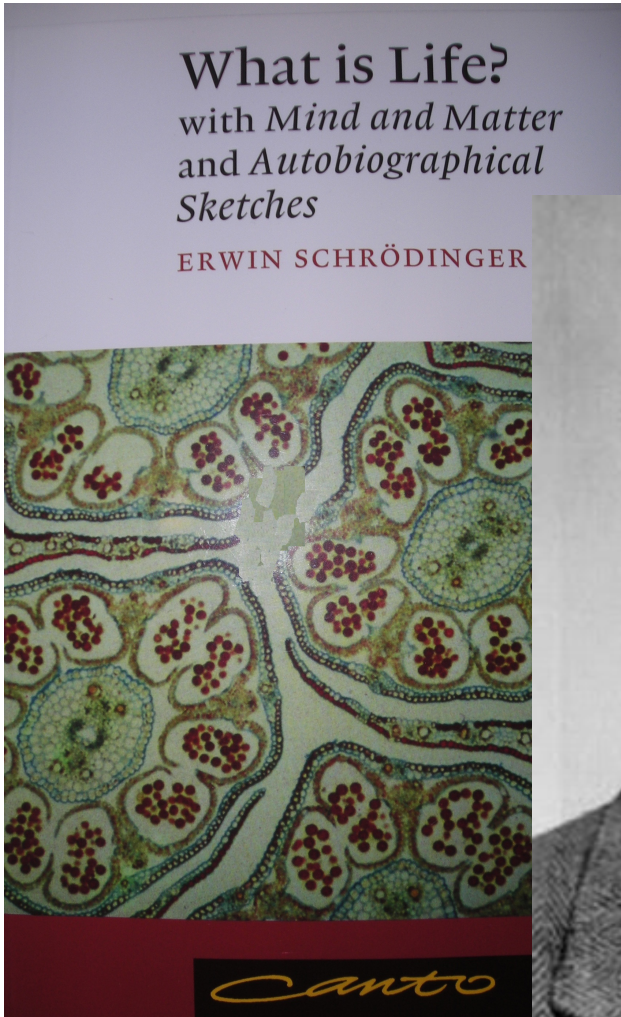
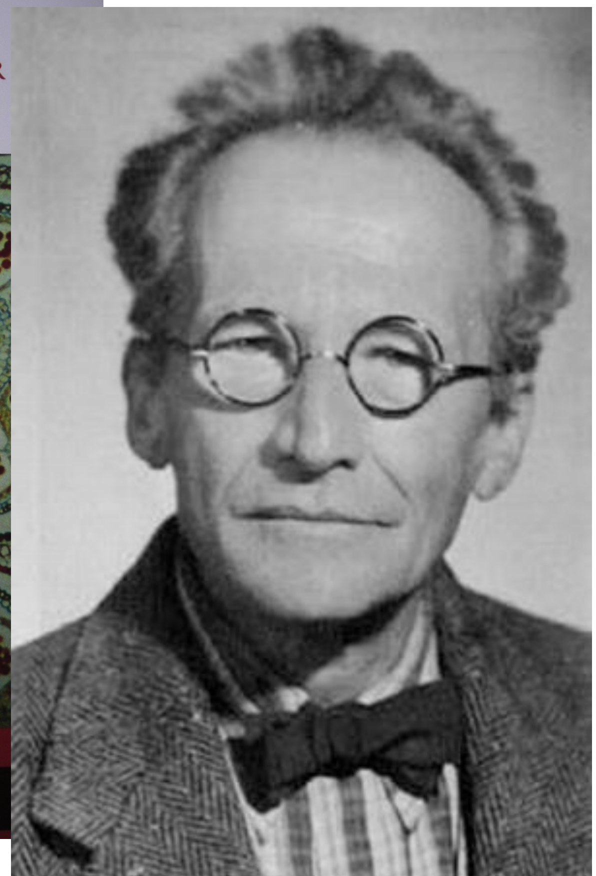
# Boston University---from humble beginnings



# Prior outrageously titled lectures (and books)



Statutory Lectures, 1943, Trinity College, Dublin

- February 5, 1943
- February 12, 1943
- February 19, 1943

"How can the events *in space and time* which take place within the boundary of a living organism be accounted for by physics and chemistry?"

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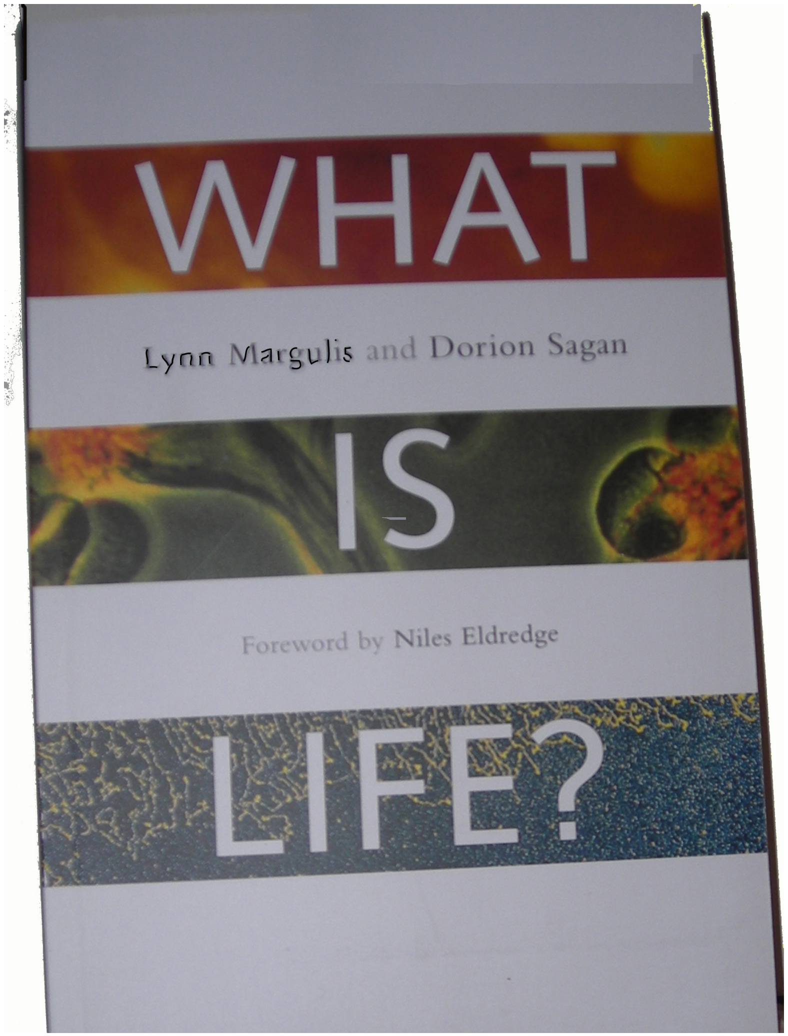
# Prior outrageously titled lectures (and books)




Professor Lynn Margulis
Boston Univeristy
University Lecture 1978
The Early Evolution of Life

Lynn Margulis and Dorion Sagan, *What Is Life?*, University of California Press (August 31, 2000), 303 pages ISBN-10: 0520220218

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# Control Theory: Talk Outline

I. The hidden technology--where is it hiding

II. *Information-based control* - the basis of engineered and natural systems regulated by feedback

III. Networked Control Systems
   - Technologies enabled by information-based control
   - Complex networks of natural and engineered systems

IV. The emerging theory of complexity-based risk and the rational management of failure

V. Controlling highly structured motions of groups of agents
   1) The theory of rigid formations
   2) Spatial and dynamic information patterns

III. Conclusions

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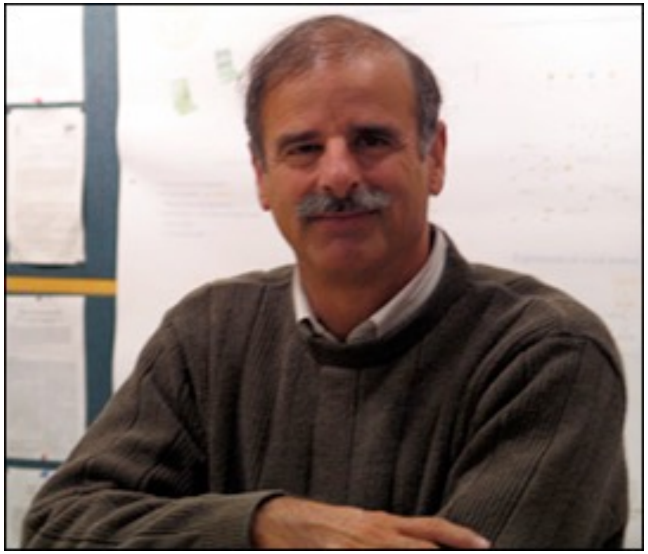
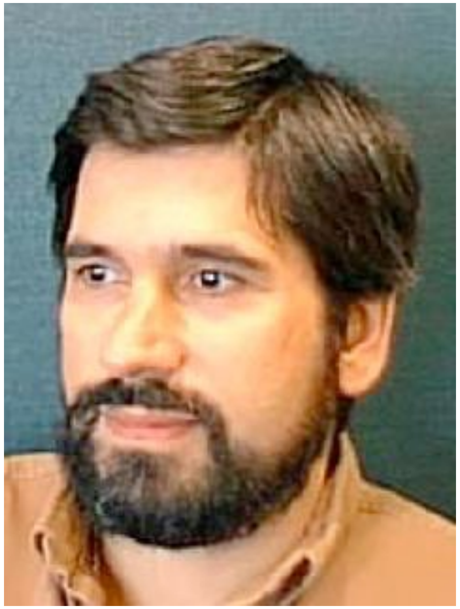
# People in Control at B.U.



Professor David A. Castañon
42-nd President of the IEEE Control Systems Society

Professor Christos G. Cassandras
46-th President of the IEEE Control Systems Society



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# People in Control at B.U.

Professor Theodore E. Djaferis
41-st President of the IEEE Control Systems Society

Emeritus Dean of Engineering
University of Massachusetts

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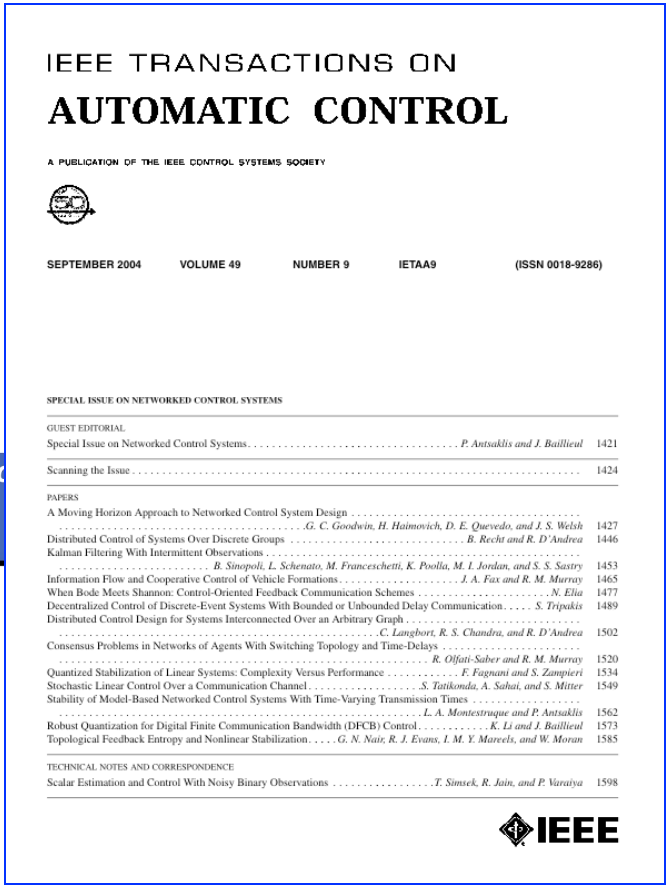
# World's leading journals at B.U.

SIAM J. on Control and Optimization

IEEE TRANSACTIONS ON

AUTOMATIC CONTROL

A PUBLICATION OF THE IEEE CONTROL SYSTEMS SOCIETY

SEPTEMBER 2004 VOLUME 49 NUMBER 9 IETAA9 (ISSN 0018-9286)

SPECIAL ISSUE ON NETWORKED CONTROL SYSTEMS



IEEE

| JCR Year and Edition: 2006 Science - Elec | | | |
|---|---|---|---|
| **Abbreviated Journal Title** | **ISSN** | **2006 Total Cites** | **Impact Factor** |
| IEEE T AUTOMAT CONTR | 0018-9286 | 15573 | 2.772 |
| ELECTRON LETT | 0013-5194 | 14983 | 1.063 |
| IEEE T PATTERN ANAL | 0162-8828 | 14708 | 4.306 |
| IEEE T INFORM THEORY | 0018-9448 | 14149 | 1.938 |
| IEEE PHOTONIC TECH L | 1041-1135 | 13528 | 2.353 |
| J LIGHTWAVE TECHNOL | 0733-8724 | 11582 | 2.824 |
| P IEEE | 0018-9219 | 11363 | 3.686 |
| IEEE T MICROW THEORY | 0018-9480 | 10815 | 2.027 |
| J VAC SCI TECHNOL B | 1071-1023 | 10633 | 1.597 |
| IEEE T MAGN | 0018-9464 | 10422 | 0.938 |

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# The Hidden Technology

- Pervasive
- Very successful
- Seldom talked about

Except when there is an accident!
Rare occasions!

- Why?

Easier to discuss devices than ideas (feedback)
We have not done our job!

K. J. Åström ECC August 31, 1999

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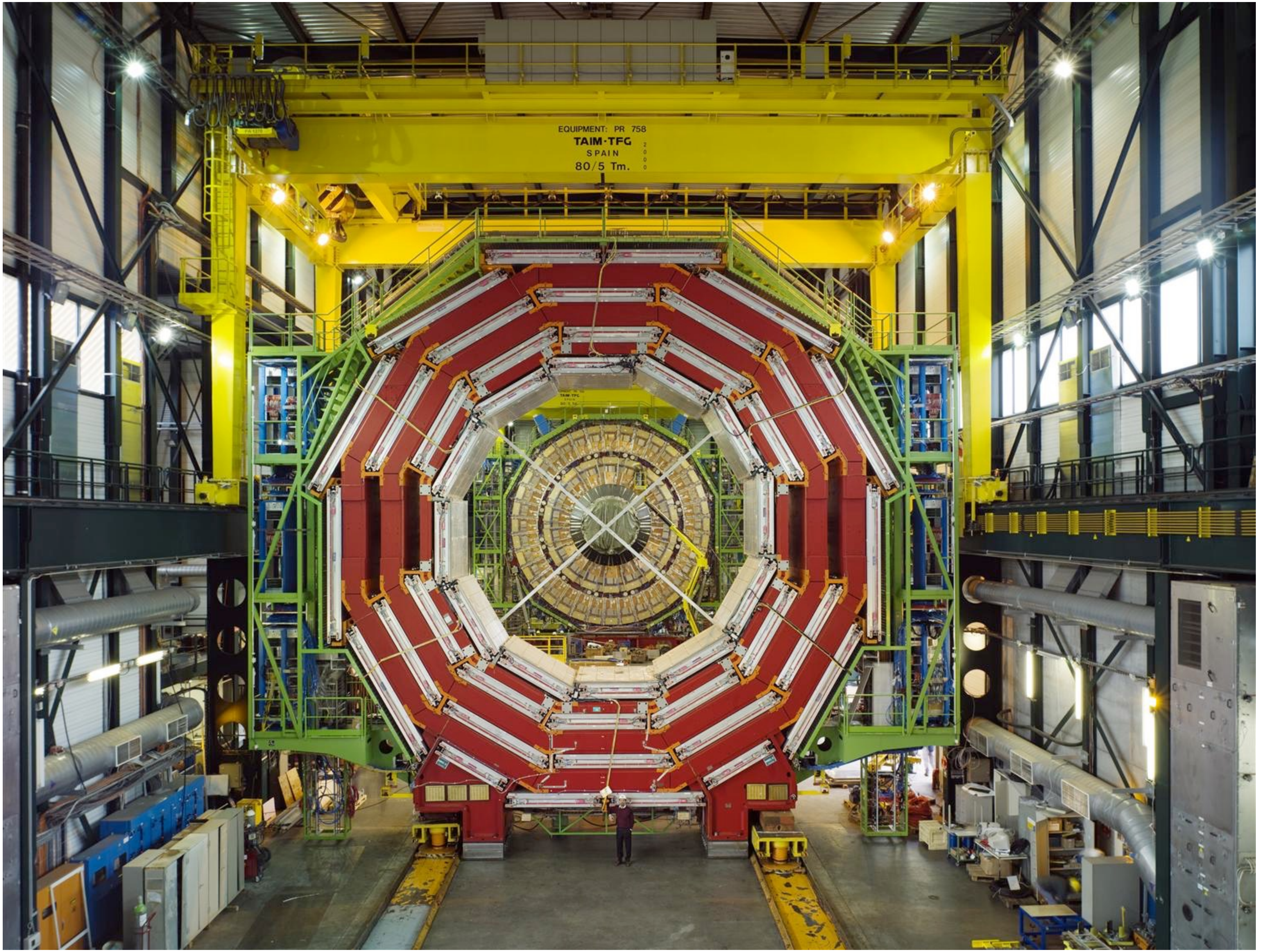
EQUIPMENT: PR 758
TAIM·TFG
SPAIN
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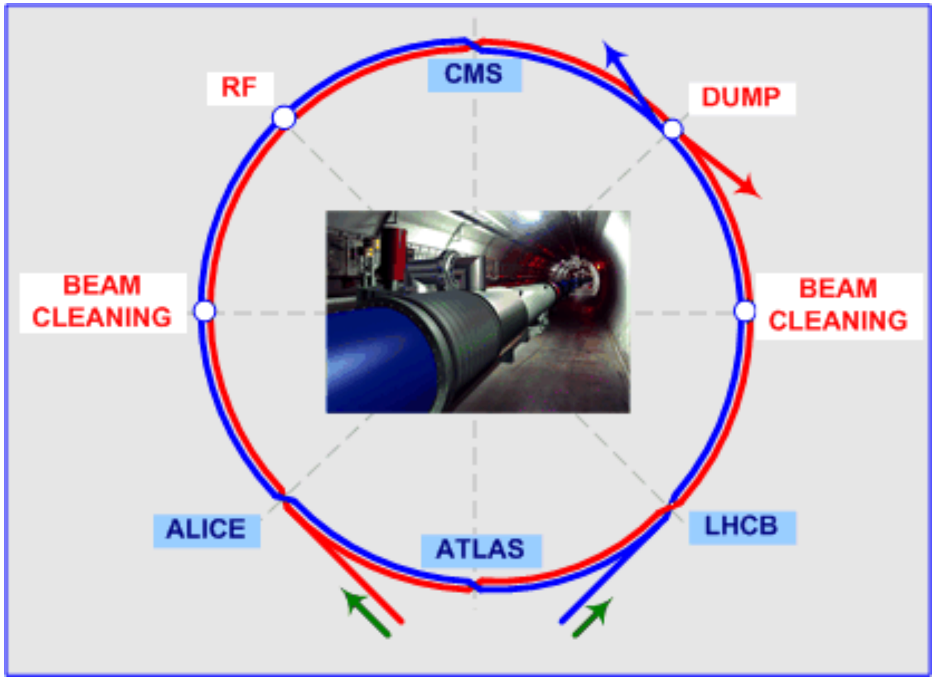
2000

# The World's largest physics experiment is enabled by control tehnologies

- 27 km. (18 mi.)circumference
- Beam steered, collimated by superconducting magnets
- Beam comprised of 2835 bunches of $10^{11}$ protons




- Experiment operates at ~$0^oK$
    - 12M litres liq. N
    - 0.7M litres liq. He
- Time constants
    - Thermal = 0.5 years
    - Beam control = nano sec. and 10 hours

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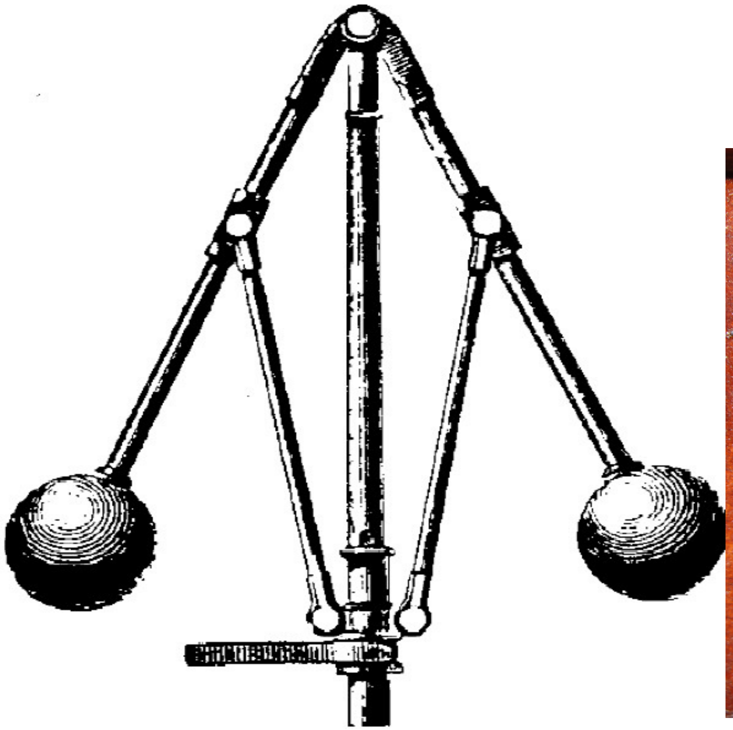
# The control of machines

From simple origins to life-saving enhancements. . .

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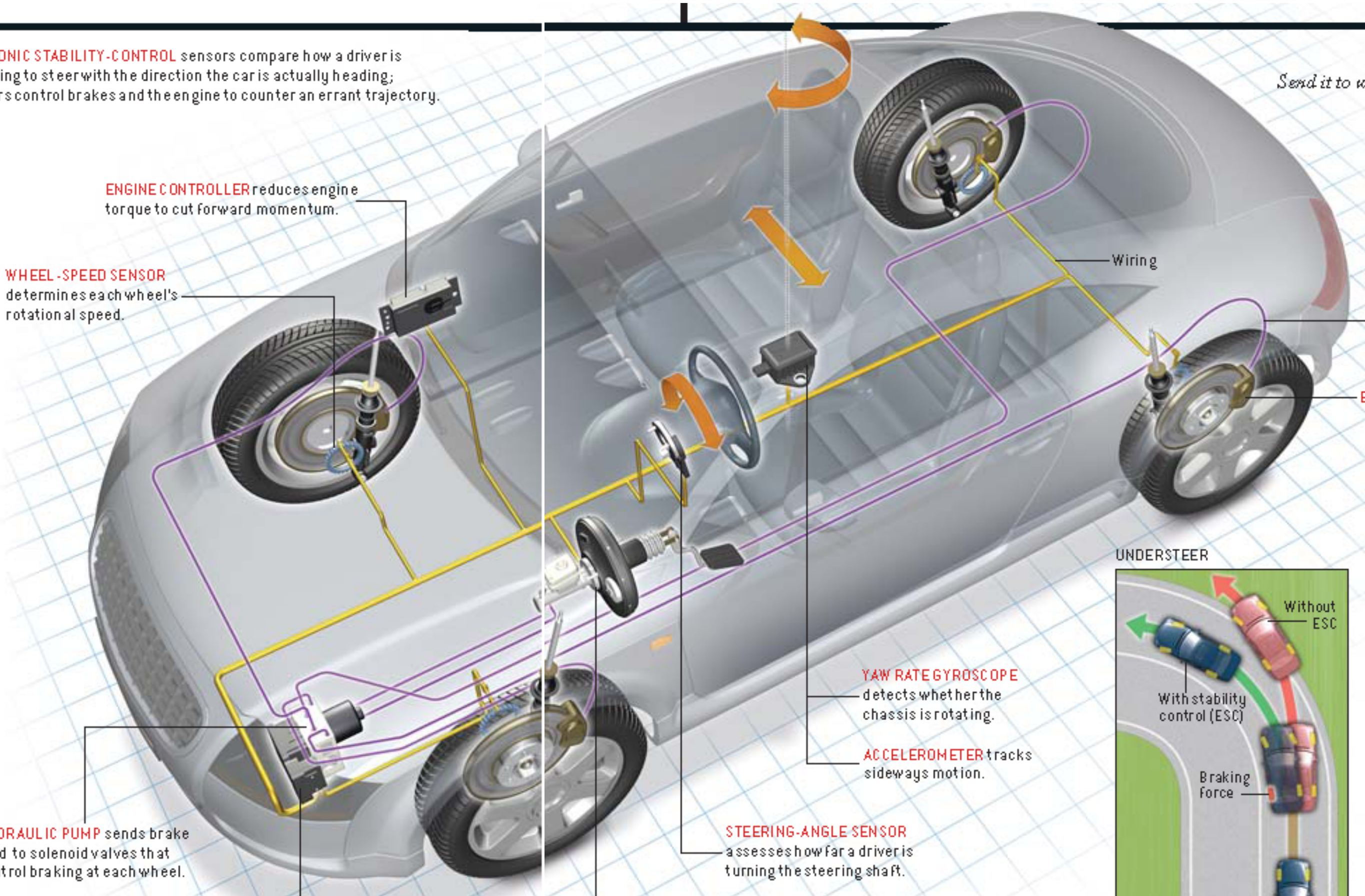
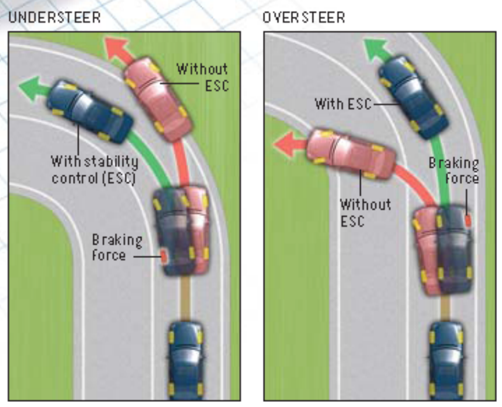
ELECTRONIC STABILITY-CONTROL sensors compare how a driver is attempting to steer with the direction the car is actually heading; actuators control brakes and the engine to counter an errant trajectory.

*Have a topic idea? Send it to workingknowledge@sciam.com*




SAMUEL VELASCO; SOURCES: CONTINENTAL AUTOMOTIVE SYSTEMS; ROBERT BOSCH




IN UNDERSTEER, a driver tries to turn, but the front wheels slide forward; brief braking on the left rear wheel adds a pivoting torque to pull the car around and reduces lateral force on the tire. In oversteer, the car turns too hard, causing the back end to fishtail and possibly spin out or even roll over; brief braking on the right front wheel adds a pivot and reduces the lateral force.







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"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. In an instant, instructions are sent to the engine, transmission and brakes, thereby encountering a skid at its onset. …"

K. J. Åström ECC August 31, 1999

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# The Position of Control as a Discipline

- Respected
- Coupled to a vast array of engineered systems
- Lacks distinct identity (CERN example)
- Lacks an identifiable industrial base (cf. computers and mobile comm. devices)
- Academic positioning

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# A Brief History of the Field

Closely tied to emerging technologies
(steam, power, electricity, telephone, aerospace ...)

Telecommunications
- Blacks invention 1927
- Nyquist 1932
- Bode 1940
- Servomechanism theory

Consequences

The second wave
- Recursive estimation
- Maximum principle

# The Third Wave

Driving forces
• New challenges
• New applications
• Mathematics
• Computers
Basic paradigm
• State Space
Rapid expansion
• Subspecialities

Optimal Control
Nonlinear Control
Stochastic Control
Computer Control
Robust Control
Robotics
Adaptive Control
CACE
Cooperative and decentralized control

# The Next Wave

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# The two ages of joint cognitive transport systems

The First Age of Joint Cognitive Transport

The Second Age

4,000 BC
First domesticated draught animals

1900 AD 2010 AD
The age of mechanized





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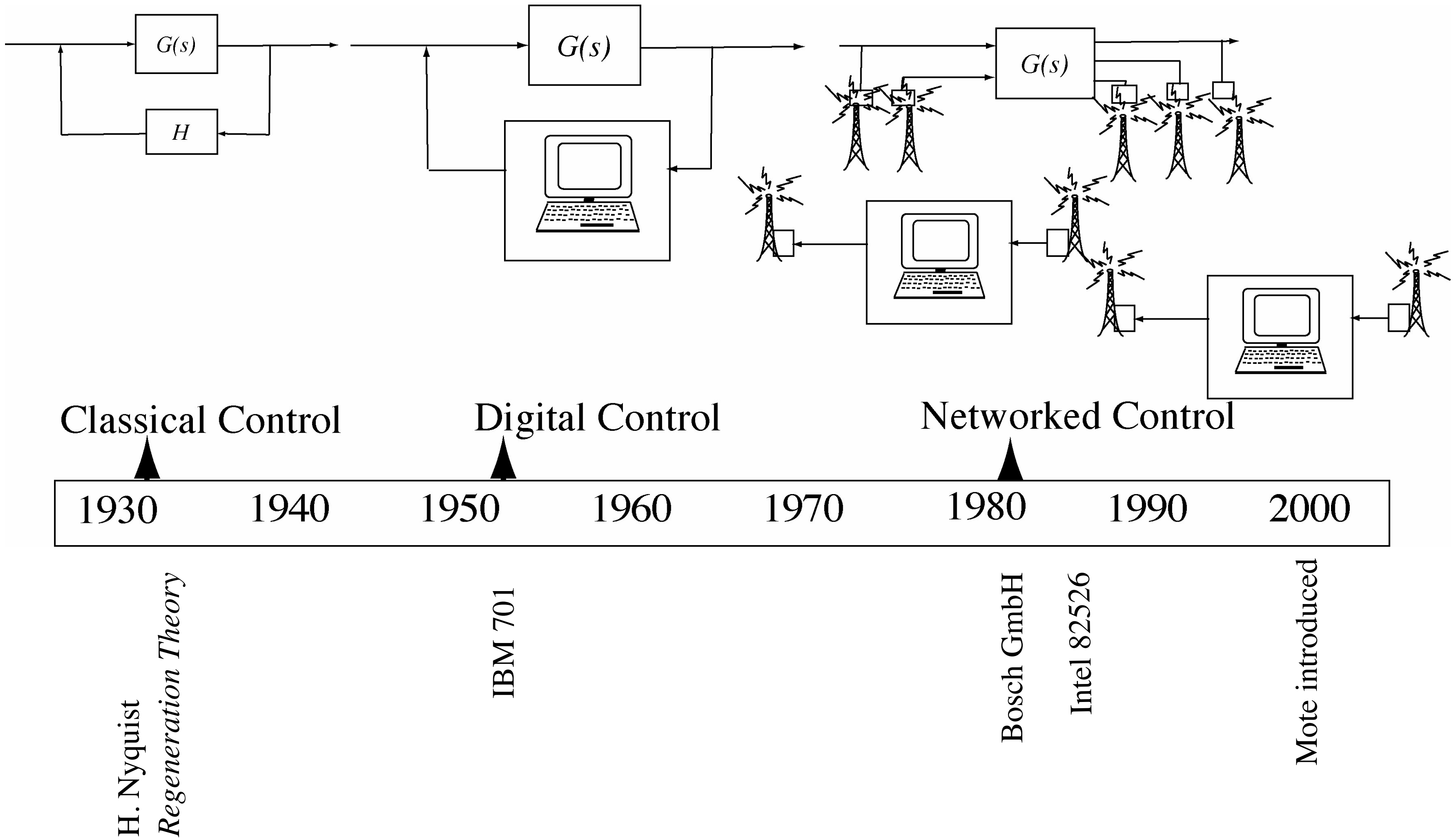
# Control of Networked Devices

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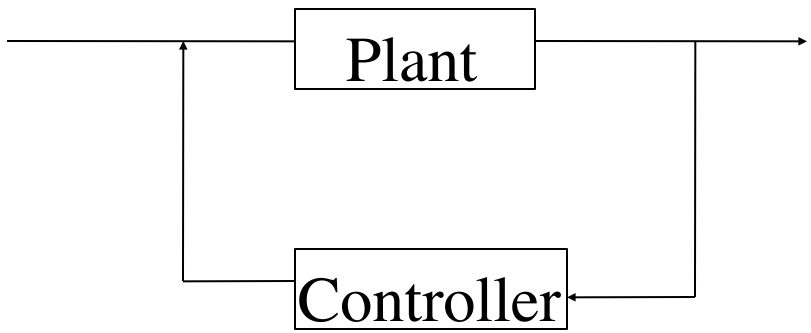
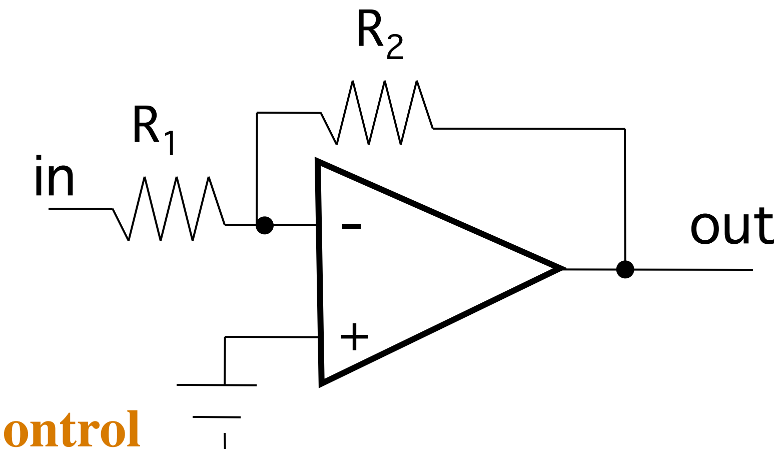
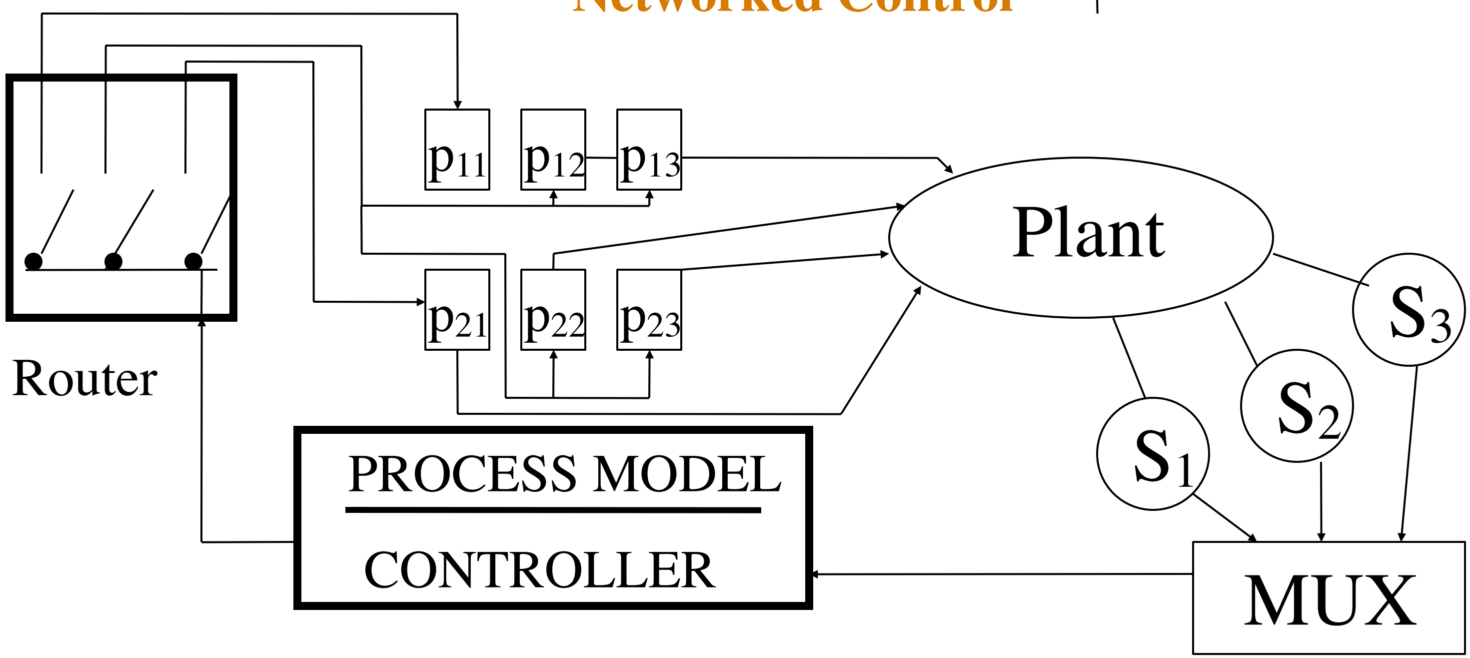
# Classical Feedback Control




# Networked Control

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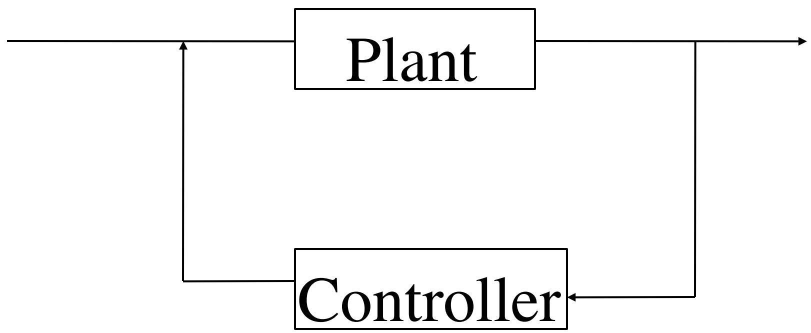
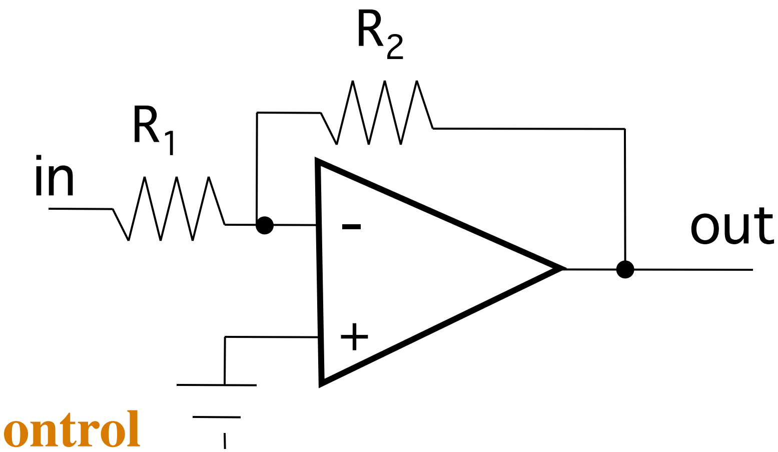
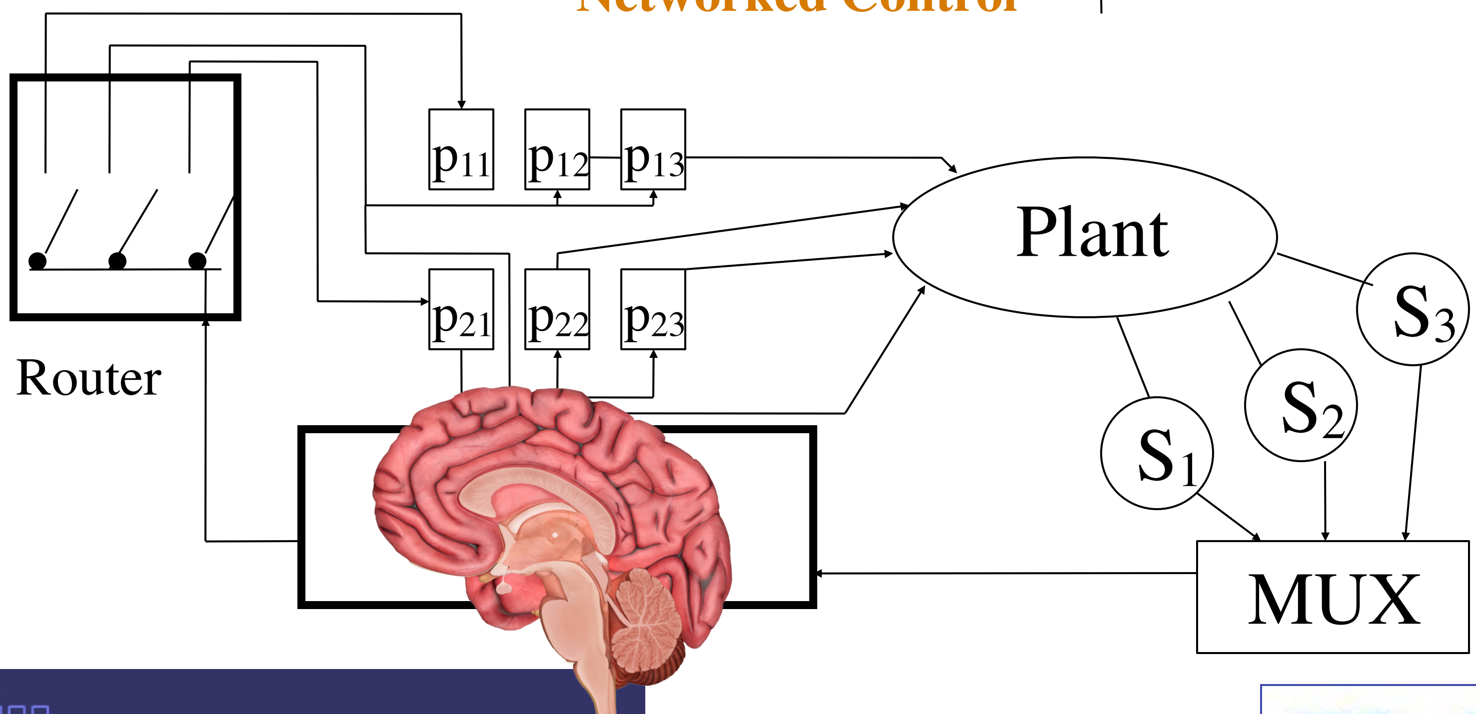
## Classical Feedback Control




## Networked Control

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# The most important paper of the decade

- W.S. Wong & R.W. Brockett, 1995, 1999, "Systems with finite communication bandwidth constraints, II: Stabilization with limited Information Feedback" *IEEE Trans. AC*, May, 1999.

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# The Data-Rate Theorem

**Theorem:** Suppose the system $G(s)$ (previous slide) is controlled using a data-rate constrained feedback channel. Suppose, moreover, $G$ has $k$ right half-plane poles $\lambda_1,\ldots,\lambda_k$. Then there is a critical data-rate

$$R_c = \log_2 e \cdot (\Re e(\lambda_1) + \cdots + \Re e(\lambda_k))$$

such that the system can be stabilized if and only if the channel capacity $R > R_c$.

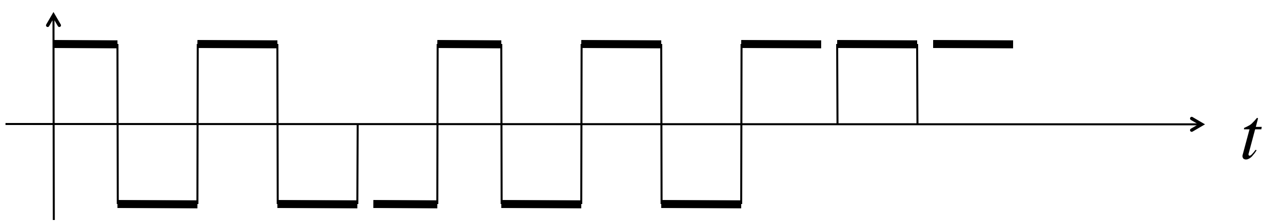
---Baillieul, 1999, (2002CDC), Nair and Evans, 2000, Tatikonda and Mitter, 2002, . . .

# Brief "Partial" History of the Data-Rate Theorem

- D. Delchamps, "Stabilizing a linear system with quantized state feedback," *IEEE Trans. AC,* 1990.
- W.S. Wong & R.W. Brockett, 1995, 1999, "Systems with finite communication bandwidth constraints, II: Stabilization with limited Information Feedback" *IEEE Trans. AC*.
- S. Tatikonda, A. Sahai, & S.K. Mitter, 1998, "Control of LQG systems under communication constraints," *CDC*
- John B., 1999, "Feedback designs for controlling device arrays with communication channel bandwidth constraints," *ARO Workshop*.
- G.N. Nair & R.J. Evans, 2000, "Stabilization with data-rate-limited feedback: tightest attainable bounds," *Sys, & Control Lett*.
- F. Fagnani and S. Zampieri, 2001, "Stability analysis and synthesis for scalar systems with a quantized feedback," Tech. Rept., Politechnico di Torino.

## Suppose there are only two (finitely many) actions that can be taken:

- Jerk the cart left or right one centimeter
- Under what circumstances can one keep the pendulum upright using this very coarse type of "control?"
- Ans: If and only if there is a sufficiently high actiel rate.

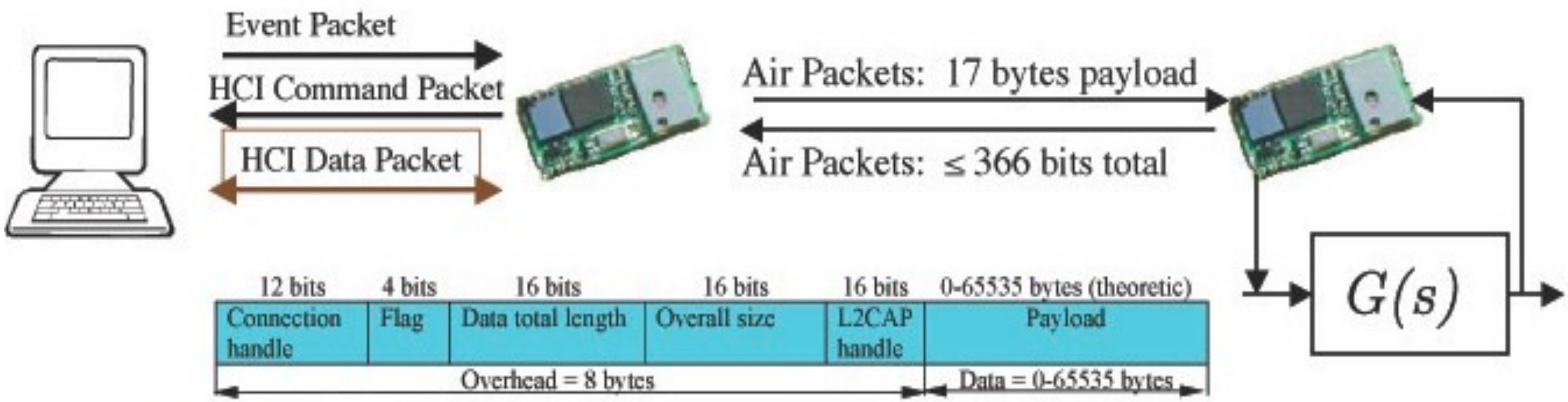



$u$ vs $t$

## When feedback loops are closed using packet-switched wireless communication links, data-rates become an issue.

Current problems:

• Develop a control theory for effectively managing wireless communications capability for automatically configuring *ad hoc* networks.




• Understand the relationship between standard network objectives (such as maximizing traffic capacity) and control objectives.

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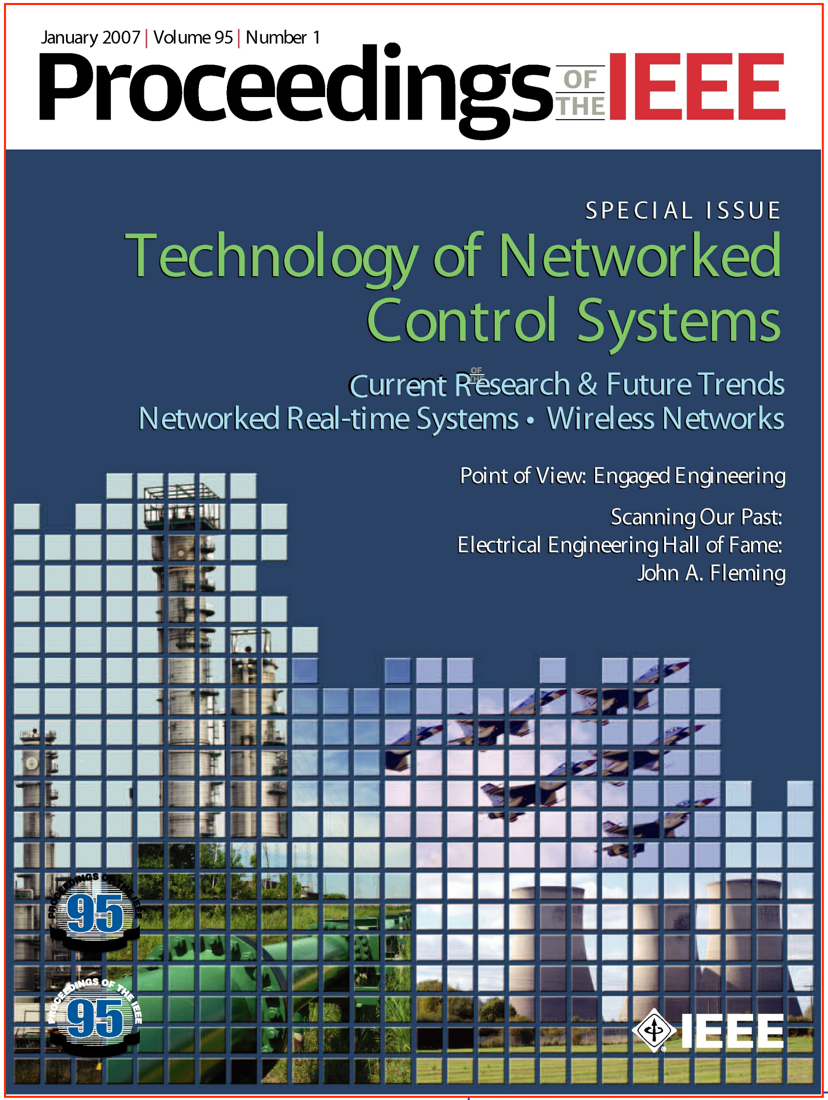
# Some References

- Keyong Li and John Baillieul, "Robust and Efficient Quantization and Coding for Control of Multidimensional Linear Systems Under Data-Rate Constraints," to appear in the *Int'l J. of Robust and Nonlinear Control*.

- K. Li and J. Baillieul, "Robust Quantization for Digital Finite Communication Bandwidth (DFCB) Control," *IEEE Trans. Automatic Control*, Special Issue on Networked Control Systems, September, 2004.

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# Control of Networked Systems

- *Communication constrained* and *information enabled* control systems
  - Coding for robustness to time-varying data-rates
  - Noise, bit-errors, and risk
  - Failure-sensitive control
  - Communication requirements with decentralized sensing and actuation
- Patterns and constraints on information flow in networked control systems
  - Sensing patterns for stable motions
  - Consensus problems for groups of autonomous agents
  - Shaping formations in motion
  - Coverage problems for groups of autonomous agents

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# Asymptotic Stability Must Be Rethought

# Asymptotic Stability Must Be Rethought

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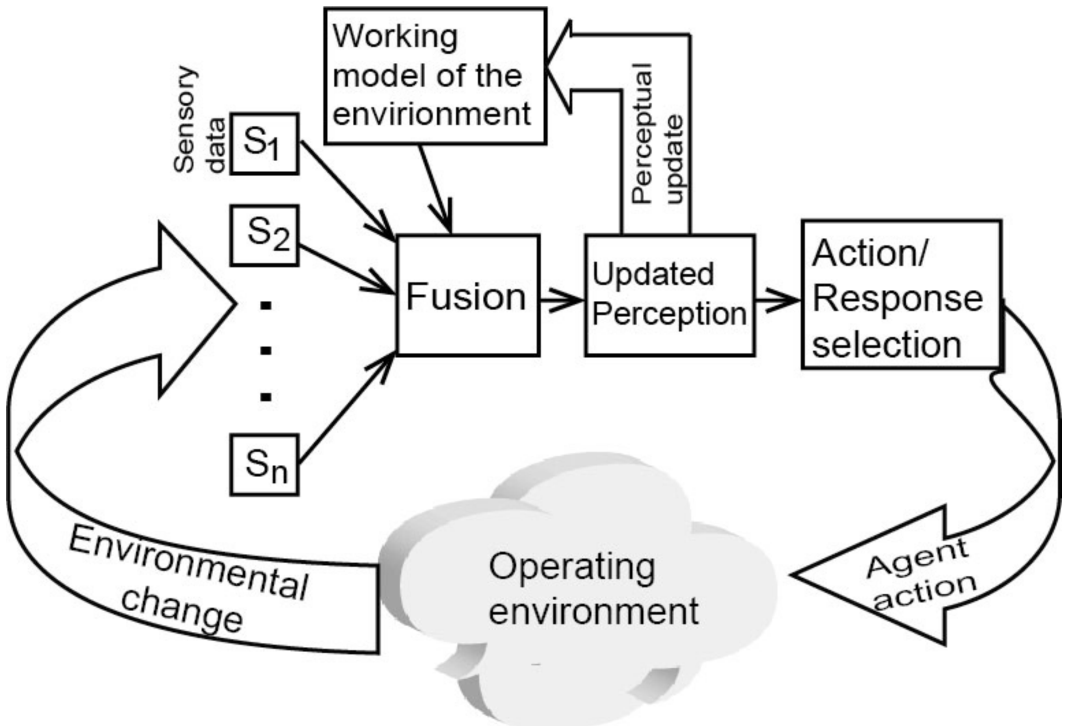
# A broader theory of *perception based control*

A fundamental distinction between humans and robots in mixed teams is that robots react rapidly to real-time sensor data, whereas humans react to more complex perceptions of the environment in which cognitive processes and prior experience play a role.

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# Understanding the perceptual basis for observed actions in the natural world - the case of looming obstacles

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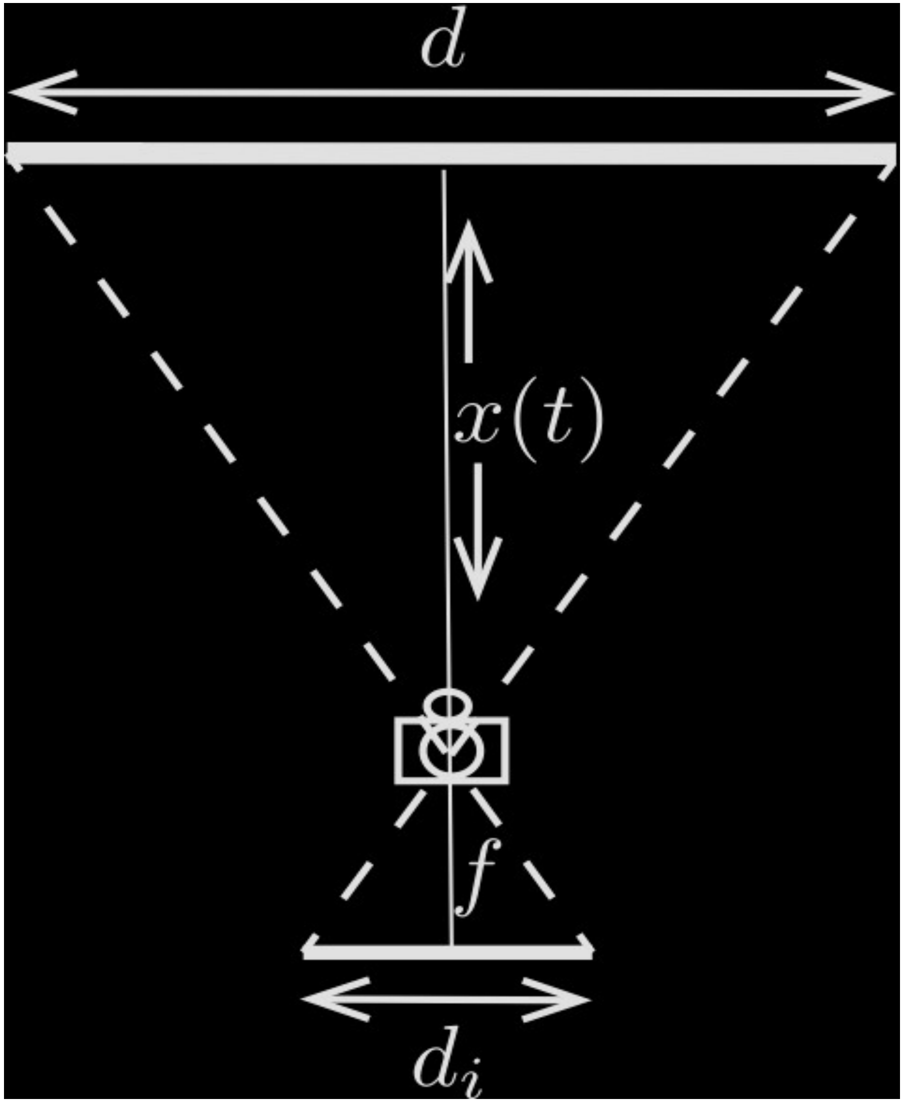
# Time-to-impact perception based on optical flow




Key assumption:

constant closing velocity

$$x(t) = x_0 - vt$$

impact occurs at $t = \tau$

s.t. $\tau = \frac{x_0}{v}$

by similar triangles

$$\tau = d_i / \dot{d}_i$$

# Time-to-impact perception based on optical flow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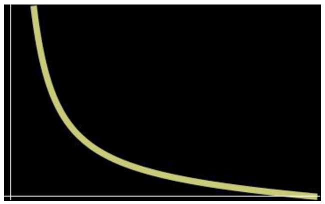
# Action attributable to perception of tau


**Fig. 2** Wing positions of diving gannet, *Sula bassana* (length ~0.9 m, wingspan 1.7 m). Illustration by John Busby. (Reprinted from ref. 7, courtesy of the author and publishers.)

D.N. Lee and P.E. Reddish, 1981. "Plummeting gannets: a paradigm of ecological optics," *Nature*, 293:293-294.

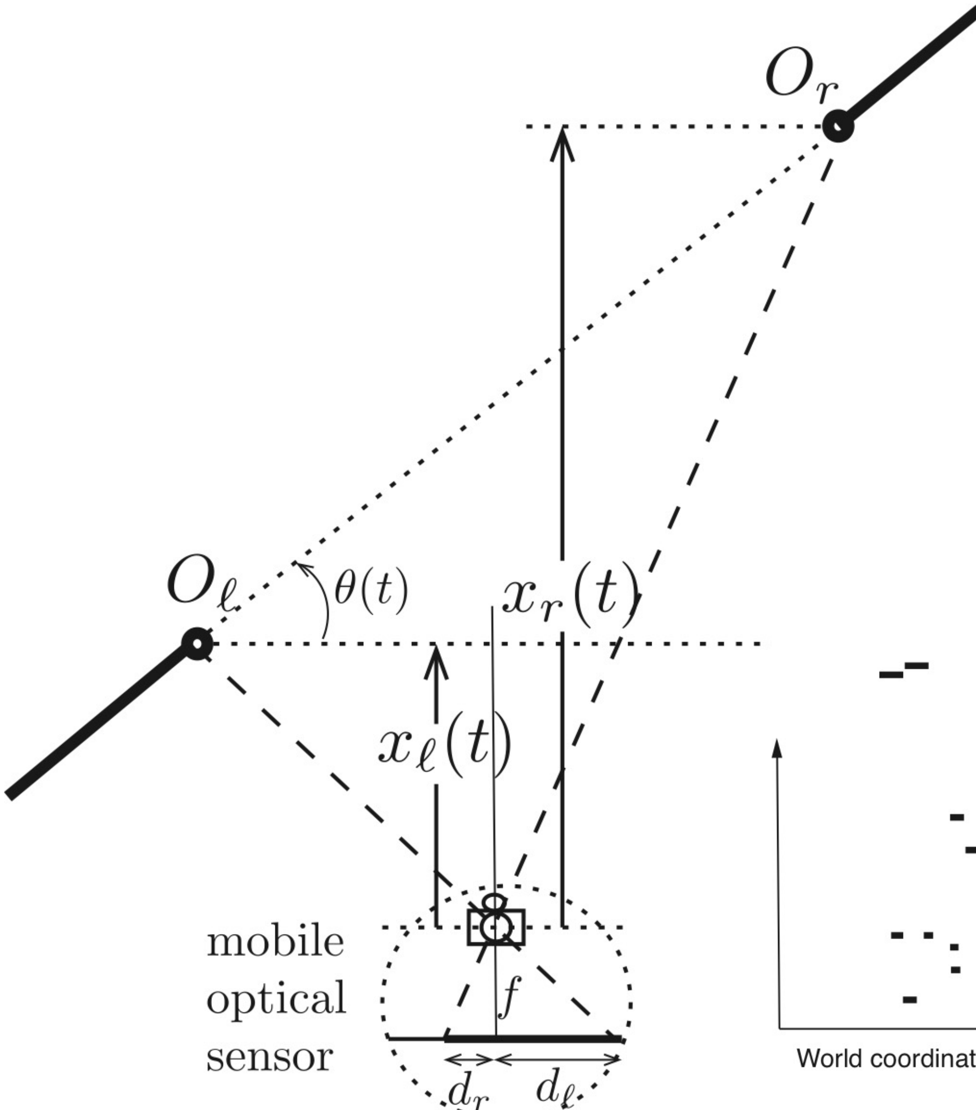
What if acceleration is constant?

$$\tau(t) = (t_d^2 - t^2)/2t$$

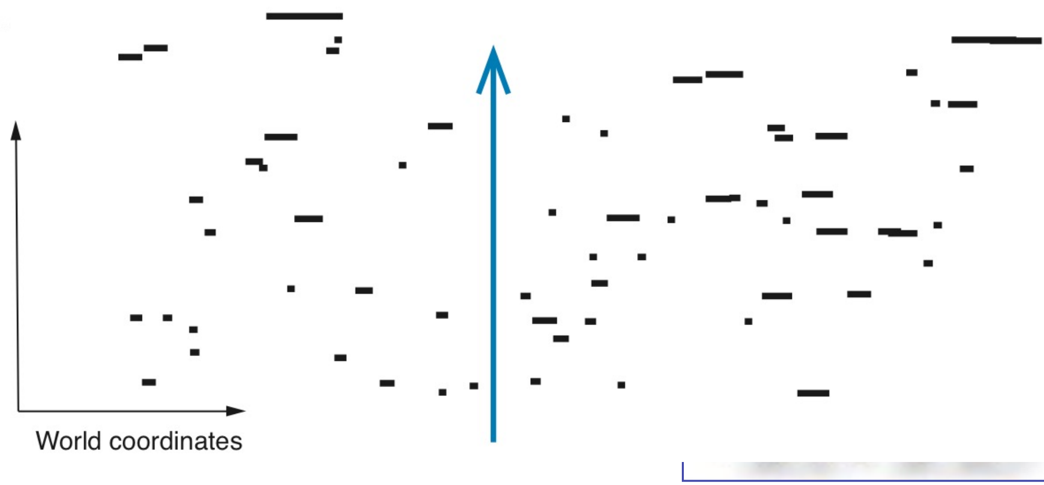


$$\tau(t_d - \epsilon) = \epsilon + o(\epsilon)$$

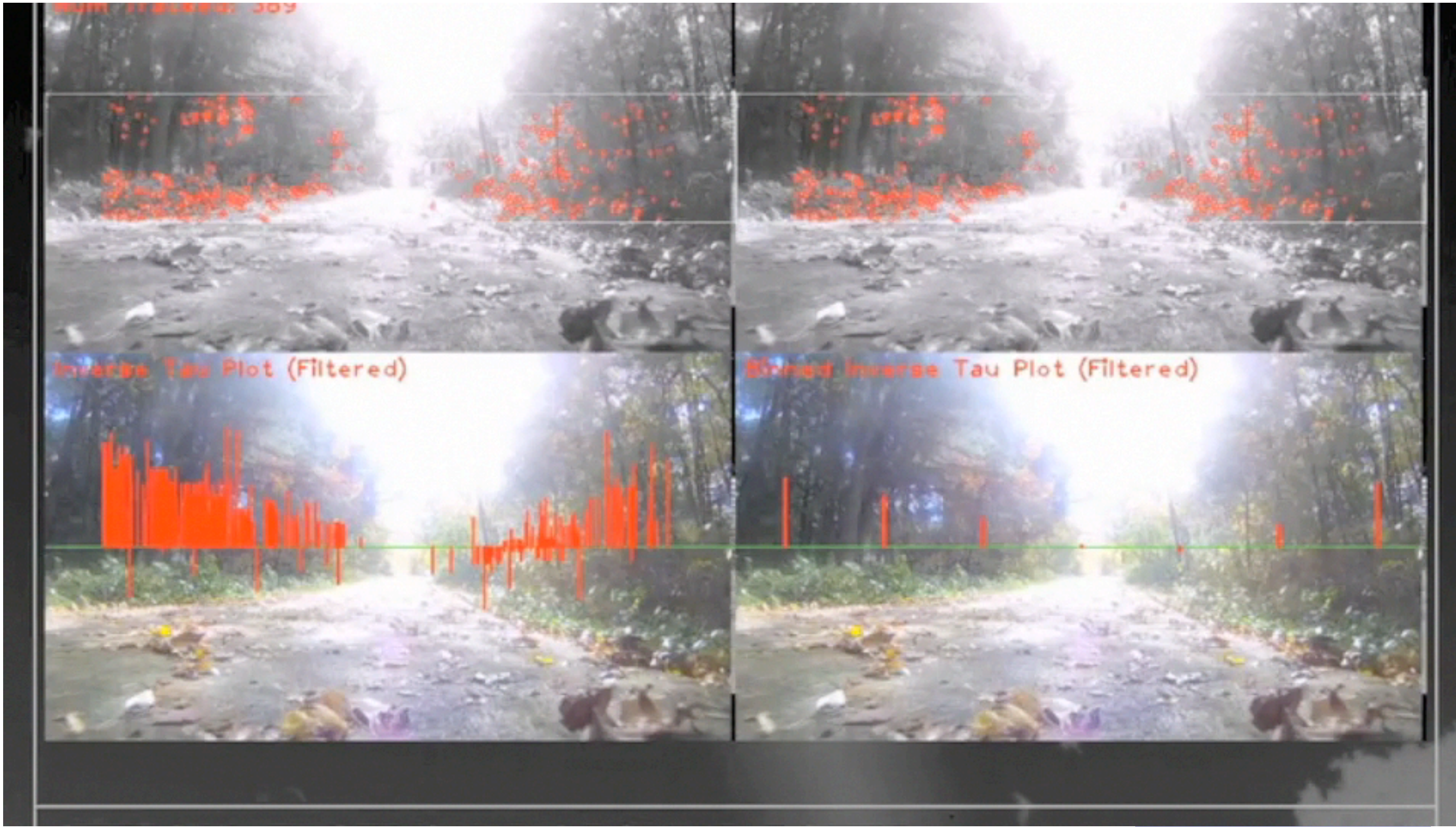
# Motion control based on perception of tau




Challenge:
Can perception of looming obstacles be used to transit an obstacle field?



# τ in the field



# Geometry/topology plays a role in sensory motor control of animal movement

Hafting et al., (2005). "Microstructure of a spatial map in the entorhinal cortex," *Nature* 436, DOI: 10.1038/nature03721

John O'Keefe, May-Britt and Edvard Moser

M. Hasselmo

Hasselmo and Brandon, (2012). "A model combining oscillations and attractor dynamics for generation of grid cell firing," *Front. Neural Circuits,* DOI: 6:30.10.3389/fncir.2012.00030

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# Emergent geometry of the entorhinal cortex


— Moser and Moser, 2010

# Emergent geometry of the entorhinal cortex

Consistent across animal subjects.

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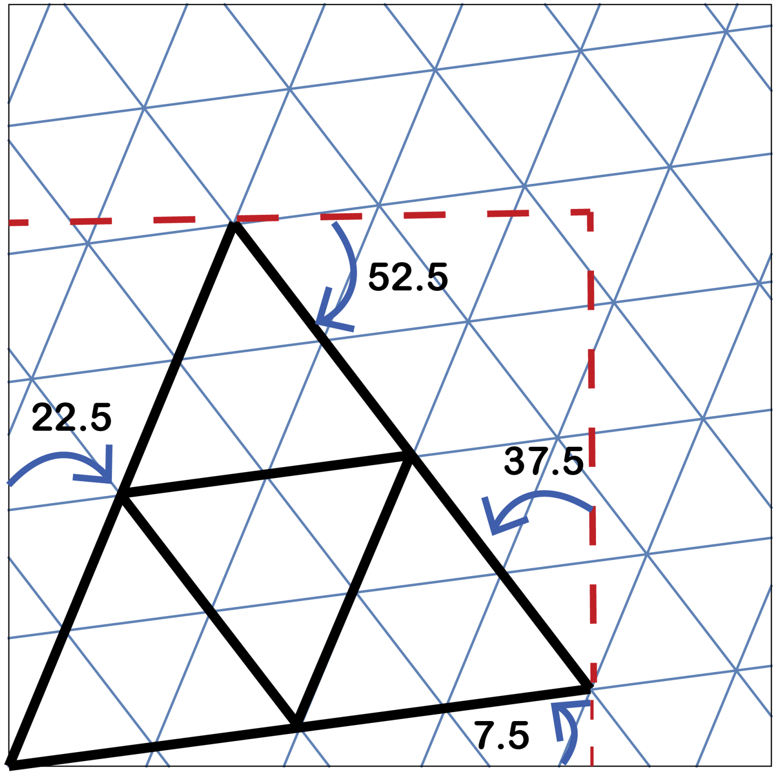
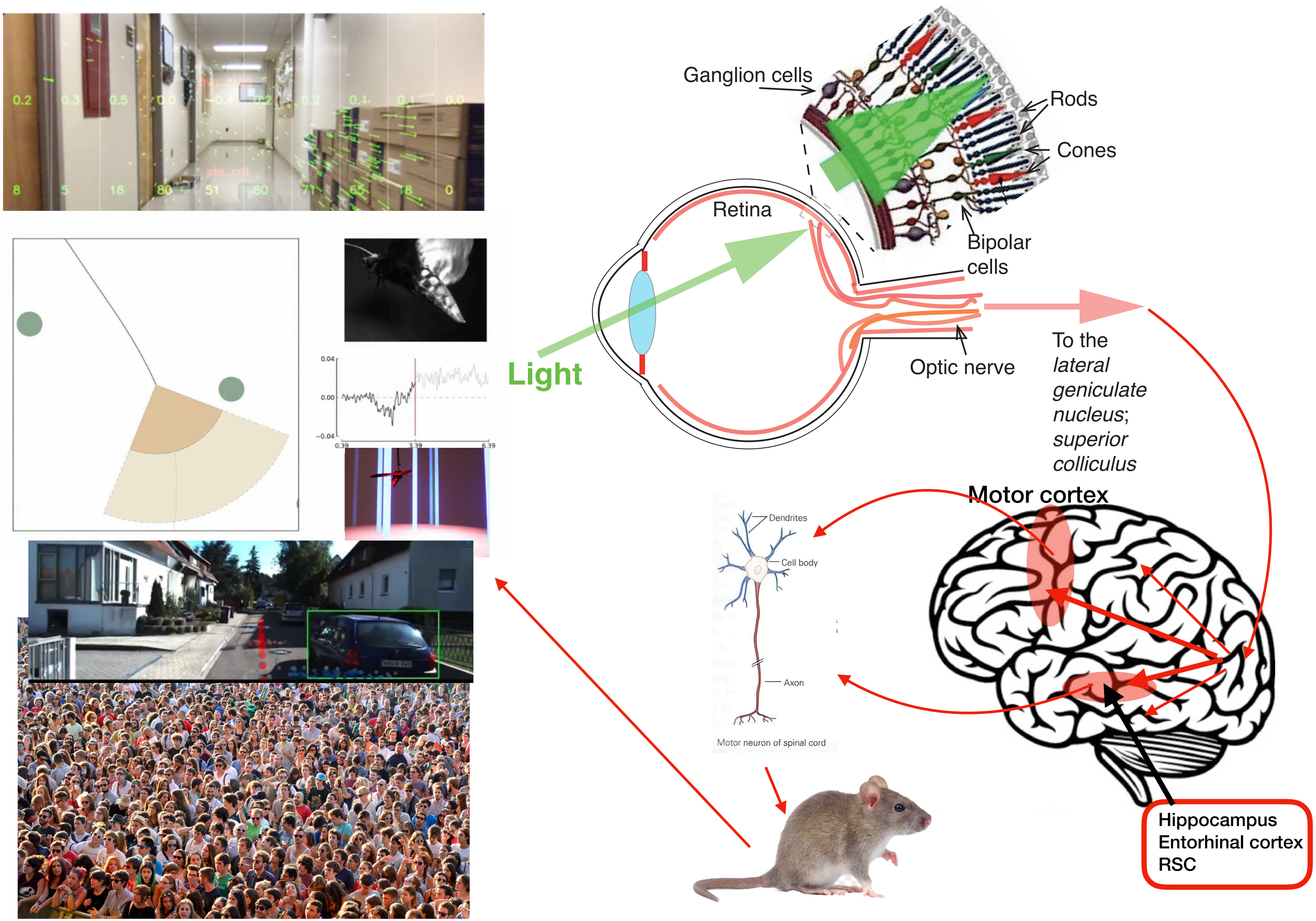
# Emergent geometry of the entorhinal cortex



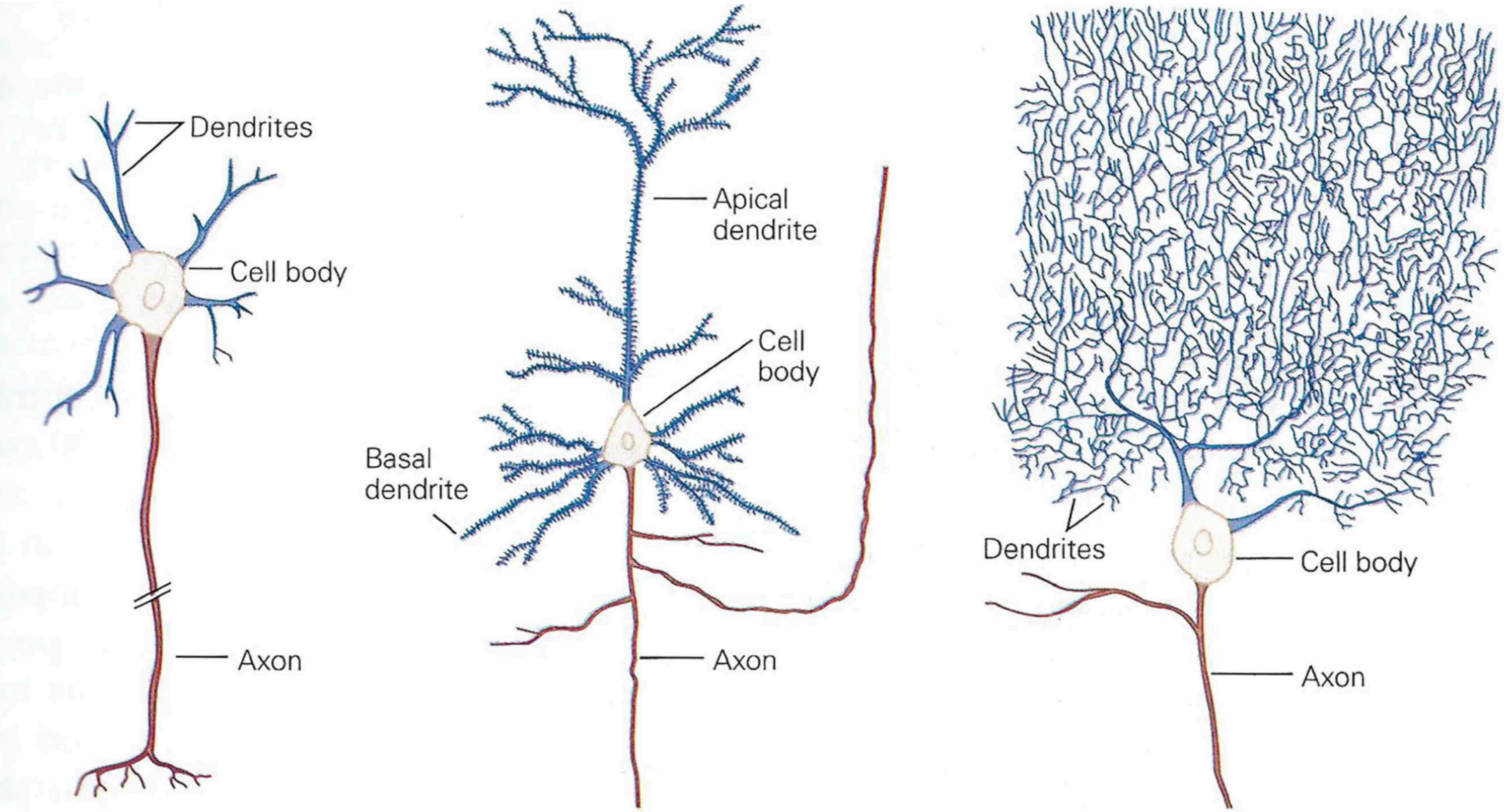

Consistent across animal subjects.

## Feature networks

## Photo-receptor networks



# Neurological enablers of animal movement




Motor neuron of spinal cord

Pyramidal cell of hippocampus

Purkinje cell of cerebellum

Neuron image thanks to Kandel et al, *Principles of Neural Science*

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# Motion control based on visual perception


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How do they do it?

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# Concluding Remarks – The state of the art

- Control is and probably will remain a hidden technology
- Networked systems are ubiquitous, and network control systems are essential to understand in both the natural and engineered world.
- The dynamics of perception are important when humans are nodes in a control network.
- The role of information in relation to the physical world remains to be understood.
- The essence of ***robustness*** and ***resilience*** in network dynamics remains to be understood.

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