Future Directions in Control:
A Look Backwards and Forwards

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2016 Hendrik W. Bode Lecture

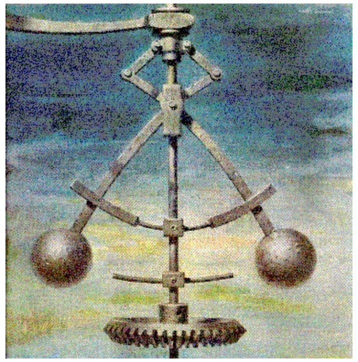
Goals for this talk:

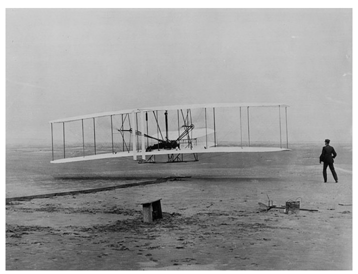
- Review some of the history of predicting the future
- Describe what well went, but also what we missed
- Provide some ideas about possible futures of control

Outline:

- View from 1995 (RMM) and 2003 (CDS Panel)
- What "decision and control" systems look like today
- Some opportunities for the future (personal bias)

What is “Control”?






Traditional view

- Use of feedback to provide stability, performance, robustness

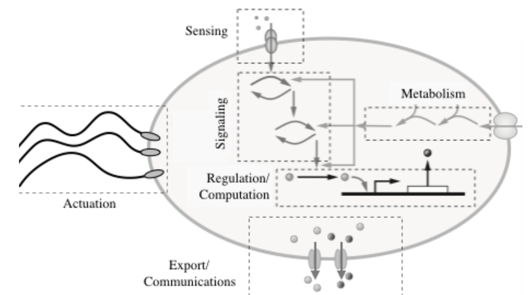
Emerging view

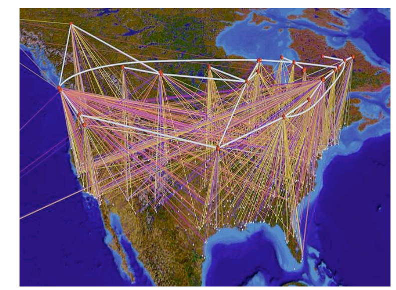
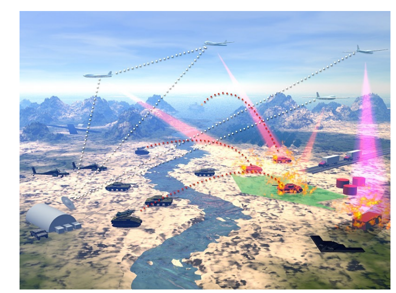
- Collection of tools and techniques for analyzing, designing, implementing complex systems in presence of uncertainty
- Combination of dynamics, interconnection (feedback/ feedforward), communications, computing and software

Control = dynamics, uncertainty, feedforward, feedback

Key principles for control systems (unchanged)

- Principle #1: Feedback as a tool for managing uncertainty (system and environment)
- Principle #2: Feedforward & feedback as tools for design of dynamics via integration of sensing, actuation & computation
- Corollary: Feedback enables subsystem modularity and interoperatitility ⇒ ability to manage complexity at scale

Future Directions in Control, circa 1995

Top Ten Research Problems in Nonlinear Control

January 1996

It's been a while since I have updated this. Probably no one is bothering to look here anymore anyway. But just in case (and because I have 15 minutes to burn before going to a thesis defense)...

Here is my personal list of the biggest research problems in nonlinear control theory (including some relevant links, where appropriate). If you don't agree with these (which is likely), feel free to send me e-mail. This is more or less a way for me to think online, so I wouldn't take any of this too seriously.

Current rank	Research problem	Previous rank
10	Building representative experiments for evaluating controllers	7
9	Convincing industry to invest in new nonlinear methodologies	1
8	Recognizing the difference between regulation and tracking	9
7	Exploiting special structure to analyze and design controllers	5
6	Integrating good linear techniques into nonlinear methodologies	10
5	Recognizing the difference between performance and operability	9
4	Finding nonlinear normal systems for control	3
3	Global robust stabilation and local robust performance	4
2	Magnitude and rate saturation	2
1	Writing numerical software for implementing nonlinear theory	8

May 1995

- #10: experiments → theory
- #3: writing good software
- #1: transition to industry

Aug 1995

- #8: writing good software
- #2: magnitude/rate saturation
- #1: convince industry to invest

Jan 1996

- #9: convince industry to invest
- #1: writing good software

Fatal flaw: done in isolation

2000-2003 Panel: Directions in Control, Dynamics, Systems

Organizing Committee

Boyd Brockett Burns Doyle Murray Stein

- **Biology & Medicine**
- **Transportation & Aerospace**
- **Information & Networks**
- **Materials and Processes**
- **Robotics and Intelligent Machines**
- **Other Areas**

Academia | Industry | Government

Apr ’00 Formation

Jun ’00 Workshop

Jan ’01 Draft 1.0

Oct ’01 Draft 2.0

Jan ’02 Draft 3.0

Apr ’02 Release + Workshop

Jul ’03 Published

Profit!

Motivation

- Articulate challenges and opportunities for the field
- Provide compelling view of the field that continues to attract top students, faculty
- Identify areas for funding

Why now [then]?

- ~12 years since prior report (W. Fleming [ed], SIAM 88)
- Changing nature of field:
  - New applications: UAVs, Internet, robotics, sys bio
  - Increasing importance of of complex systems

http://www.cds.caltech.edu/~murray/cdspanel

Control in an Information Rich World
R. Murray (ed), SIAM, 2003

2003 CDS Panel Recommendations

http://www.cds.caltech.edu/~murray/cdspanel

1. **Substantially increase research aimed at the integration of control, computer science, communications, and networking**
2. **Substantially increase research in control at higher levels of decision making, moving toward enterprise level systems**
3. **Explore high-risk, long-range applications of control to areas such as nanotechnology, quantum mechanics, electromagnetics, biology, and environmental science**
4. **Maintain support for theory and interaction with mathematics, broadly interpreted**
5. **Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences**

- IFAC NetSys TC
- NSF CPS (2008)
- IEEE TCNS

- Formal methods
- Smart X (grid, …)
- CSS TC Smart X

- Quantum control
- Synthetic biology
- Geoengineering

- Support slipping?
- Strong app focus

- New textbooks
  - for Computing Systems
  - for Everyone
- New report!

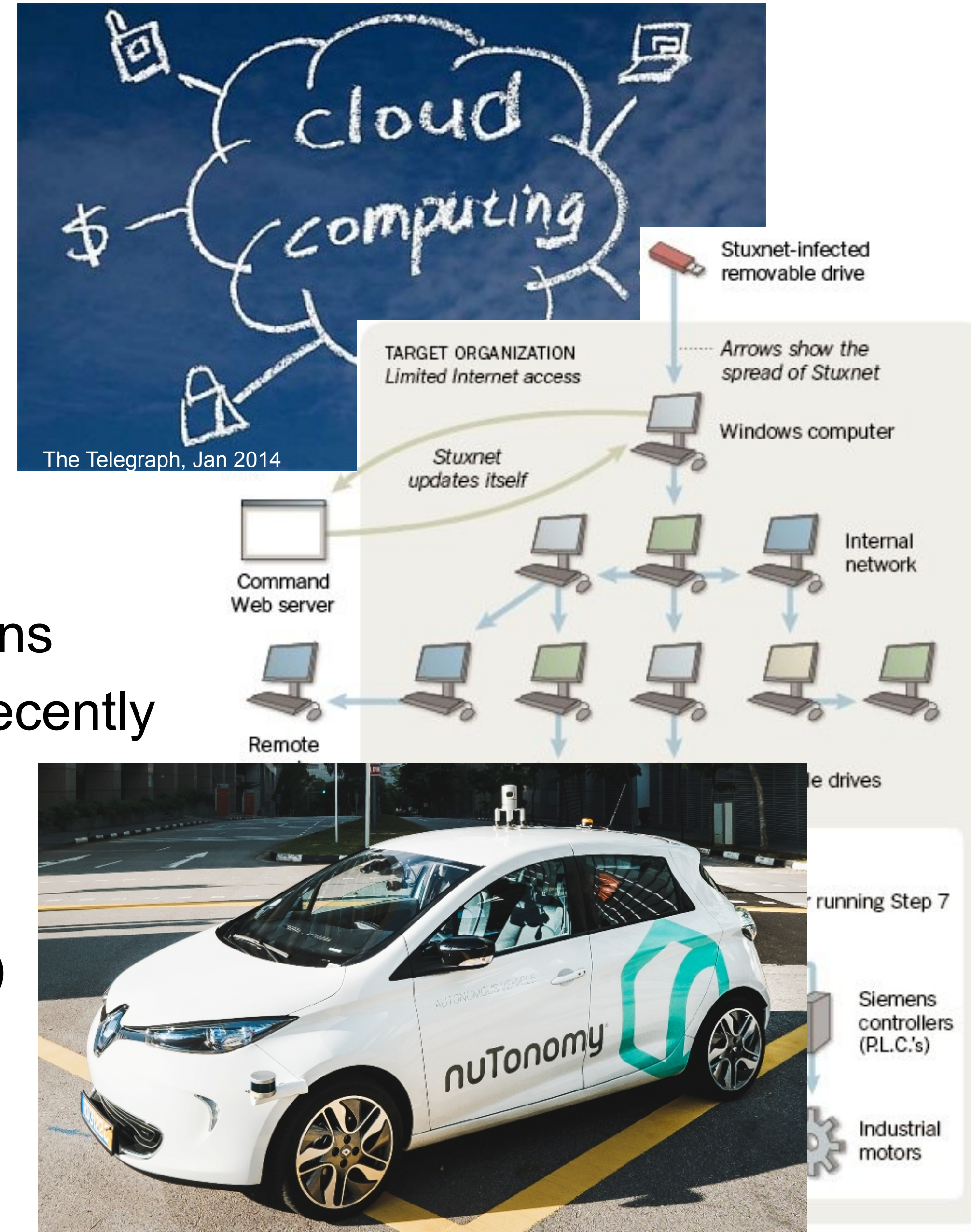
What We Missed (in 2003)

Cloud computing, big data and machine learning
- Scale was present in “enterprise level systems”
- Data as second order object → data as first order object

Security and privacy
- Stuxnet (2010) demonstrated need for security
- Work on privacy just starting; may be important for IoT?

Human interaction
- Discussion of “human in/on the loop” in military applications
- Major element in robotics; largely absent in control until recently

Energy and sustainability
- Some presence of “smart grid” in control of networks
- Some notion of control of environment (“geoengineering”)



Conclusion: Combined with ongoing advances, there is still a lot more to be done!

Important Trends in Control in the Last Decade

(Online) Optimization-based control

- Increased use of online optimization (MPC/RHC)
- Use knowledge of (current) constraints & environment to allow performance and adaptability

Layering, architectures, networked control systems

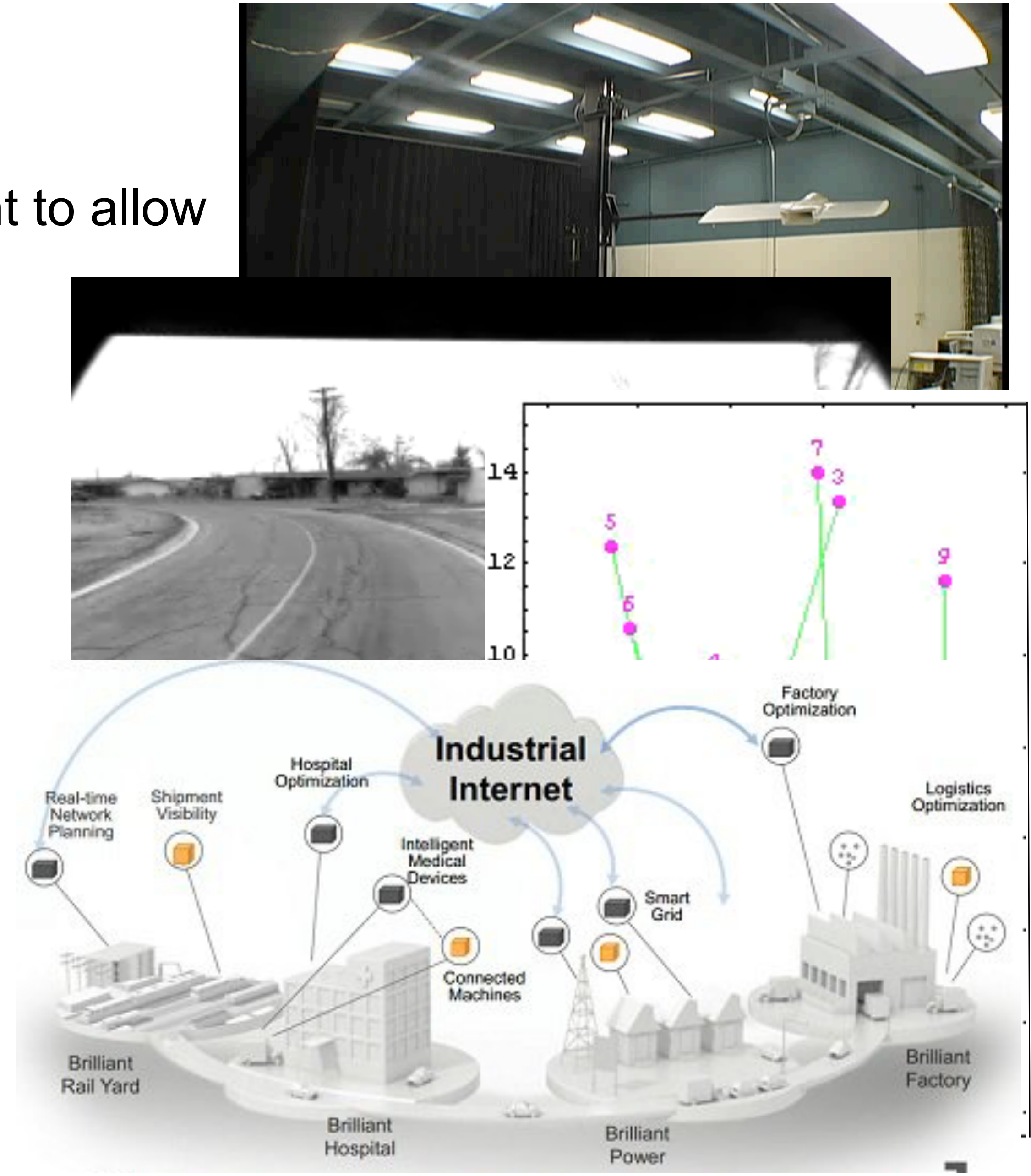
- Command & control at multiple levels of abstraction
- Modularity in product families via layers

Formal methods for analysis, design and synthesis

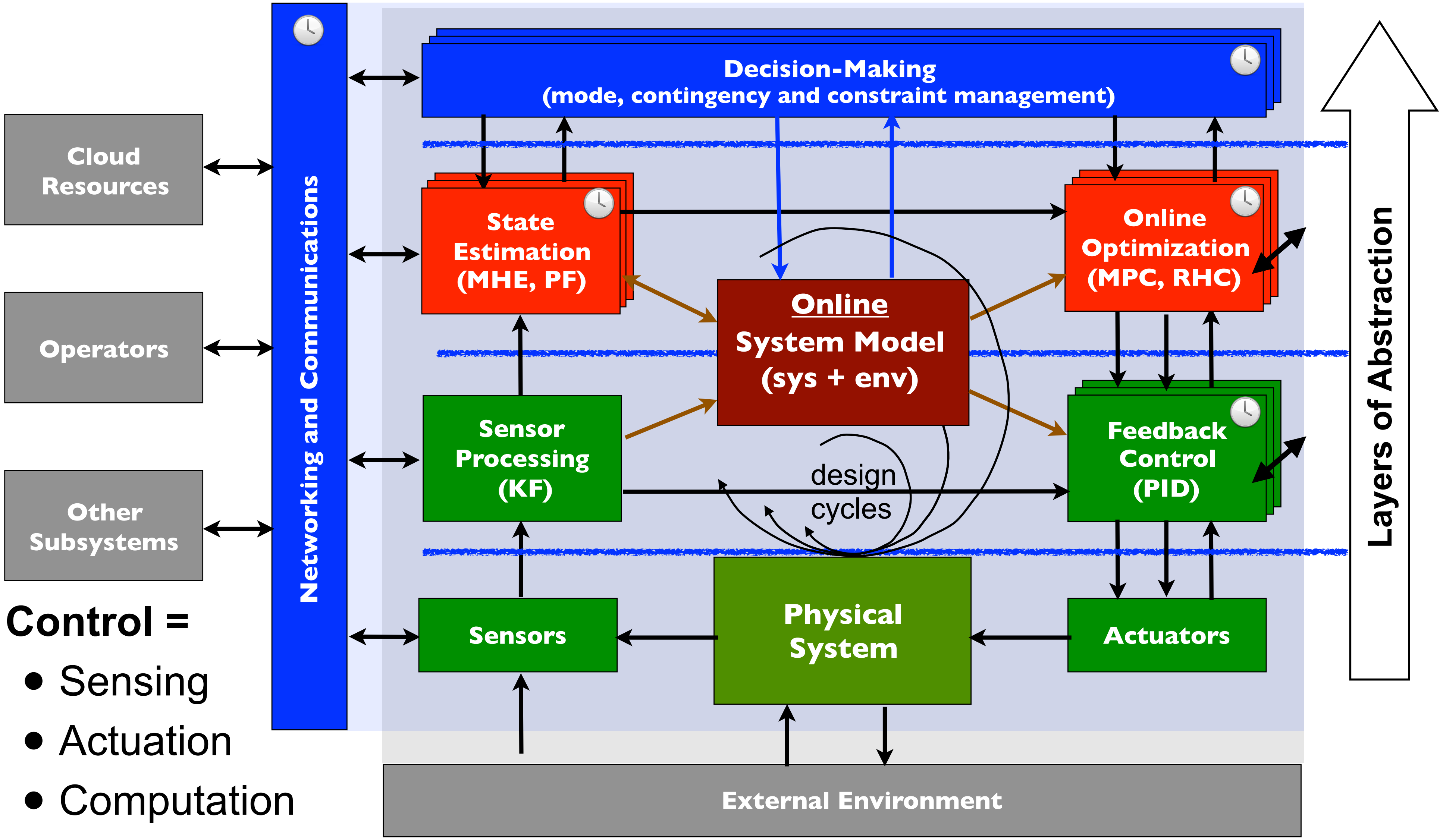
- Build on work in hybrid and discrete event systems
- Formal methods from computer science, adapted for "cyberphysical" (computing + control) systems

Components → Systems → Enterprise

- Increased scale: supply chains, smart grid, IoT
- Use of modeling, analysis and synthesis techniques at all levels. Integration of "software" with "controls"



Design of Modern (Networked) Control Systems



Control =

- Sensing
- Actuation
- Computation

Examples

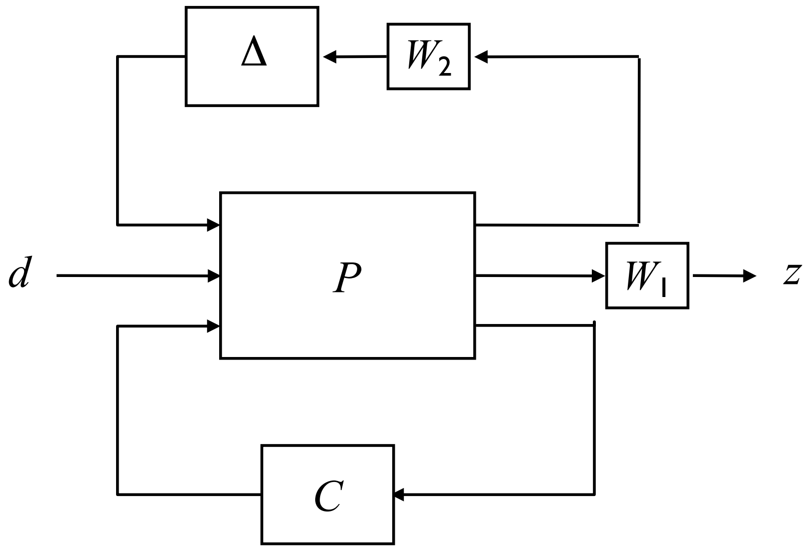
- Aerospace systems
- Self-driving cars
- Factory automation/ process control
- Smart buildings, grid, transportation

Challenges

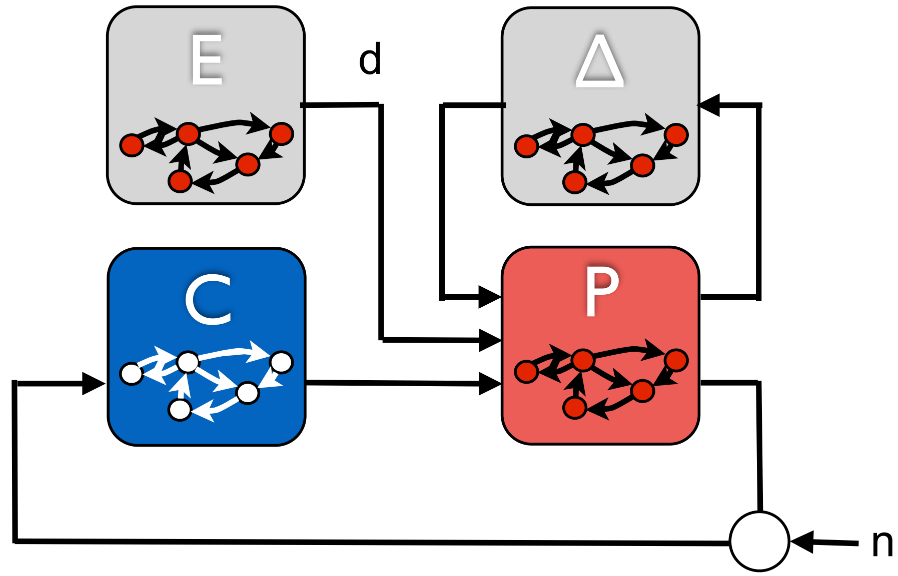
- How do we define the layers/interfaces (vertical contracts)
- How do we scale to *many* devices (horizontal contracts)
- Stability, robustness, *security, privacy*

Control = dynamics, uncertainty, feedforward, feedback

Rapprochement Between Formal Methods and Control



$\|z\|_2 \le \gamma \|d\|_2$ for all $\|\Delta\| \le 1$

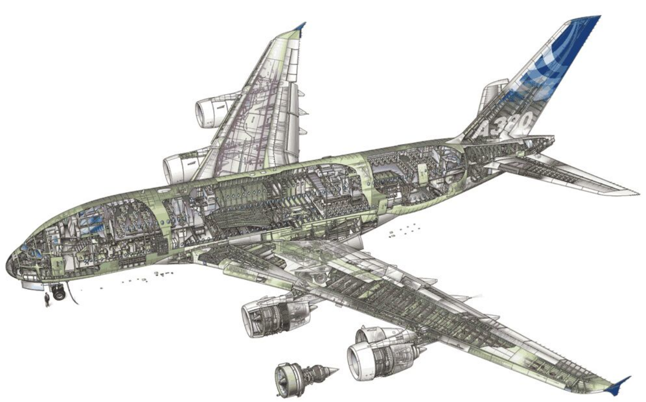


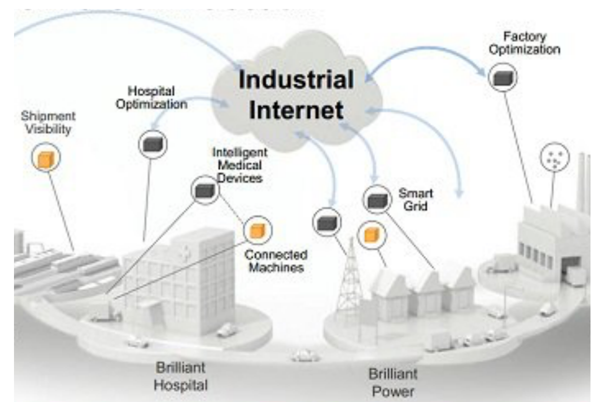
$\Box\phi^{e}_{\text{safe}} \wedge \Box\Diamond\phi^{e}_{\text{prog}} \to \Box\phi^{s}_{\text{safe}} \wedge \Box\Diamond_{\le T}\phi^{s}_{\text{prog}}$

Getting more rigorous about control of reactive systems

- Systems are too complex to be tested by trial and error
- Systems are too safety-critical to be tested by trial and error
- Move from "design then verify" to
  - specify then synthesize
  - synthesis of contracts
- Combine data-driven with formal methods to achieve safety, performance and "human-like" interactions
- Incorporate security and privacy as guarantees

Controlling cyberphysical systems requires solving *both* problems

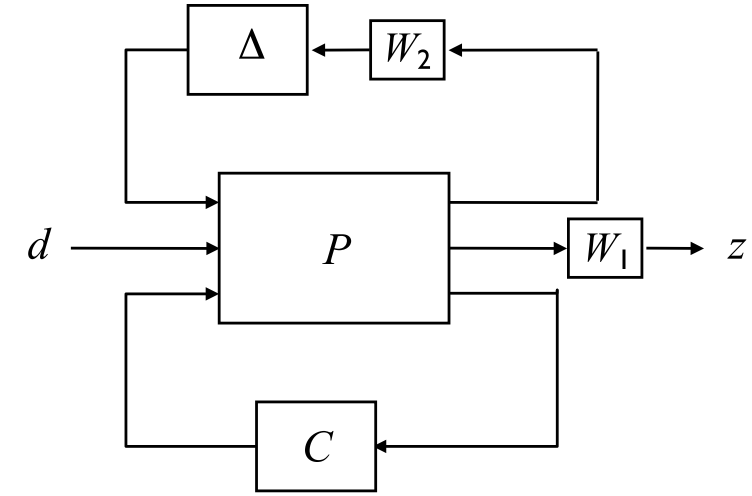




Opportunities for the Future (“Traditional”)

Continue focus on rigorous design of complex *systems*

- Hybrid (continuous + discrete) ≠ “cyberphysical” (CS + CDS)
- Large scale systems (5G = 50B!), safety-critical systems
- Don’t forget: data, security, privacy, humans



$$\|z\|_2 \le \gamma \|d\|_2 \quad \text{for all} \quad \|\Delta\| \le 1$$

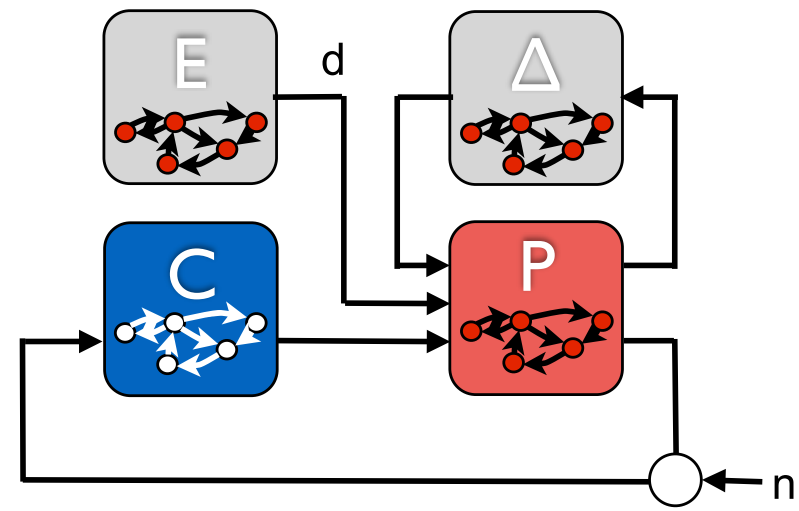
$$\Box\phi^{e}_{safe} \wedge \Box\Diamond\phi^{e}_{prog} \rightarrow \Box\phi^{s}_{safe} \wedge \Box\Diamond_{\le T}\phi^{s}_{prog}$$

Change how we teach: {Ae, ChE, EE, ME} → {CS, BE, Ec, Ph}

- Req’d (all majors): feedback systems (key principles, state space + frequency domain, mainly SISO, analysis and design)
- Req’d (CDS): optimization-based control (real-time trajectory generation, optimal control, MPC, Kalman filtering)
- Req’d (CDS): automata theory, verification, (synthesis)
- Rec’d: probabilistic systems or hybrid systems (to taste)

Continue to get out of the “box” (linear, NL, hybrid)

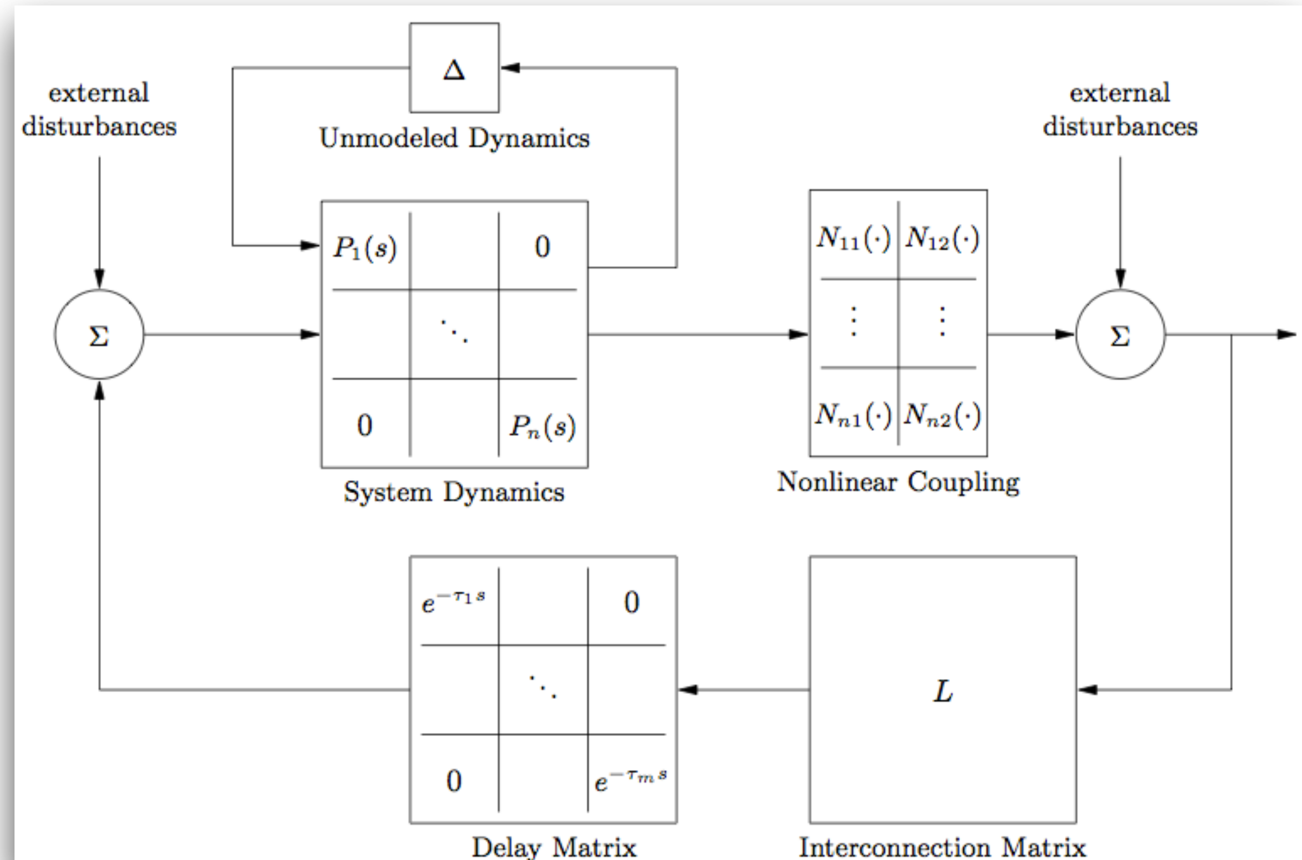
- Control = dynamics, uncertainty, feedforward, feedback
- ODE, PID, LQG, MPC → CS, ML, AI, Syn Bio, Ec, Ph
- Conferences to attend: CDC, HSCC, NIPS, POPL, ICML

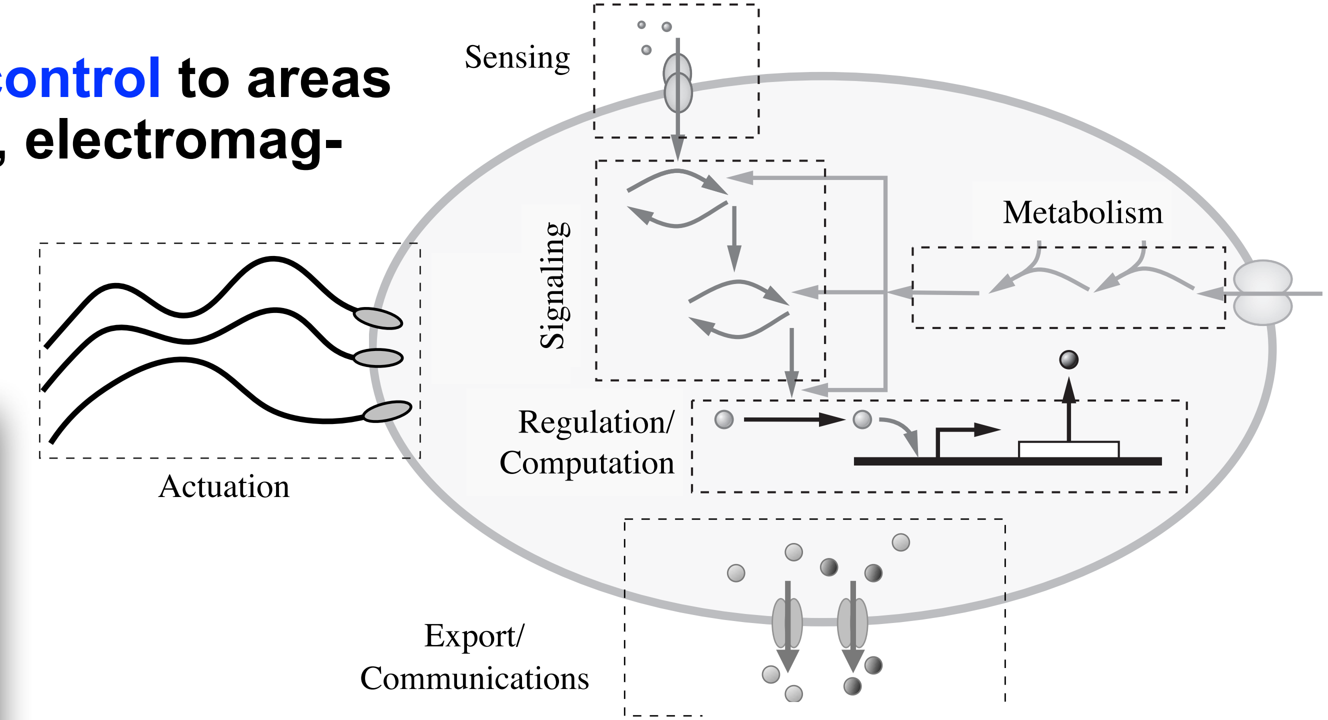


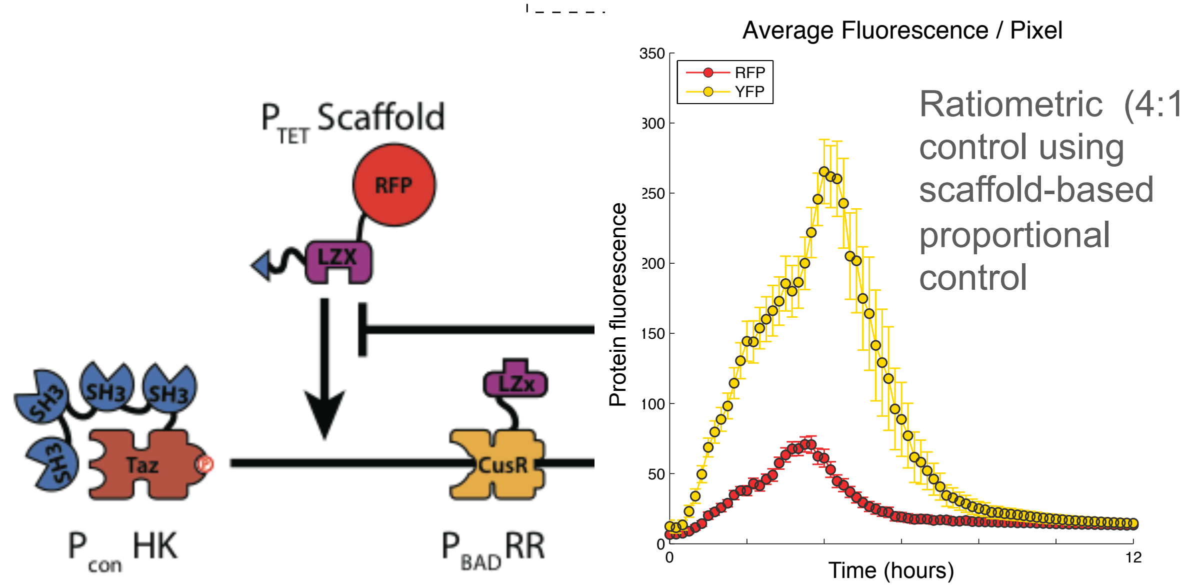
Opportunities for the Future ("Non-Traditional")

Explore high-risk, long-range applications of control to areas such as nanotechnology, quantum mechanics, electromag-netics, biology, and environmental science

- Requires new sensing, actuation, computation + new architectures, tuned to application area







Hsiao and de los Santos et al, *ACS Synthetic Biology* 2014

Credit and Thanks

Future directions in control

- Karl Åström, Siva Banda, Stephen Boyd, Roger Brockett, John Burns, John Doyle, Marc Jacobs, Gunter Stein

Collaborators (joint students, papers, projects)

- Caltech: Harry Atwater, Kaushik Bhattacharya, David Baltimore, Pamela Bjorkman, Joel Burdick, Mani Chandy, Tim Colonius, Fred Culick, Michael Dickinson, John Doyle, Michelle Effros, Michael Elowitz, Dave Goodwin, Steven Low, Jerry Marsden, Hideo Mabuchi, Doug MacMartin, Steve Mayo, Manfred Morari, Niles Pierce, Paul Rothemund, Steve Wiggins, Erik Winfree
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Mentors, teachers and co-conspirators

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Caltech PhD students and postdocs

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Caltech SURF students (~150) **Visiting students/faculty (~40)**