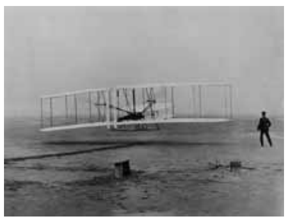





Control in and Information Rich World: Future Directions in Control, Dynamics, & Systems

Richard M. Murray
Control and Dynamical Systems
California Institute of Technology

Outline

I. CDS Panel Review
II. Some Grand Challenges (& first steps)
III. Future Directions for Control Theory




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

Motivation for the Panel (Apr 00)

Articulate the challenges and opportunities for the field

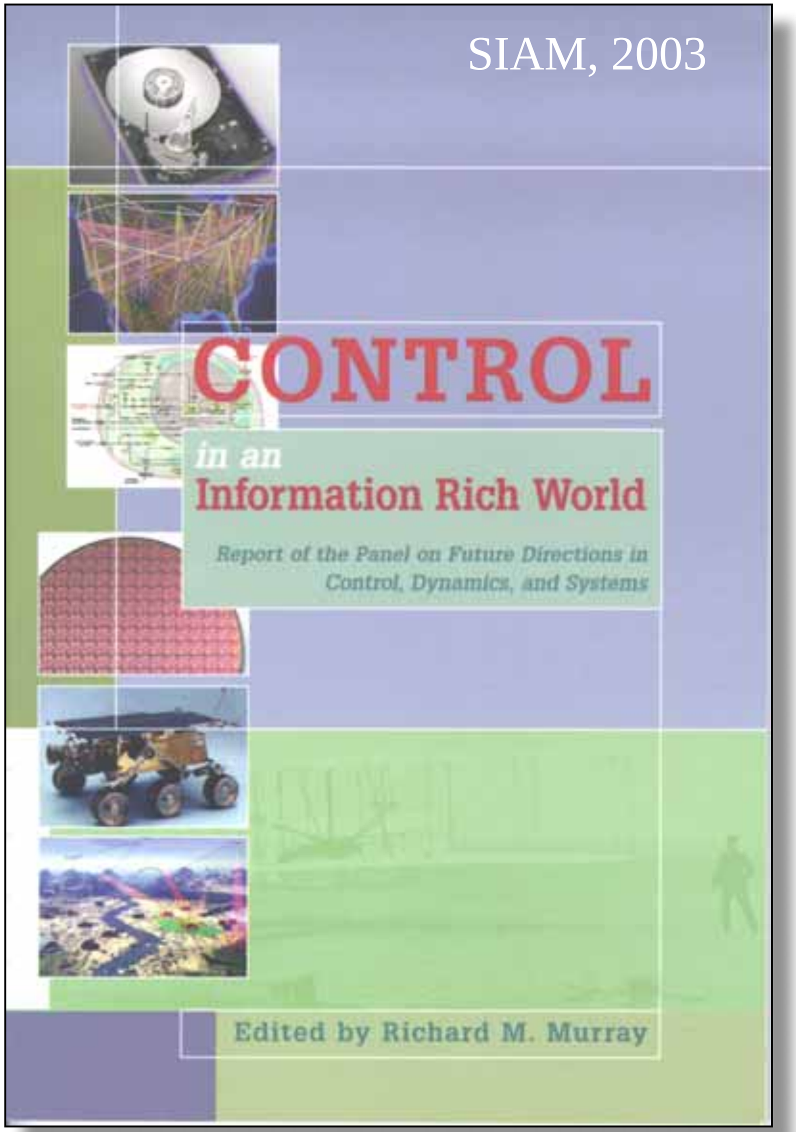
- Present a vision to inform high level decision makers of the importance of the field to future technological advances
- Identify possible changes in the way that research is funded and organized that may be needed to realize new opportunities
- Provide a compelling view of the field that continues to attract the brightest scientists, engineers, and mathematicians to the field

Respond to the changing nature of control, dynamics, and systems research

- Many new application areas where controls is playing a stronger role: biology, environment, materials, information, networks, …
- Controls engineers taking on a much broader, systems-oriented role, while maintaining a rigorous approach and practical toolset

Control in an Information Rich World

1. **Executive Summary**
2. **Overview of the Field**
   - What is Control?
   - Control System Examples
   - Increasing Role of Information-Based Systems
   - Opportunities and Challenges
3. **Applications, Opportunities & Challenges**
   - Aerospace and Transportation
   - Information and Networks
   - Robotics and Intelligent Machines
   - Biology and Medicine
   - Materials and Processing
   - Other Applications
4. **Education and Outreach**
5. **Recommendations**



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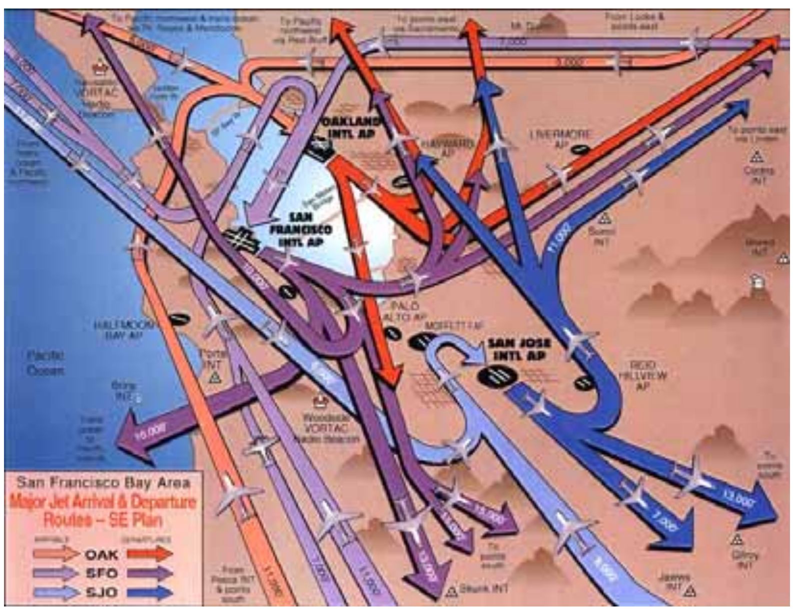
Transportation and Aerospace

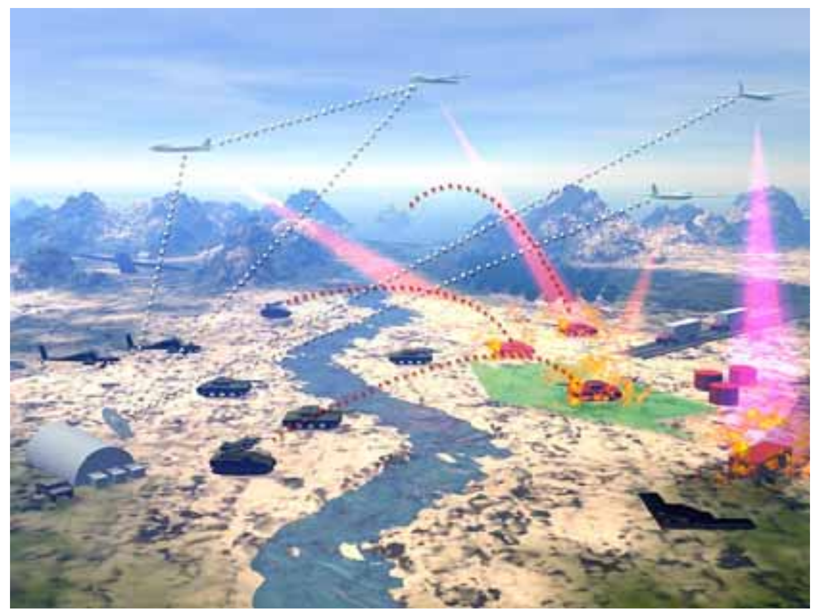
Themes

- Autonomy
- Real-time, global, dynamic networks
- Ultra-reliable embedded systems
- Multi-disciplinary teams
- Modeling for control
  - more than just $\dot{x} = f(x, u, p, w)$
  - analyzable accurate hybrid models

Technology Areas

- Air traffic control, vehicle management
- Mission/multi-vehicle management
- Command & control, human in the loop
- Ground traffic control (air & ground)
- Automotive vehicle & engine control
- Space vehicle clusters
- Autonomous control for deep space





Information and Networks

Pervasive, ubiquitous, convergent networking

- Heterogeneous networks merging communications, computing, transportation, finance, utilities, manufacturing, health, entertainment, ...
- Robustness/reliability are dominant challenges
- Need “unified field theory” of communications, computing, and control

Many applications

- Congestion control on the internet
- Power and transportation systems
- Financial and economic systems
- Quantum networks and computation
- Biological regulatory networks and evolution
- Ecosystems and global change

Control <u>of</u> the network

Control <u>over</u> the network

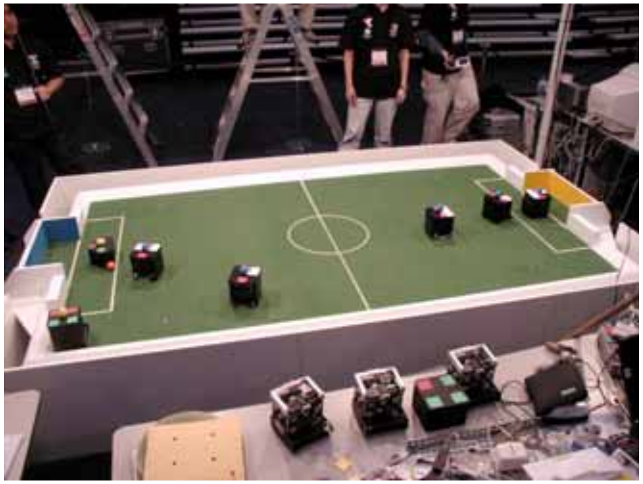
Robotics and Intelligent Machines

Wiener, 1948: Cybernetics

- Goal: implement systems capable of exhibiting highly flexible or ``intelligent'' responses to changing circumstances

DARPA, 2003: Grand Challenge

- LA to Las Vegas (400 km) in 10 hours or less
- Goal: implement systems capable of exhibiting highly flexible or ``intelligent'' responses to changing circumstances



Biology and Medicine

“Systems Biology”

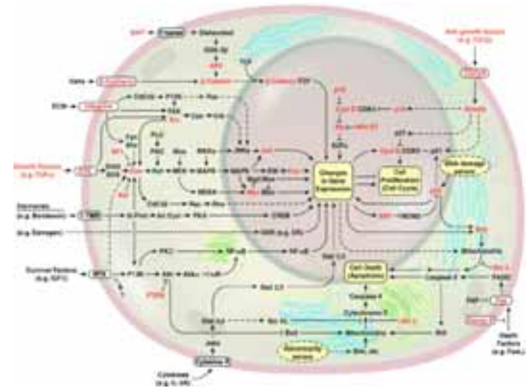
- Many molecular mechanisms for biological organisms are characterized
- Missing piece: understanding of how network interconnection creates robust behavior from uncertain components in an uncertain environment
- Transition from organisms as genes, to organisms as networks of integrated chemical, electrical, fluid, and structural elements

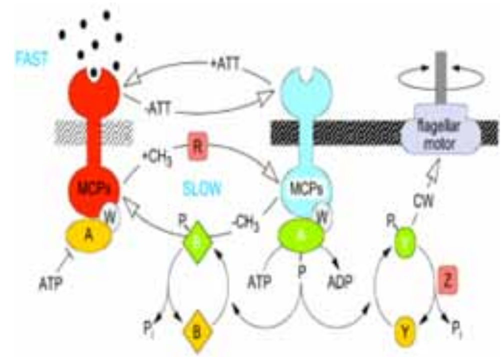
Key features of biological systems

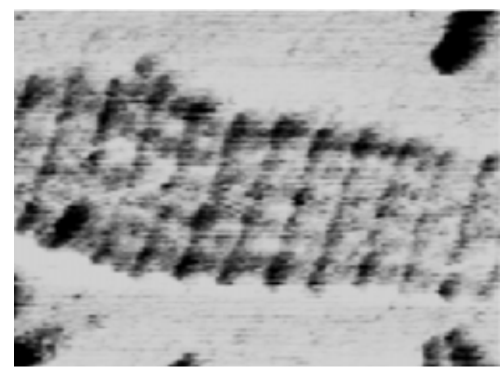
- Integrated control, communications, computing
- Reconfigurable, distributed control, at *molecular* level

Design and analysis of biological systems

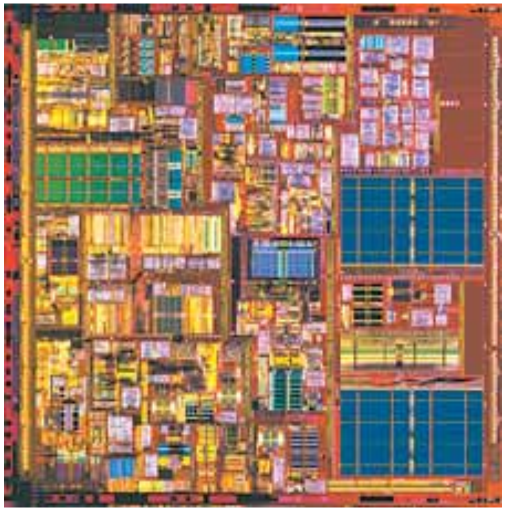
- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow of information is key







Materials and Processing

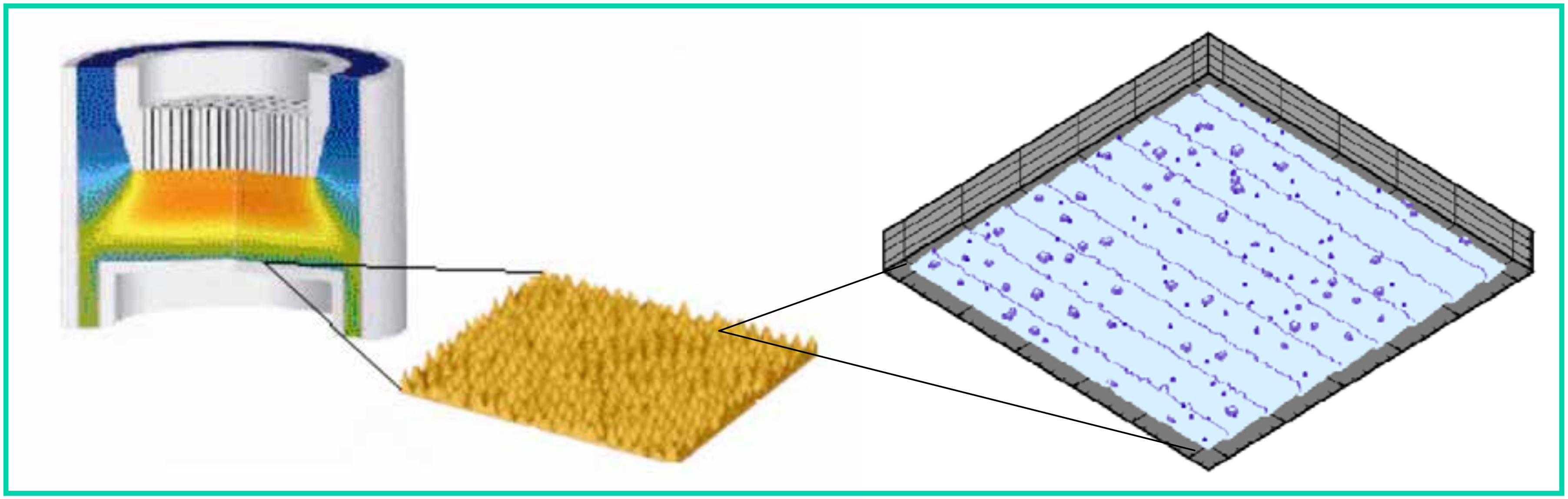


Multi-scale, multi-disciplinary modeling and simulation

- Coupling between macro-scale actuation and micro-scale physics
- Models suitable for control analysis and design

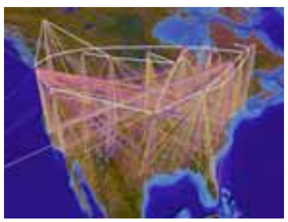
Increased use of in situ measurements

- Many new sensors available that generate real-time data about microstructural properties



CDS Panel
2002-03

CDS Panel Recommendations



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.**

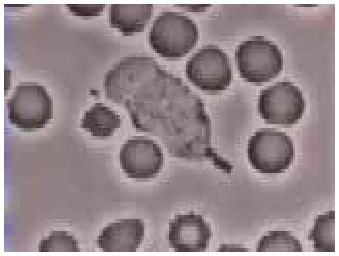
4. **Maintain support for theory and interaction with mathematics, broadly interpreted.**

5. **Invest in new approaches to education and outreach for the dissemination of control concepts and tools to non-traditional audiences.**

NSF workshop, 2003
NSF workshop, 2006

Some Grand Challenges for Control

1. **Robotic Soccer Team capable of winning the World Cup**
2. **InternetRT™ - real-time control across the Internet**
3. **Dynamically Reconfigurable Air Traffic Control**
4. **Human Life Stabilization Bay (& personalized medicine)**
5. **Redesign the Feedback Control System of a Bacteria**
6. **Control 101 - make control accessible to Bi, CS, Ec, …**
7. **Slow Computing™ - PDA using 1 kHz (1 msec) devices**
8. **Write a 100,000+ line program that works correctly on first execution**
9. **Build a car capable of fully autonomous operations in urban environments**



Example 1: Autonomous Driving (Alice)

Team Caltech

- 50 students worked on Alice over 1 year
- Course credit through CS/EE/ME 75
- Summer team: 20 SURF students + 6 graduated seniors + 4 work study + 4 grads + 2 faculty + 6 volunteers (= ~40)

Alice

- 2005 Ford E-350 Van
- Sportsmobile 4x4 offroad package
- 5 cameras: 2 stereo pairs + roadfinding
- 5 LADAR units: long, medium*2, short, bumper
- 2 GPS units + 1 IMU (LN 200)
- 6 Dell 750 PowerEdge Servers (P4, 3GHz, gentoo linux)
- 1 IBM Quad Core AMD64 (fast!)
- 1 Gb/s switched ethernet

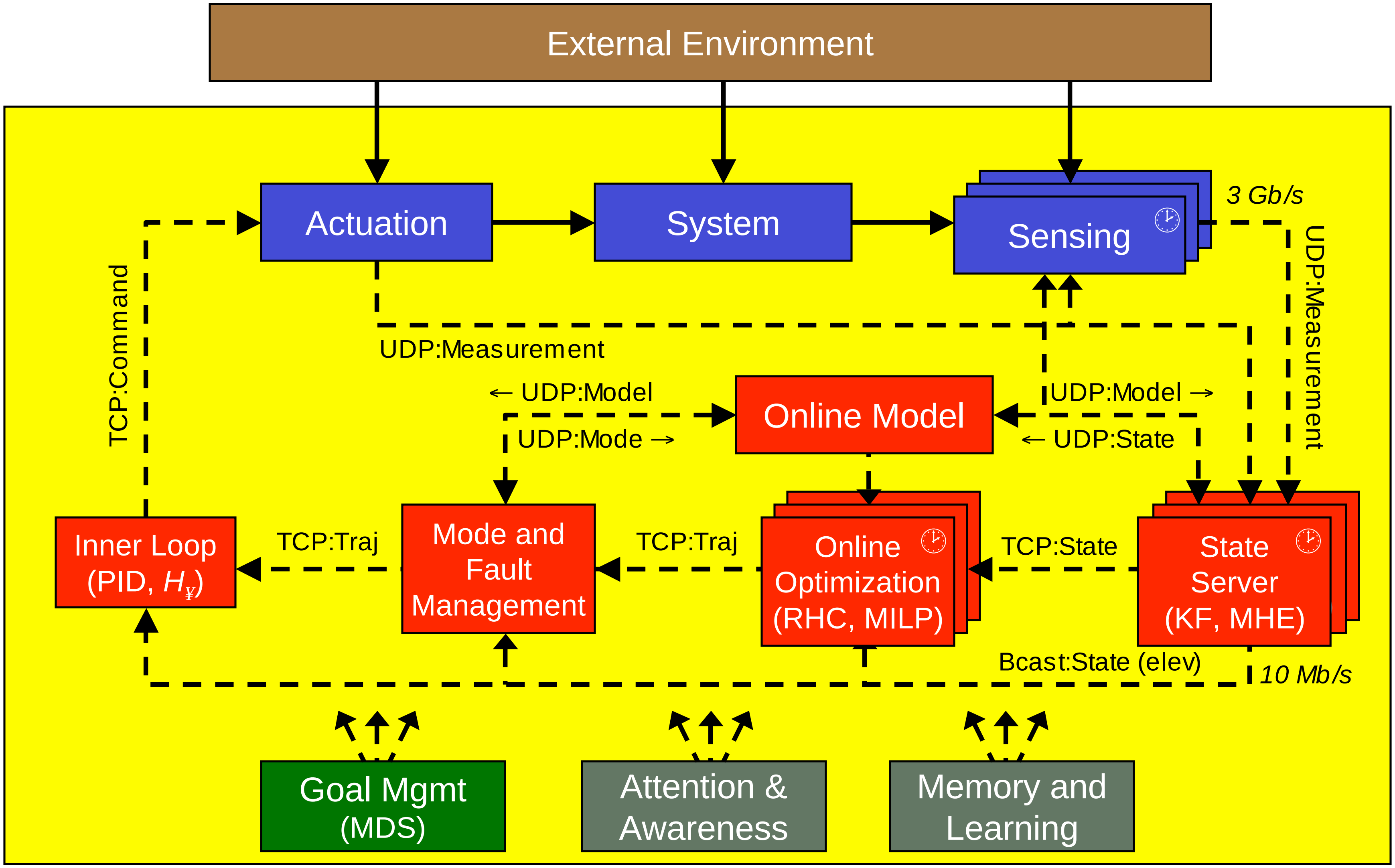
Software

- 15 individual programs with ~50 threads of execution
- FusionMapper: integrate all sensor data into a speed map for planning
- PlannerModule: optimization-based planning over a 10-20 second horizon

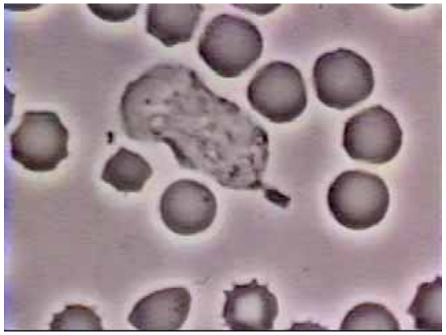
Alice

Networked Control Systems (ala Alice)

(with thanks to P.R. Kumar)



Example 2: Synthetic Biology

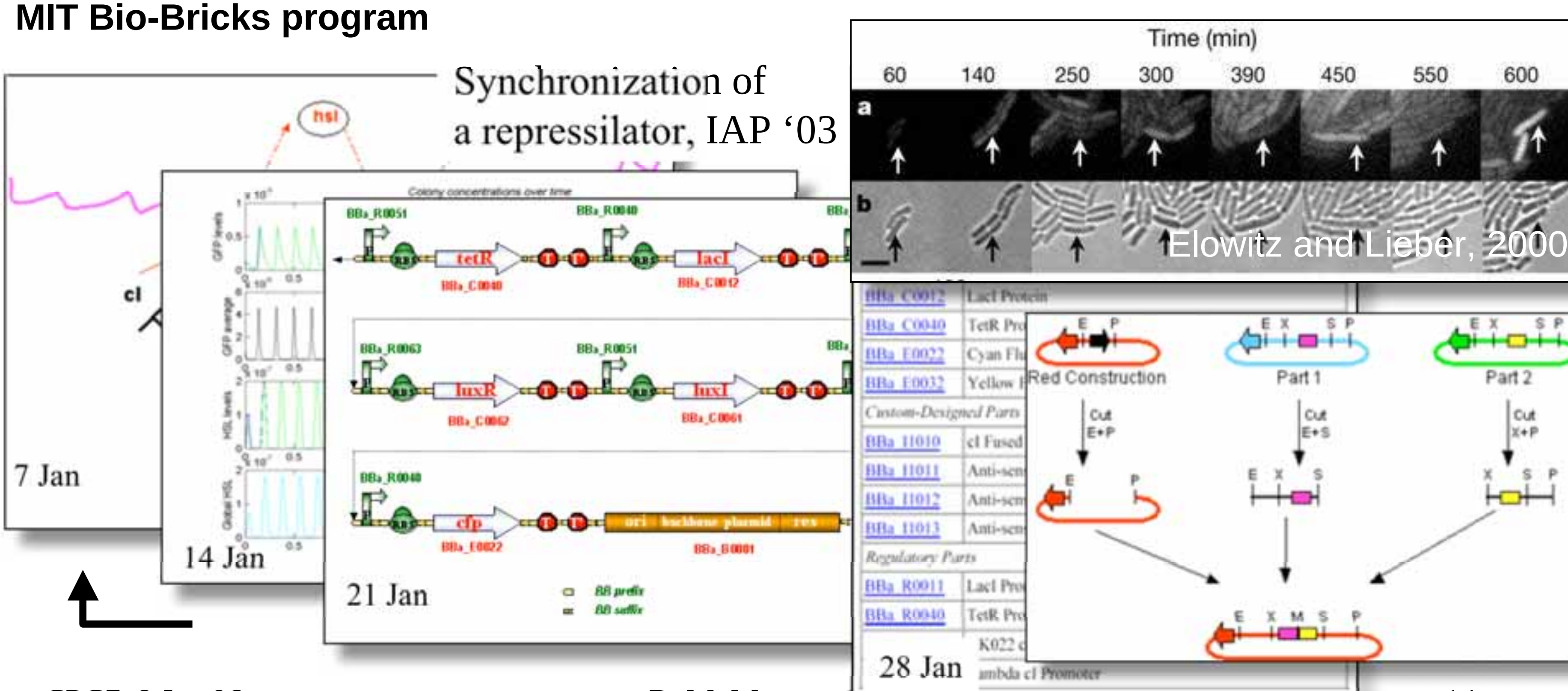


Crawling Neutrophil "Chasing" a Bacterium

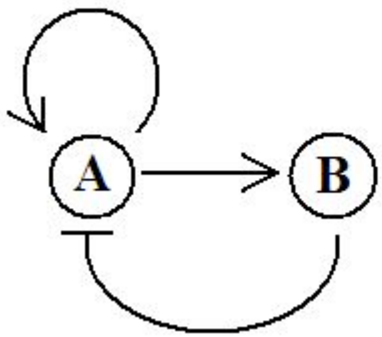
- Human polymorphonuclear leukocyte (neutrophil) on blood film
- Red blood cells are dark in color, principally spherical shape.
- Neutrophil is "chasing" Staphylococcus aureus micro-organisms, added to film.

Tom Stossel, June 22, 1999
http://expmed.bwh.harvard.edu/projects/motility/neutrophil.html

MIT Bio-Bricks program

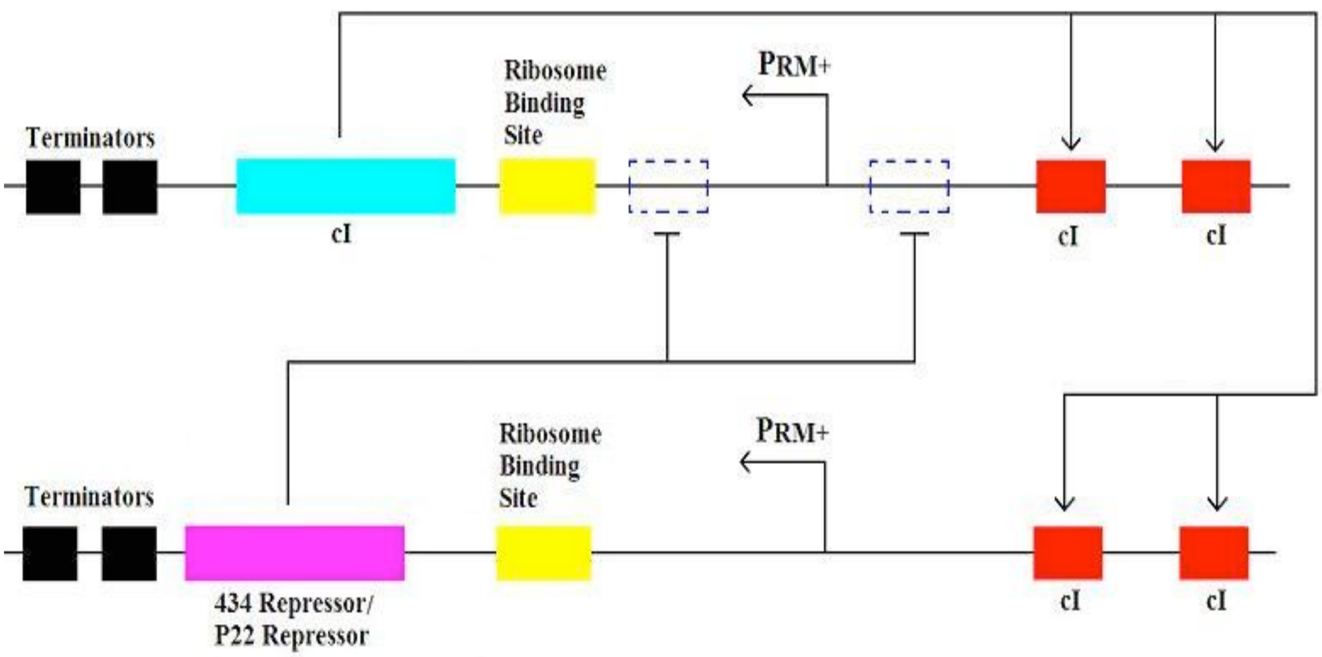


Example: Synthetic Biology Competition 2004



Boston U, Caltech, MIT, Princeton, U Texas

- Caltech: 7 undergrads + 3 grad students + 3 faculty
- Project #1: alternative oscillator designs
- Project #2: serial "adder" (finite state machine)
- Caltech faculty: Elowitz (Bi/APh), Smolke (ChE), M



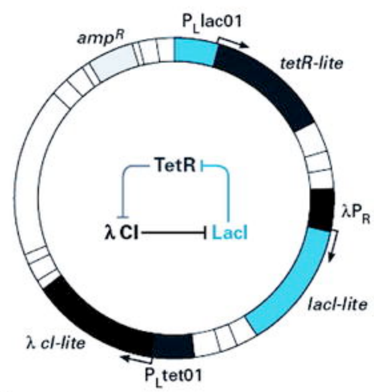
Status:

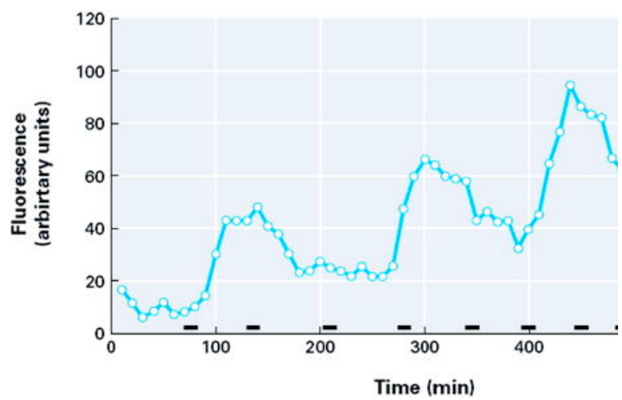
- Two gene regulator circuits customed design, relying on simulations
- Two test parts sent out for fabrication; currently being tested
- BBa_I12019 – 3352 base pairs
- BBa_I12020 – 5171 base pairs

State of the Art: Synthetic Biology

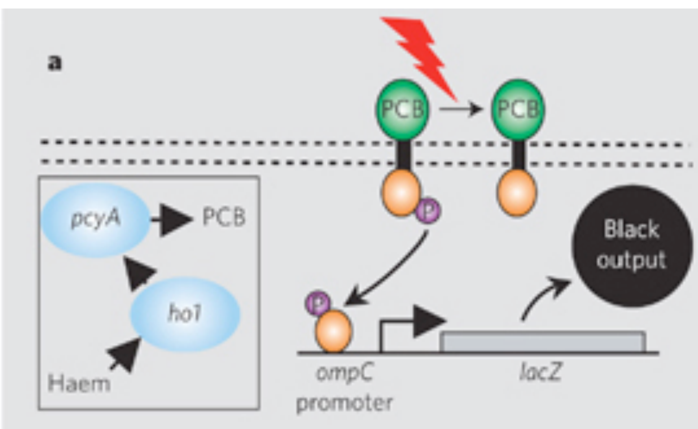
Applications

- Repressillator (Elowitz, 2000)





- Biological "polaroid" (UCSF, UT Austin, 2005)



Theory

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- Some modeling, but mainly after the fact
- Only simple circuits are possible
- More progress on modeling existing systems (in nature)

Some Future Directions in ~~Control Theory~~ Network Science

NRC, 2005

1. **Dynamics, spatial location and information propagation in networks**
   - Integrated communications, computation and control
   - Distributed representations and coordinated operations
2. **Verification and validation of large feedback systems**
   - Proof certificates for complex embedded SW sysems
3. **Design and synthesis of networks and protocols**
   - What should the network topology look like (and why)
   - When do I use TCP vs UDP vs broadcast
4. **Increased rigor and mathematical structure**
   - How do we model & analyze Alice? MS Word? E. coli?
5. **Abstracting common concepts across fields**
   - Bio, Ec, CS …
6. **Robustness and security of networked control systems**