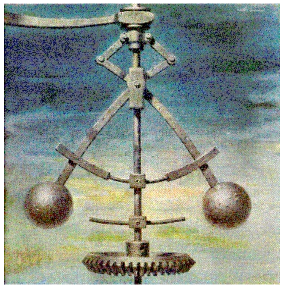
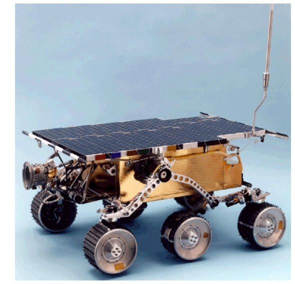
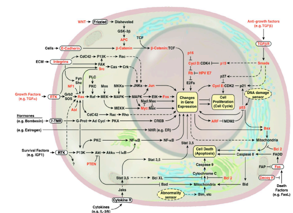
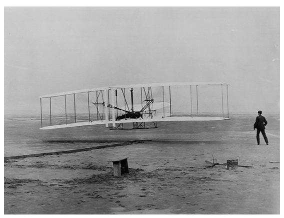
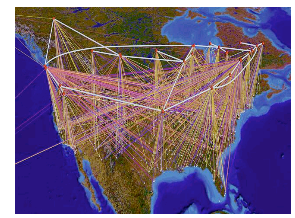



Control in an Information-Rich World

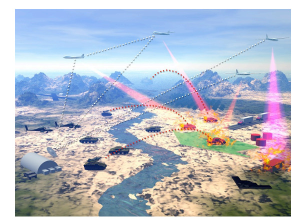



Richard M. Murray
Control and Dynamical Systems
California Institute of Technology

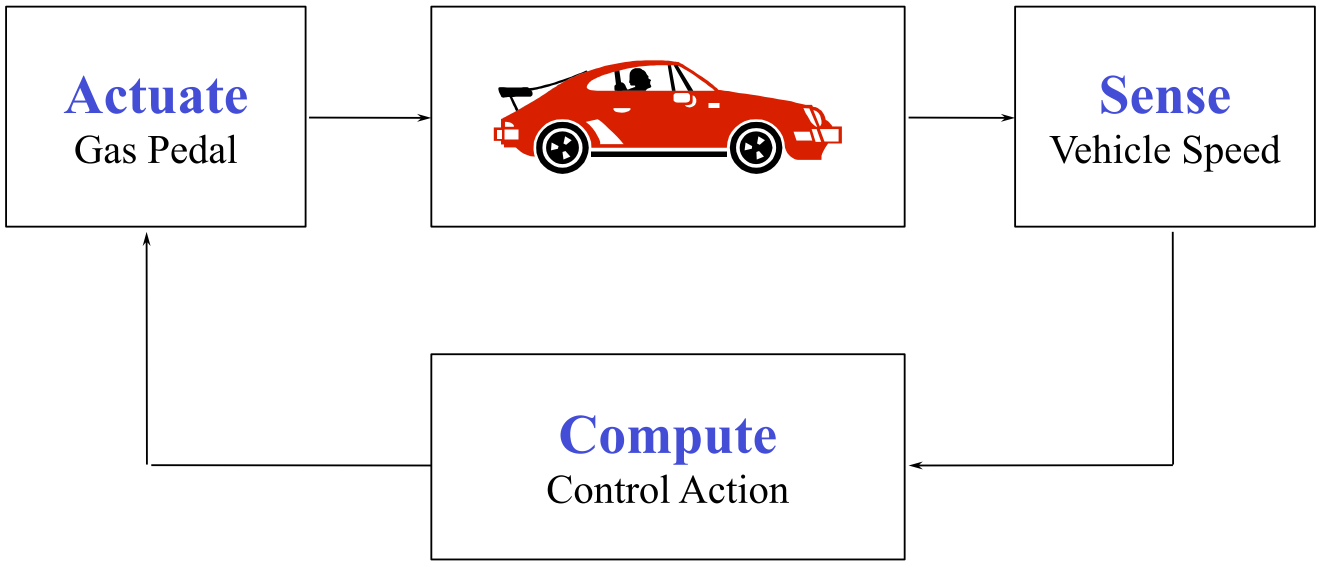
Outline

I. CDS Panel Overview
II. Findings and Recommendations
III. Control.“Computational Worldview”
IV. Summary

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

Control = Sensing + Computation + Actuation
(in feedback loop)

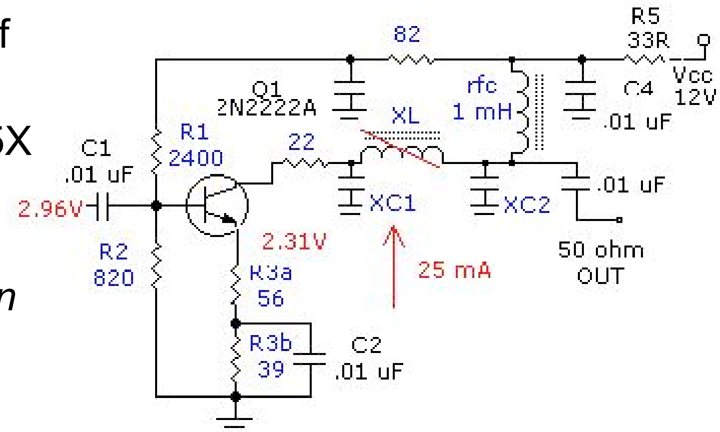


Goals: Stability, Performance, Robustness

Two Main Principles of Control

Robustness to Uncertainty thru Feedback

- Feedback allows high performance in the presence of uncertainty
- Example: repeatable performance of amplifiers with 5X component variation
- Key idea: accurate *sensing* to compare actual to desired, correction through *computation* and *actuation*



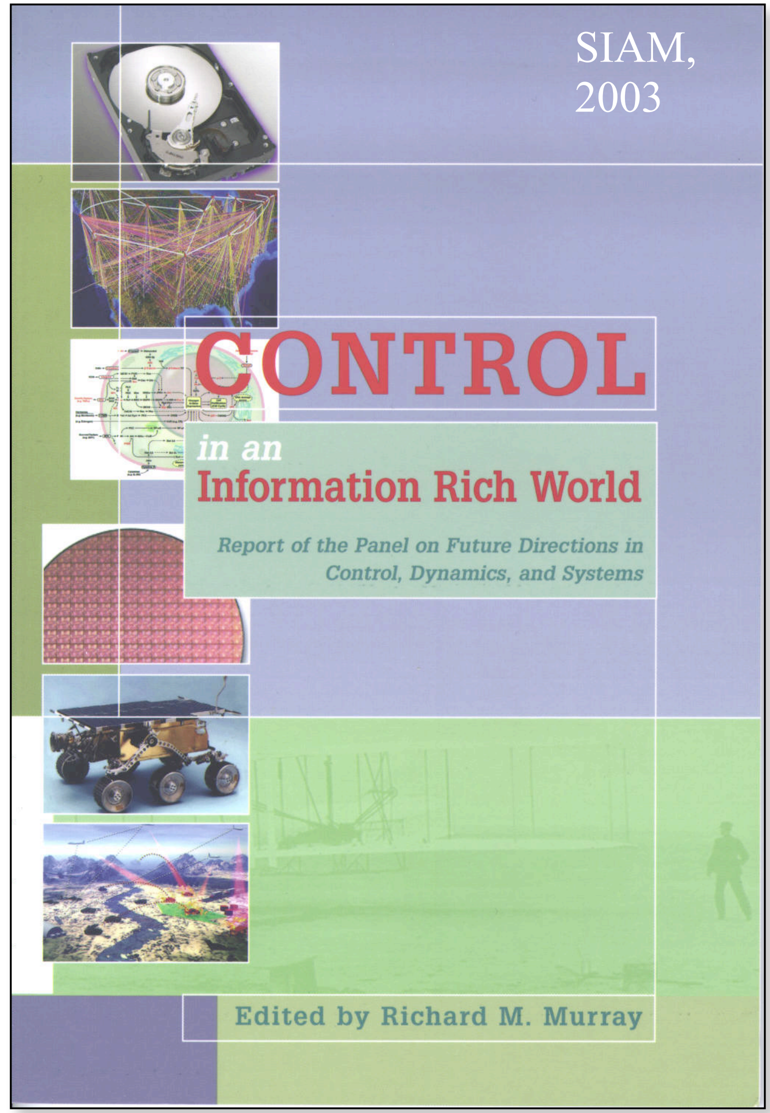
Design of Dynamics through Feedback

- Feedback allows the dynamics of a system to be modified
- Example: stability augmentation for highly agile, unstable aircraft
- Key idea: interconnection gives *closed loop* that modifies natural behavior

NB: Control involves (computable) *tradeoffs* between robustness and performance

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**



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

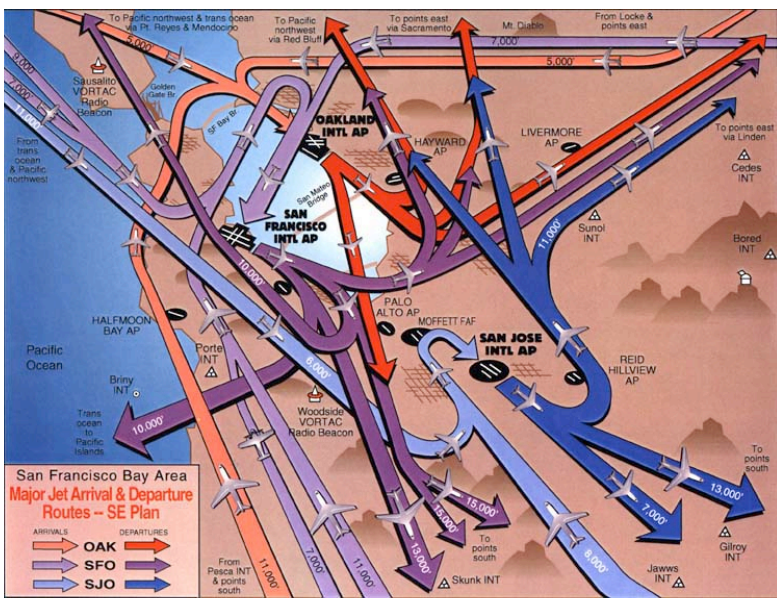
Transportation and Aerospace

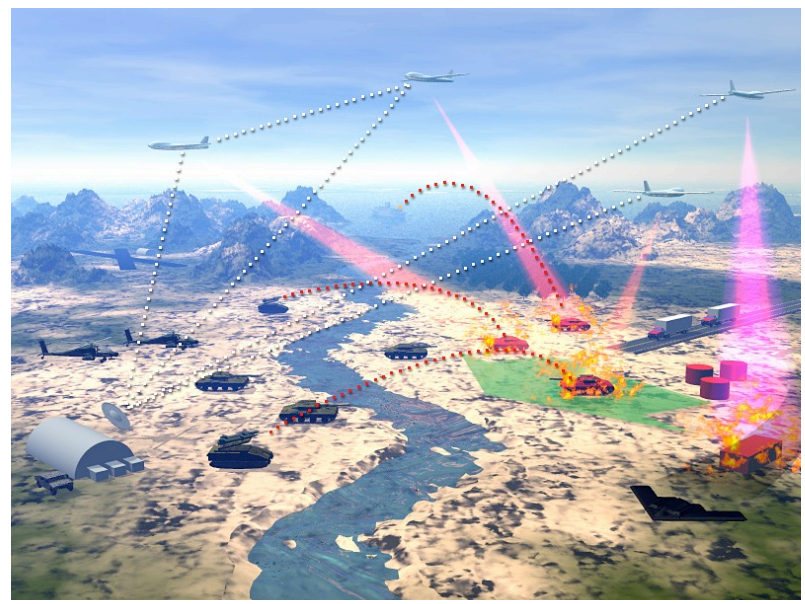
Themes

- 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

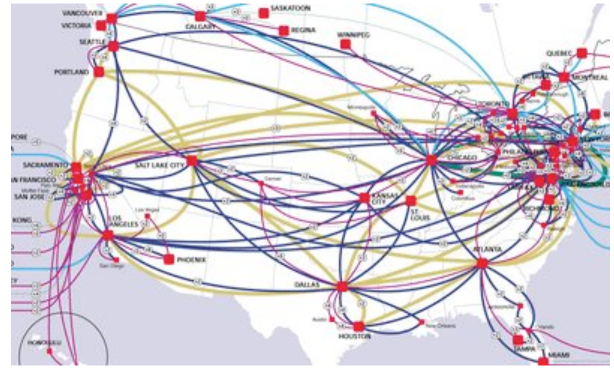
- Heterogeneous networks merging communica-tions, computing, transportation, finance, utili-ties, manufacturing, health, entertainment, ...
- Robustness/reliability are dominant challenges
- Need "unified field theory" of communications, computing, and control

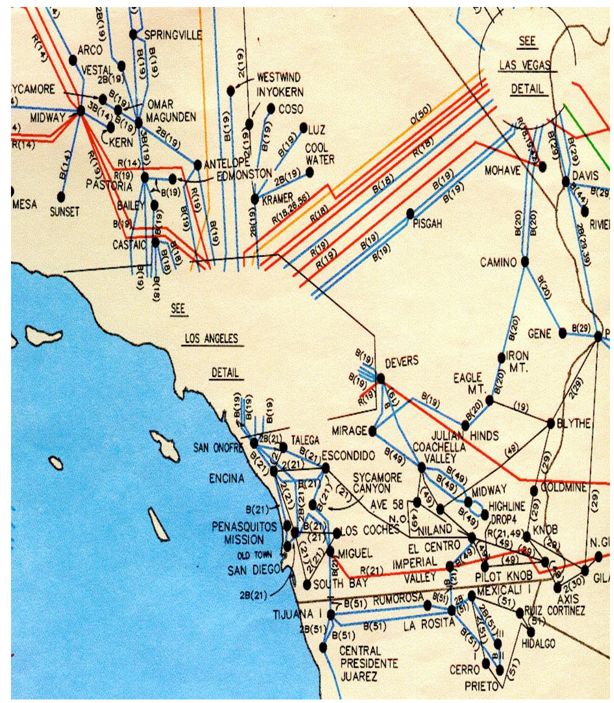
Many applications

- 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





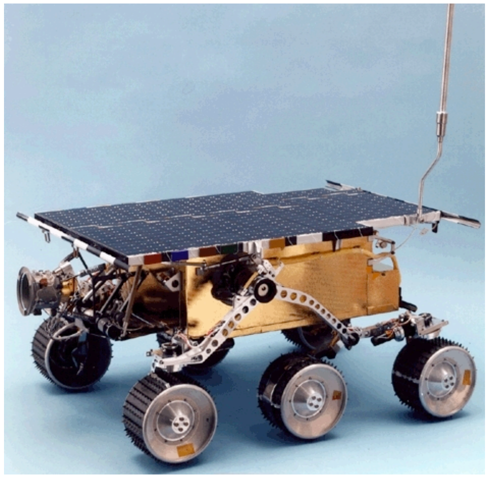
Robotics and Intelligent Machines

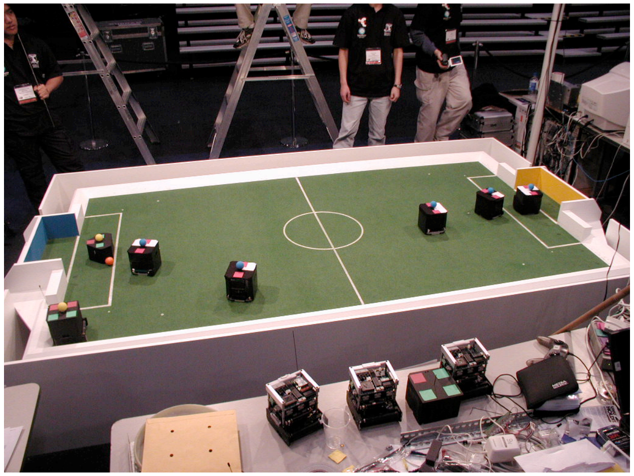
Wiener, 1948: Cybernetics

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

DARPA, 2003-07: 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

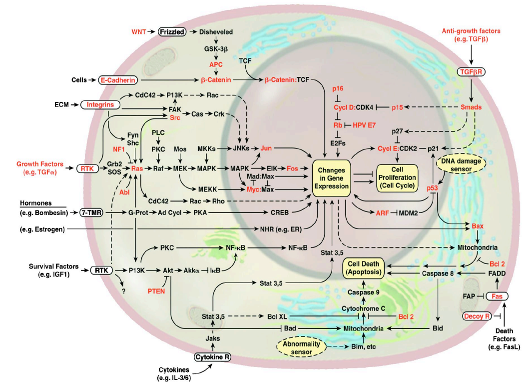




Biology and Medicine

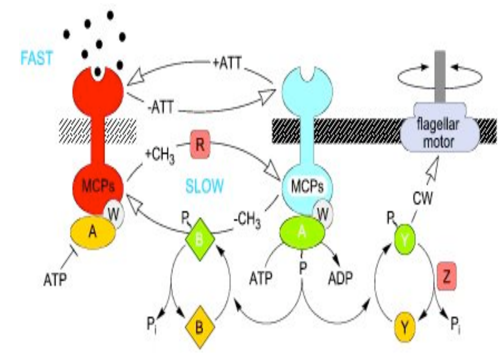
“Systems Biology”

- 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



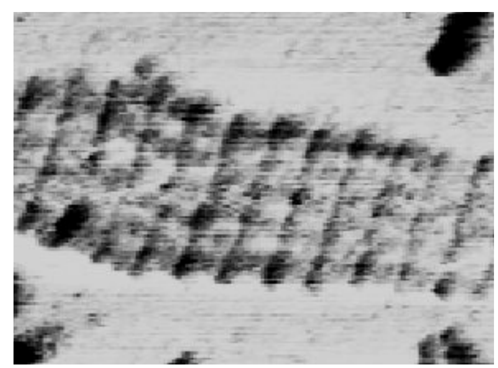
Key features of biological systems

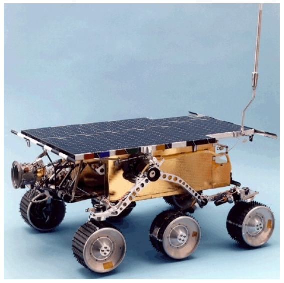
- Integrated control, communications, computing
- Reconfigurable, distributed control, at *molecular* level

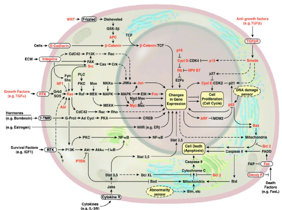


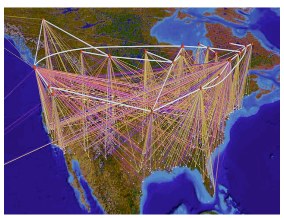
Design and analysis of biological systems

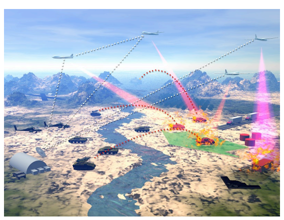
- Apply engineering principles to biological systems
- Systems level analysis is required
- Processing and flow of information is key

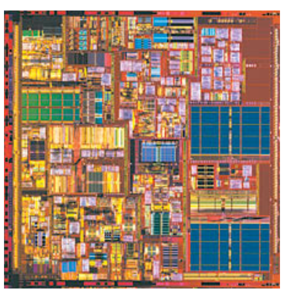












CDS Panel Recommendations

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.**

Control."Computational Worldview"

Example #1: Feedback Sorting

- How a control theorist would sort a list

Example #2: Networked Control Systems

- Emerging architectures for autonomous systems

Example #3: Distributed Control (Ali Jadbabaie)

- Flocking, synchronization, coverage

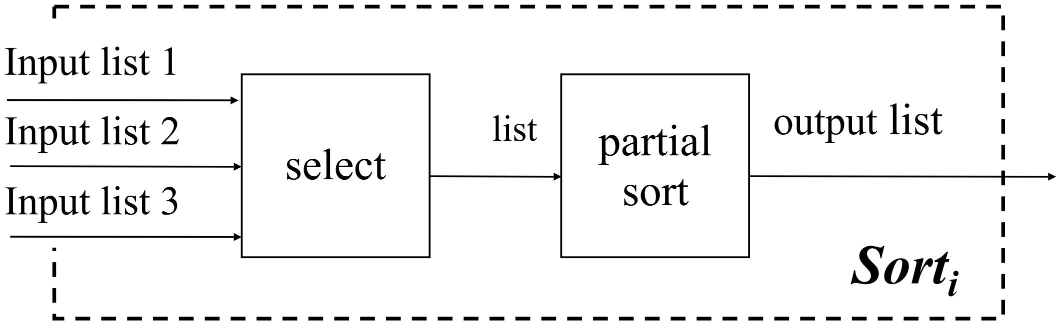
Example #4: Synthetic biology (if time)

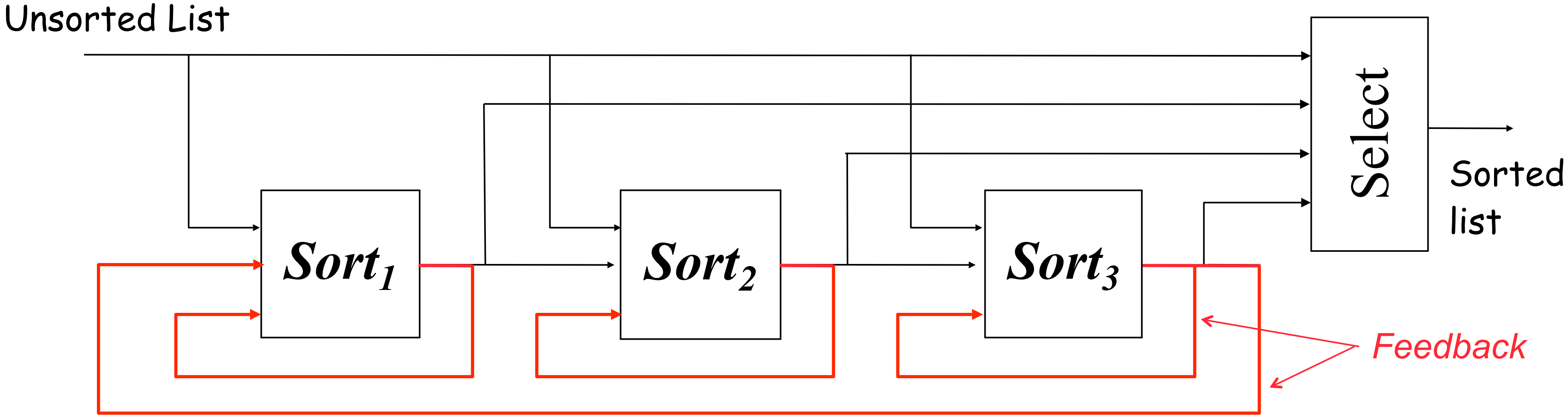
- Assembly language programming using DNA

Feedback Algorithm for Sorting

Idea: use fast and accurate sensing to sort using feedback

- Suppose we can quickly check whether one list is more sorted than another (accurate sensor)
- Use this to select most sorted input and then interconnect several partial sorters (via feedback)

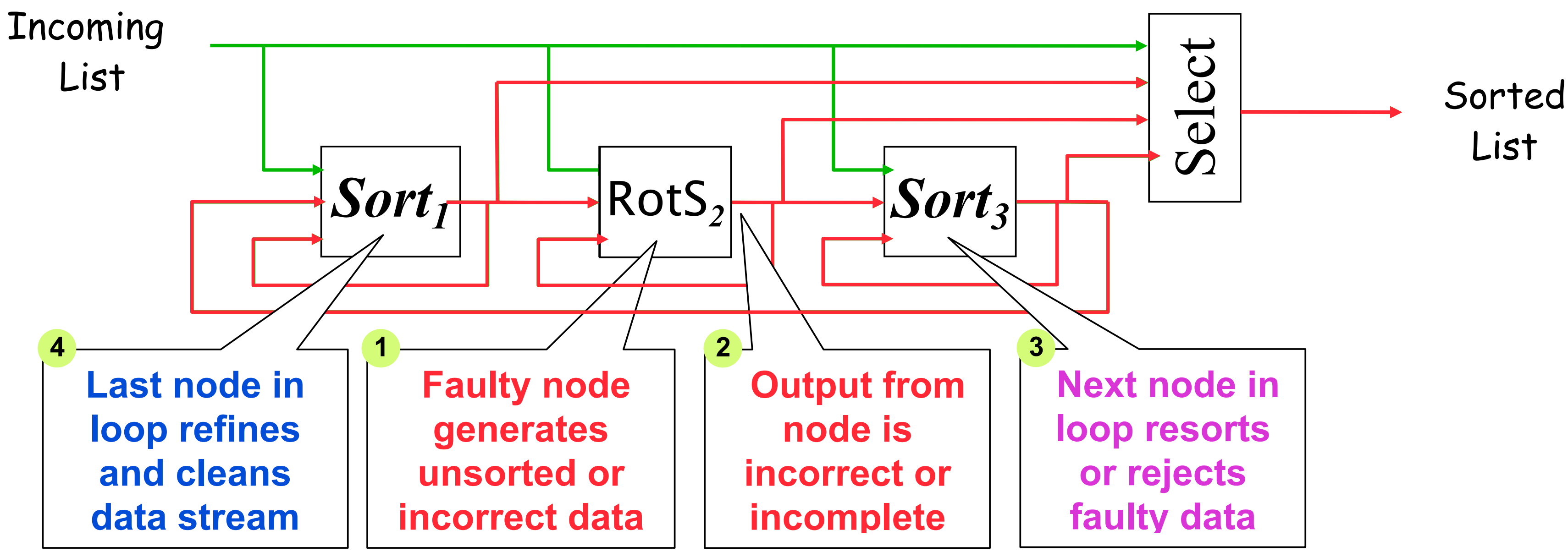




Upgrade and Repair in Sort Example

Question: what happens if we insert faulty code into sort loop?

- **Feedback mechanisms correct (resort or reject) data**



Team Caltech: Alice

Team Caltech

- Started in 2003, for DGC04
- 2004-05: 50 Caltech undergraduates, 1 MS student, 3 TAs, 2 faculty

Alice

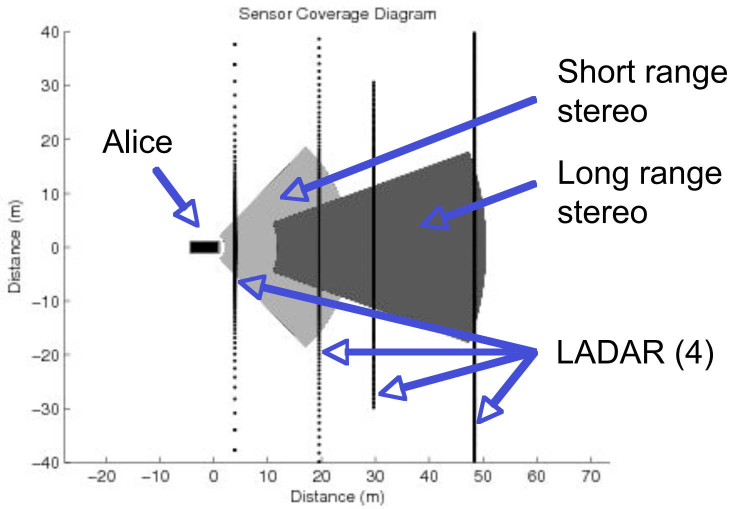
- 2005 Ford E-350 Van
- 5 cameras: 2 stereo pairs, roadfinding
- 5 LADARs: long, med*2, short, bumper
- 2 GPS units + 1 IMU (LN 200)

Computing

- 6 Dell PowerEdge Servers (P4, 3GHz)
- 1 IBM Quad Core AMD64 (fast!)
- 1 Gb/s switched ethernet

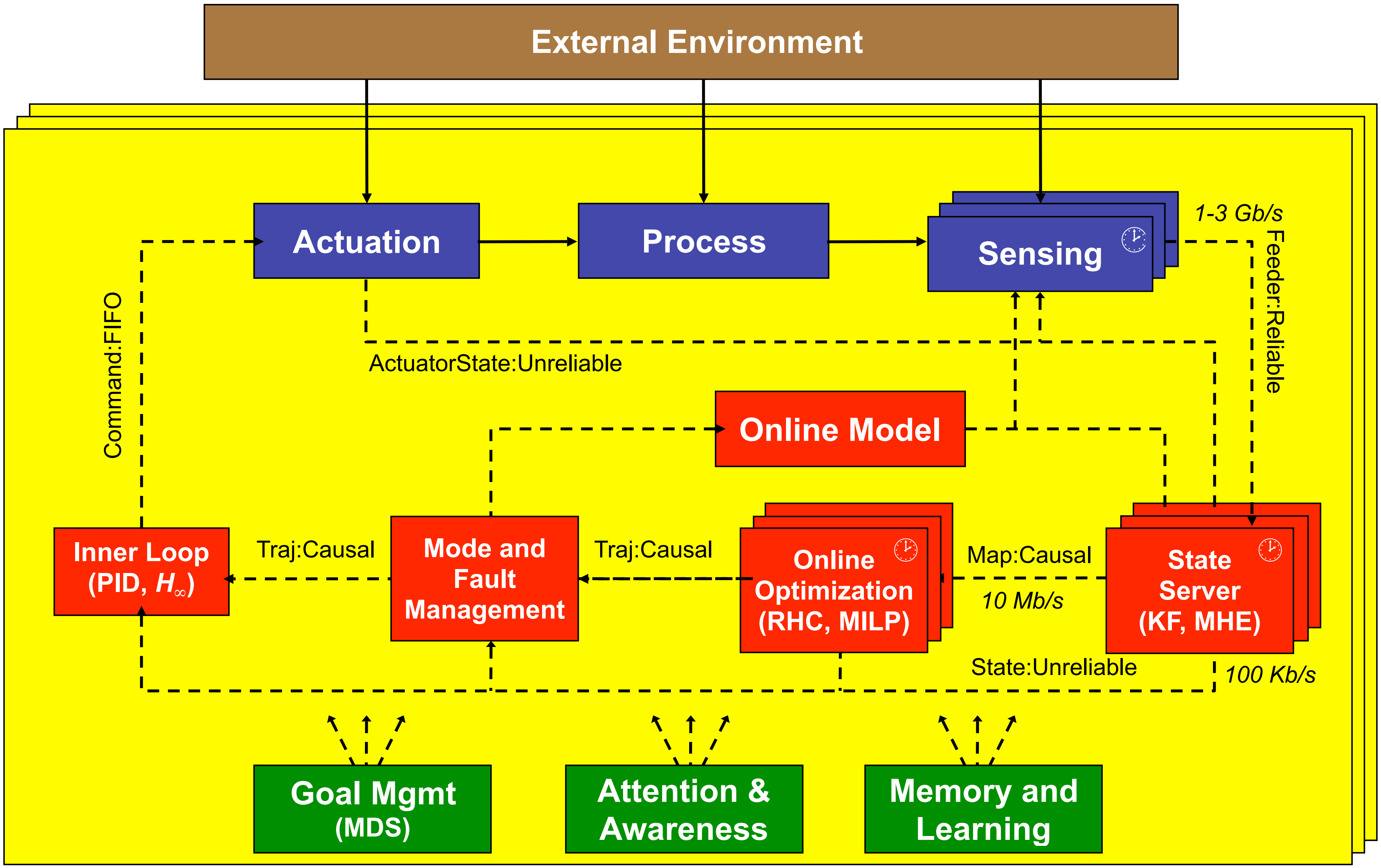
Software

- 15 programs with ~100 exec threads
- 100,000+ lines of executable code

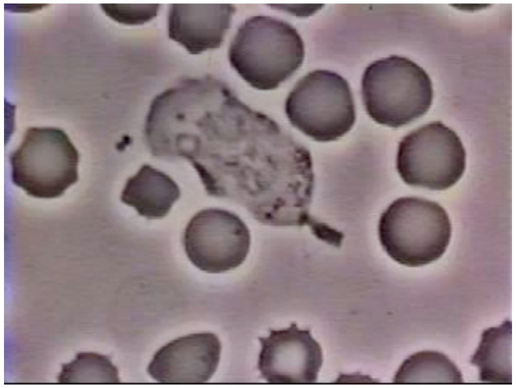


Networked Control Systems

(following P. R. Kumar)



Biological Systems



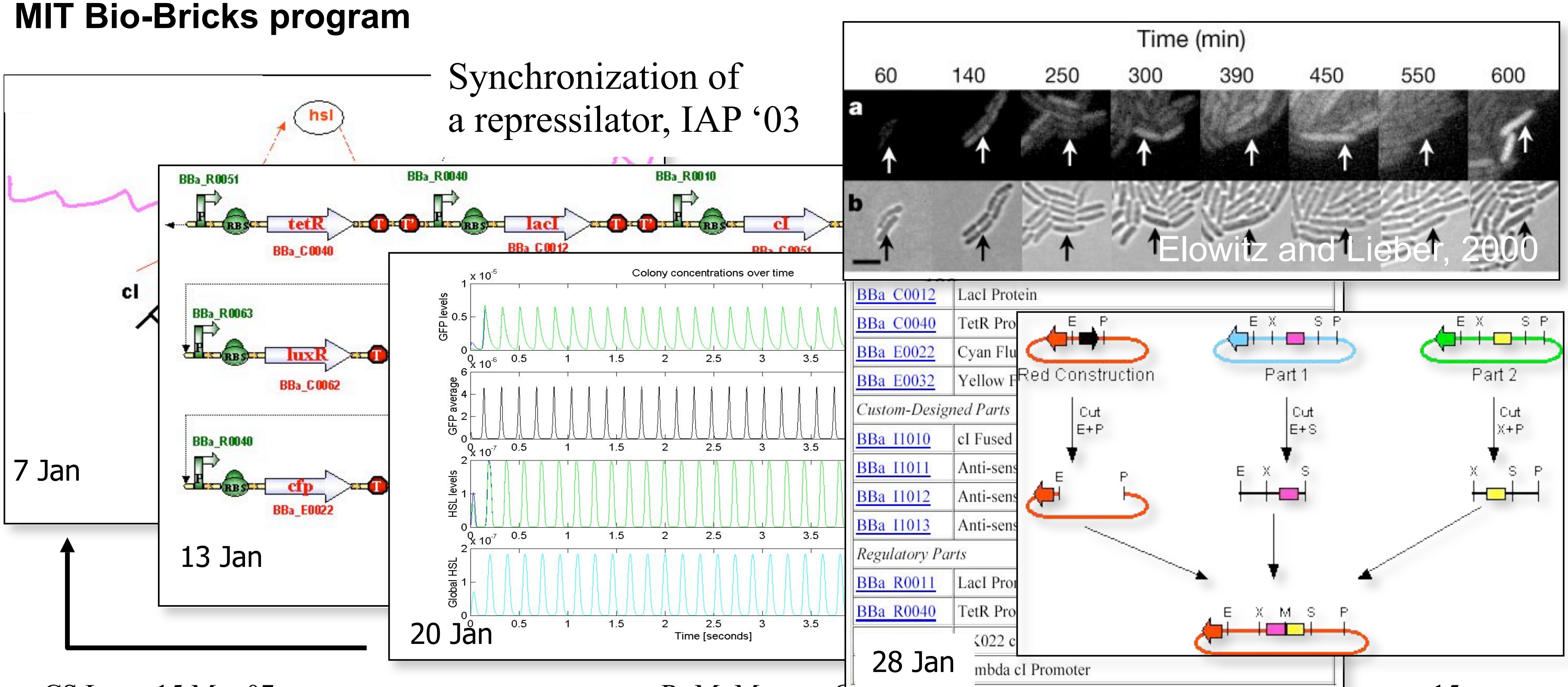
Crawling Neutrophil "Chasing" a Bacterium

- 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.

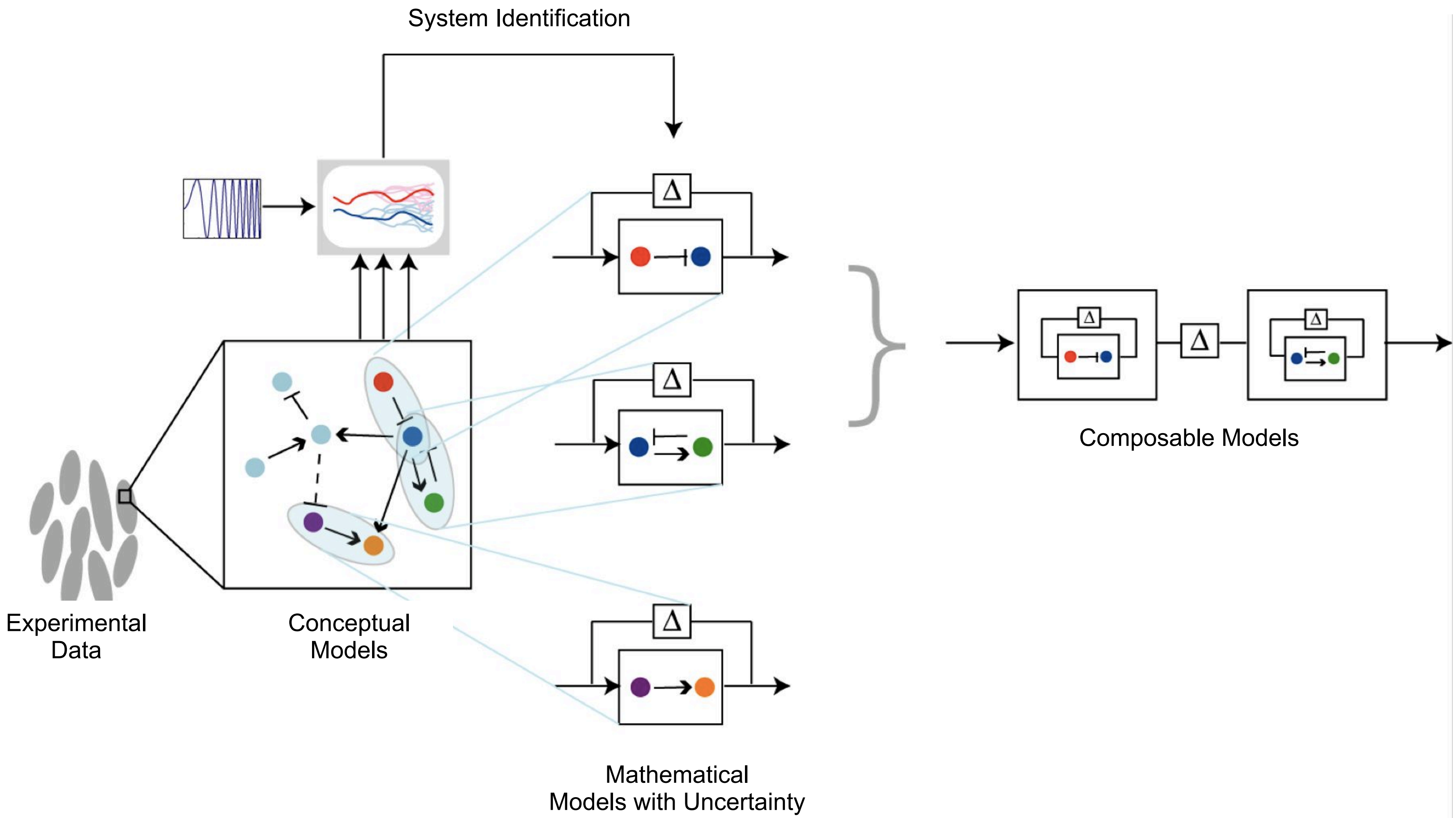
Tom Stossel, June 22, 1999
http://expmed.bwh.harvard.edu/projects/motility/neutrophil.html

MIT Bio-Bricks program

Synchronization of a repressilator, IAP '03



Composition of Biological Circuits



Summary: Future Directions in Control

Control remains an exciting area, with *many* new applications

- Community needs to get involved in new applications (already happening!)
- Need to maintain support for control research by government, industry

Panel Recommendations

1. Increase research aimed at the integration of control, computer science, & communications
2. Increase research in control at higher levels of decision making, moving toward enterprise level systems
3. Explore high-risk, long-range applications of control in nanotechnology, quantum mechanics, electro-magnetics, biology, environmental science, etc
4. Maintain support for theory and interaction with mathematics
5. New approaches to education to disseminate con-trol concepts and tools to non-traditional audiences