Future Directions in Control in an Information-Rich World

Summary of a Report of the Panel on

Future Directions in

Control, Dynamics and Systems

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or
www.cds.caltech.edu/~murray/cdspanel/

Evolution of Control Engineering

- **Ancient Greek and Roman Times**
  - Mechanical Level Controller in Ketsebios‘ Clock
- **~ 1780 Flyball Governor**

  J. Watt steam engine, Fig. 1
  - Safe, reliable, consistent operation
  - Rapid spread of steam-powered factories
- **19th and Early 20th Century**
  - Enabler for power, communications, transportation, processing, manufacturing technologies
- **~ 1960 Computers in Control** (flexibility)

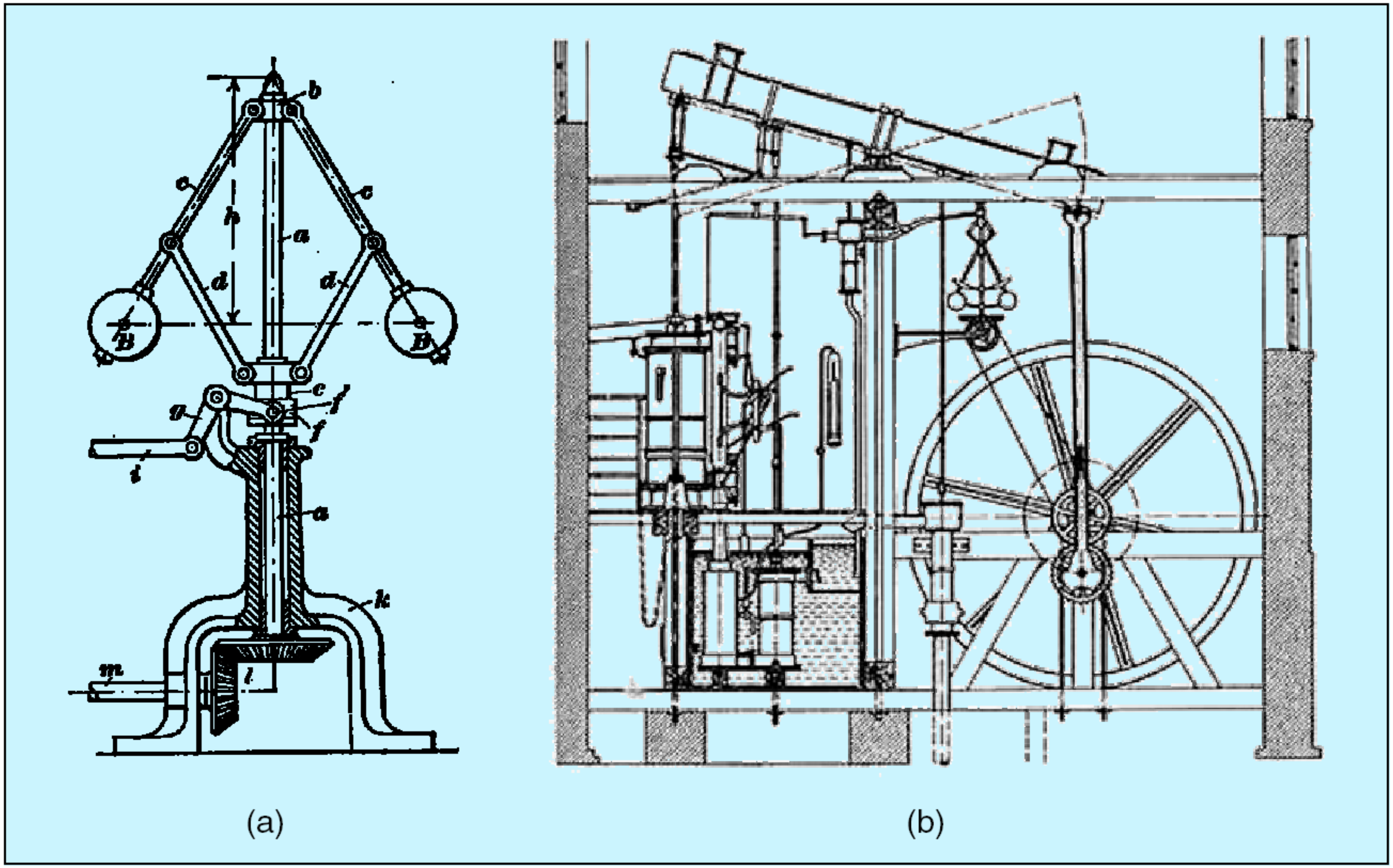

Figure 1. *(a) The centrifugal governor, developed in the 1780s, was an enabler of (b) the successful Watt steam engine, which fueled the industrial revolution. (Figures courtesy Richard Adamek (copyright 1999) and Cambridge University.)*

- **Contributions to the Development of Controls from Many Fields, e.g.**
  - ➢ CE, ME, EE, ChemE
  - ➢ Applied/Pure Mathematics
  - ➢ OR and Economics
  - ➢ Physical and Bio Sciences
  - ➢ ....

✓ Importance of cross-disciplinary interaction

Recent Success and Impact

through advent of analog and digital electronics

Examples of Visible Success

- **Guidance and Control Systems**

  Military/commercial aircraft, missiles, launch vehicles, satellites, Fig. 2a

  - ➢ Stability, tracking in presence of large uncertainties

- **Controls in Manufacturing Industries**

  From Automotive electronics to ICs, CNC, ..., Fig. 2b

  - ➢ Precise positioning / assembly for high-yield / high-quality fabrication of components and products

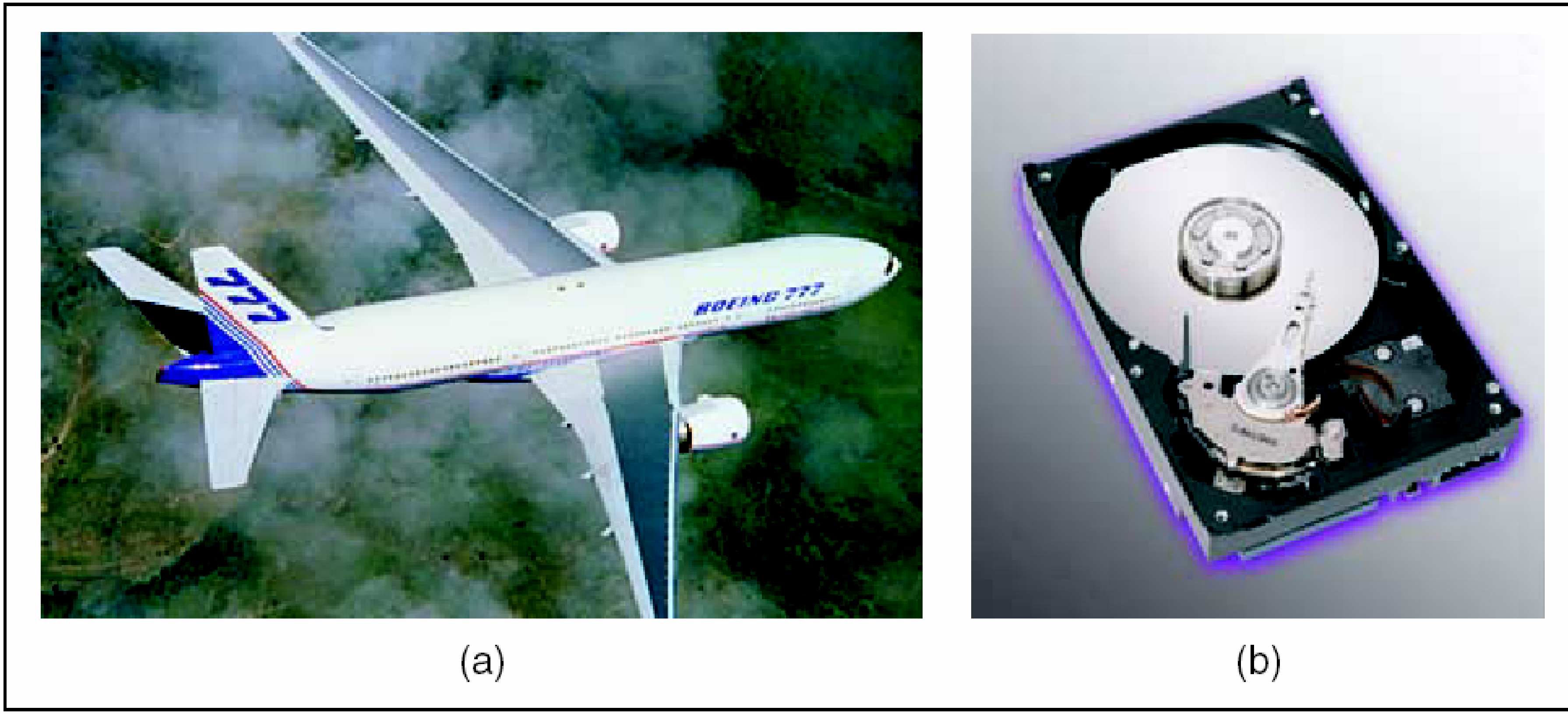

Figure 2. *Applications of control: (a) the Boeing 777 fly-by-wire aircraft and (b) the Seagate Barracuda 36ES2 disk drive. (Photographs courtesy of the Boeing Company and Seagate Technology.)*

- **Industrial Controls in Processing Industries**

  Hydro carbon, petroleum, chemical, food, etc.

  - Maintain high product quality by monitoring of 1000s of sensor signals and adjusting 100s of valves, pumps, heaters, other actuators

- **Control of Communication Systems**

  Telephone and cell phone systems, Internet, ...

  - Regulate signal power level in transmitters /receivers; provide adaptive noise cancellation; manage packet buffers

✓ **Enormous impact on productivity and quality of life of modern society**

Future Opportunities and Challenges

- New applications will build upon advances in control theory and technology
- Impact of ubiquitous, distributed computation, communication, sensing systems provides access to enormous amounts of real-time data
- Ability to process and communicate that data, unimagined 20 years ago
- Profound effect on military, commercial, scientific applications

- Future control systems: heterogeneous collection of physical and information systems, with intricate interconnections and interactions
- Inexpensive and pervasive computation, communication, and sensing (= information-based systems) stimulate shift of interest from low-level control to higher levels of decision-making and control
    - Increased autonomy through machine perception
    - Integration of local feedback loops into enterprise-wide scheduling and resource allocation
    - This extension results in enormous opportunities for improved efficiency, productivity, safety

- Interaction of SW systems with physical systems in integrated systems, e.g. power networks, Fig. 3a and b
- Increasing importance for defense systems, fight against terrorism, asymmetric threat
    - Autonomous/semiautonomous unmanned systems
    - Micro-systems and sensor-webs
    - Command and control systems with reconfigurable decision-making capabilities

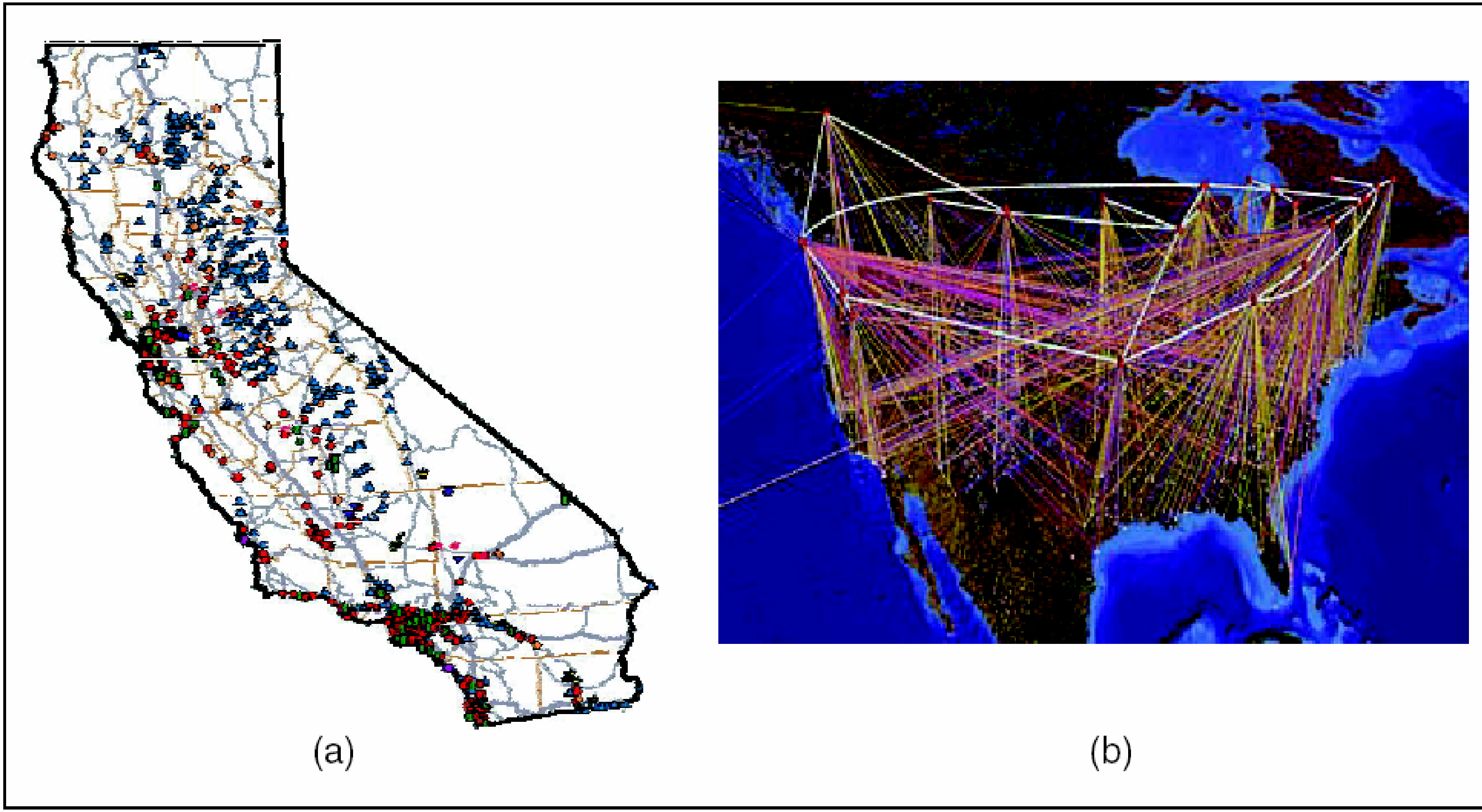

Figure 3. *Modern networked systems: (a) the California power network and (b) the NSFNET Internet backbone. (Figures courtesy of the State of California and the National Center for Supercomputer Applications (NCSA) and Robert Patterson.)*

New Methods and Approaches to be Developed

- Control systems with both symbolic and continuous dynamics
- Control in distributed, asynchronous, networked environments
- High-level coordination and autonomy
- Automatic synthesis of control algorithms, with integrated validation and verification
- Building highly reliable systems from unreliable parts

Five Advanced Application Areas

- **Aerospace and Transportation**, Fig. 4
  - From inner loops to outer loops = vehicle management (configuration, payload, health, etc.)
  - Large collections of distributed enteties, e.g. swarms

- **Information and Networks**
  - Control *of* Networks, Fig. 5
    - Congestion control, QoS control, routing, data caching, power management
    - Extremely large scale, decentralized, instability due to varying time delays, diversity in traffic characteristics

(a)

(b)

Figure 4. *(a) The F-18 aircraft, one of the first production military fighters to use "fly-by-wire" technology, and (b) the X-45 (UCAV) unmanned aerial vehicle. (Photographs courtesy of NASA Dryden Flight Research Center.)*

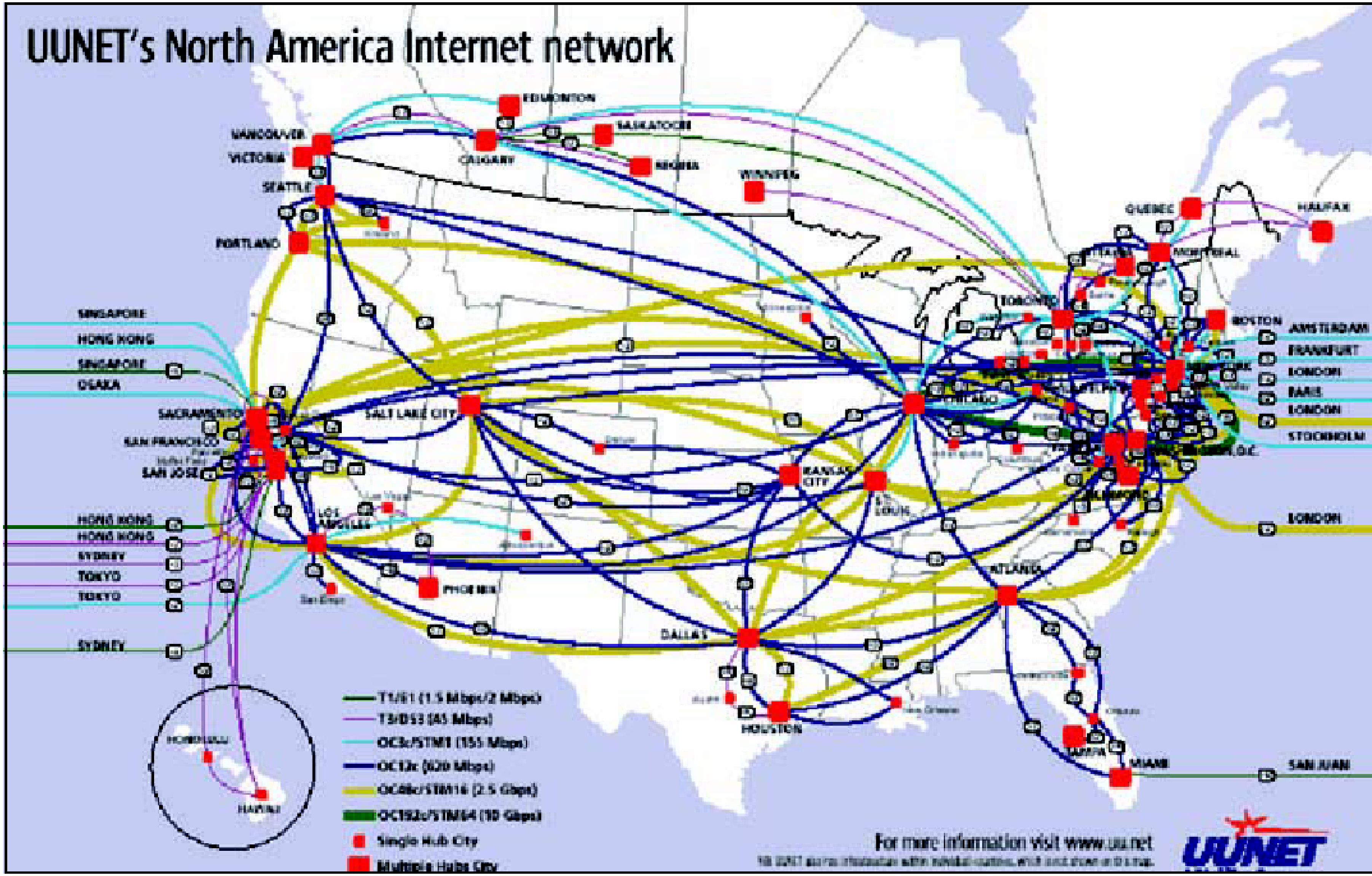

Figure 5. *UUNET network backbone for North America. (Figure courtesy of WorldCom.)*

- Control *over* Networks

  - Interaction over Internet with physical environment:

    e.g. tele-operation , -presence, -existence, e-shopping

  - Network of sensory / actuator nodes:
    wireless or by wires

    e.g. automobiles, smart homes /buildings,
    enterprise-wide supply and logistic chains

  - Industrial IT = InIT: HW / SW interaction

    Convergence of
    communications, computing and control

  - Communication:
    distributed, asynchronous, packet-based

❖ Robotics and Intelligent Machines

- Development of machines with human-like behaviour
  - control will be central element
- *From* manufacturing robots *to* wheeled and legged machines:
  - robotic competitions (RoboCup) and entertainment, planet exploration, UAV (ground, marine, satellite), new medical devices and tools
- Increased autonomy by machine perception and cognition capabilities
- Increased interaction with humans and society

- Building upon ideas of N. Wiener, H.S. Tsien, ...
  - Cybernetics, 1948, Fig.
- Sample examples, Fig. 6a and b:
  - Mars Sojourner, Spirit and Opportunity, (Beagle)
  - AIBO (AI technologies), ...
- Future intelligent machines require:
  - Merging of AI (planning, adaptation, learning) and control community (modeling, analysis, design of feedback systems)
  - Tools for higher level perception, reasoning , and decision-making.

A Remarkable Early Book on Control Science

CYBERNETICS

OR CONTROL AND COMMUNICATION IN THE ANIMAL AND THE MACHINE

Norbert Wiener

PROFESSOR OF MATHEMATICS
THE MASSACHUSETTS INSTITUTE
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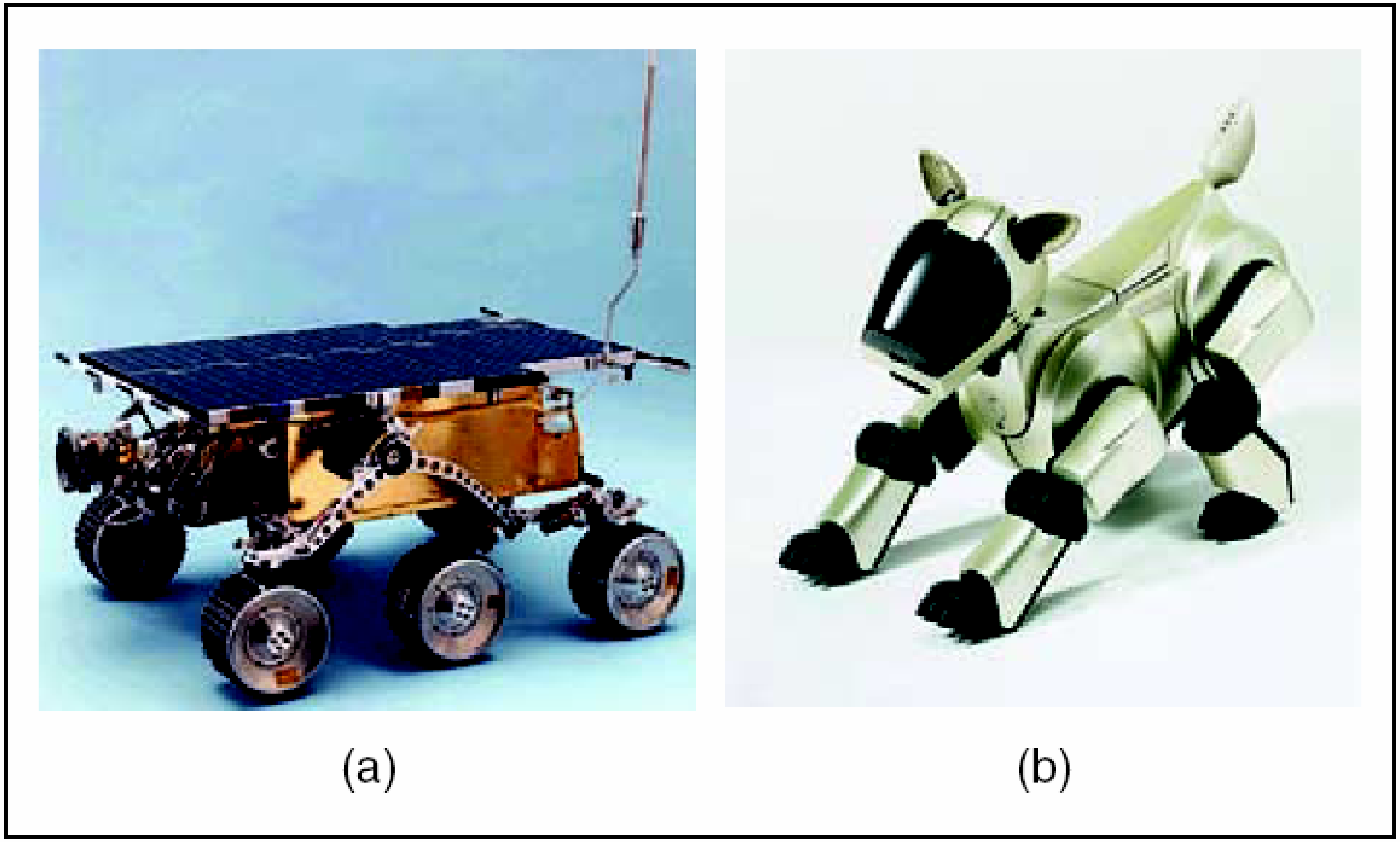

Figure 6. *(a) The Mars Sojourner rover and (b) Sony AIBO Entertainment Robot. (Photographs courtesy of Jet Propulsion Laboratory and Sony Electronics Inc.)*

❖ Biology and Medicine

Biology

- Levels of organization: from *molecular* to *cellular* to *organisms* to a *population*
- Bio Sciences uses approaches from (systems) engineering, i.e. “system biology“
- Discoveries in bio sciences: important applications in man-made (engineering) systems
- Synergy at interface of biology and engineering offers novel opportunities
- Reverse (or forward) engineering of biological (control) networks, Fig. 7

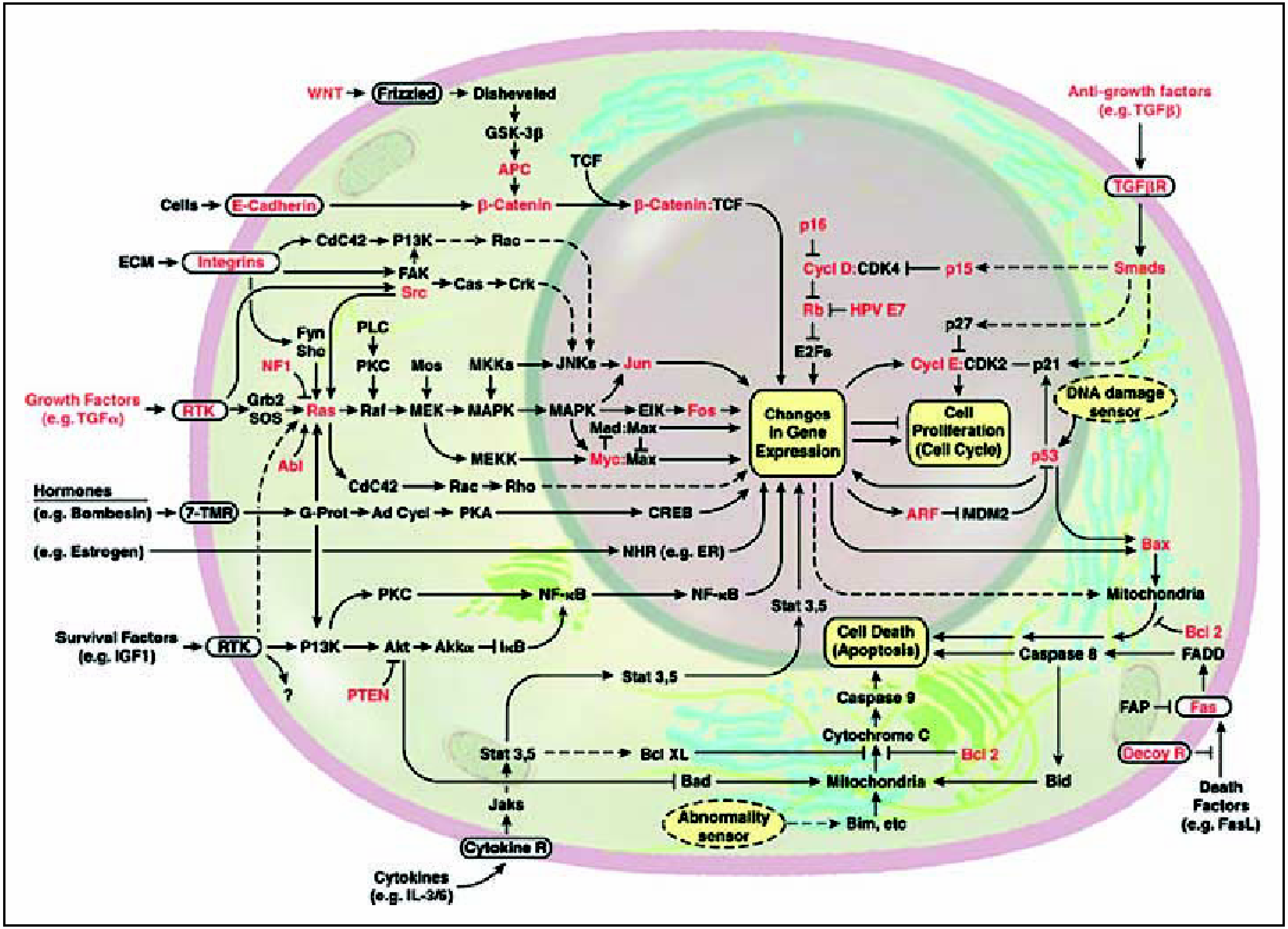

Figure 7. *The wiring diagram of the growth signaling circuitry of the mammalian cell [16]. (Reprinted from [16] with permission from Elsevier Science)*

- 80% of nervous activity: sensing, actuation and control

- **Examples**: for various levels of organization
  - Gene regulation;
  - Hormanal, immunulogical, and cardiovascular feedback mechanisms;
  - Muscular control and locomotion
  - Active sensing, vision and proprioception
  - Attention and consciousness
  - Population dynamics and epidemics e.g. spread of HIV or SARS

Medicine and Biomedical Research

- Intelligent operating rooms and hospitals
- Image-guided surgery and therapy
- HW and soft tissue integration
- Development of physical and neural prostheses, some overlap with robotics

❖ Materials and Processing

- Chemical industry
  - process manufacturing operations need advanced information **and** process control technologies in highly competitve markets
- Nanotechnologies in electronics, chemistry, biomaterials
- Thin film processing and design of integrated systems
  - Substantial payoffs for semiconductor materials to pharmaceuticals to bulk materials, Fig. 8
- Need for process modeling, use of in situ/online measurements
- Environmental statutes and safety
  - Pollution control devices: reduce production of pollutants
  - Smaller storage capacities: risk reduction of leaks
  - Highly integrated plants: reduce energy cost

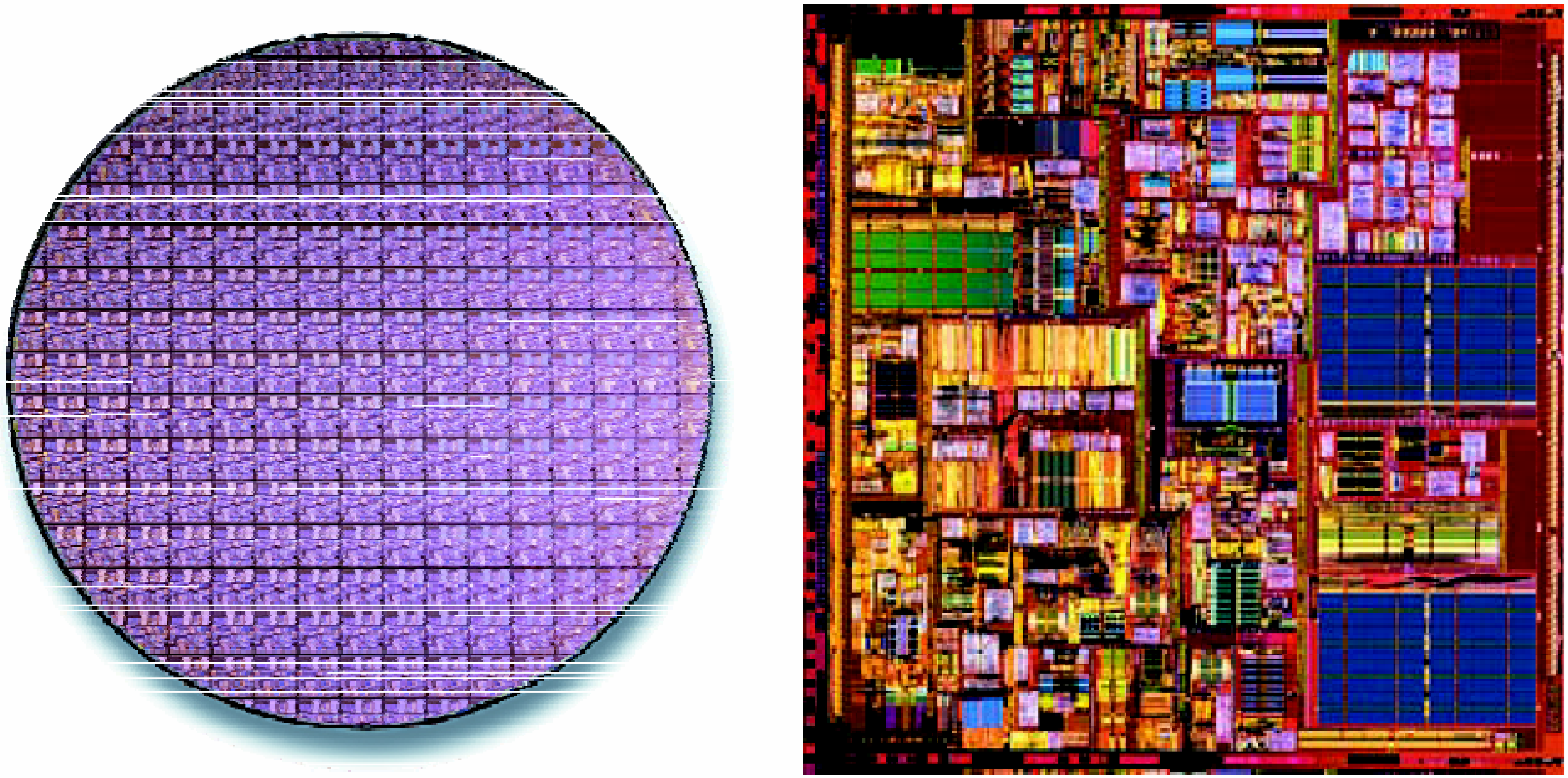

Figure 8. *Intel Pentium IV wafer and die.*

❖ Other Application Areas

- Environmental Science and Engineering:
  - atmospheric and microbiological systems
- Economics and Finance
- Electromagnetics, e.g nulling stealth
- Molecular, quantum and nano-scale systems
- Novel decentralized and heterogeneous energy systems based on conventional or renewable energies

Education and Recommendations

Education

- Role of control engineer as a *systems engineer*
- Go beyond discipline boundaries: create cross-disciplinary centers
- Make basic principles of feedback and control known to a wider community
- Create new ways of providing background for understanding of principles, methods, ...

Recommendations

- Integrated control, computation, and communication
- Control of complex decision systems
- High-risk, long-range applications of control to new domains such as nano-technology, quantum mechanics, biology, environmental science, ...
- Support for theory and interaction with Maths
- New approaches to education and outreach

The End