Cyber-Physical Systems Research Challenges

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Cars Drive Themselves

Cars are Networks of Computers

A BMW is "now actually a network of computers"

- [R. Achatz, Seimens, Economist Oct 11, 2007]

Cars are Nodes in a Network

"As smart as in-car navigation devices are, they could be smarter. They could talk to each other via the Internet and share information on how fast traffic is moving on the roads they have just traveled. And they could also use the Internet to let you search for places of interest, get map updates, or even receive new destinations wirelessly."

Wall Street Journal, March 27, 2008

Cars Are Sensors and Actuators

- Anti-locking braking
- Adaptive cruise control
- Automatic airbags
- Automatic collision notification
- Blind spot reduction
- Collision sensing bumpers
- Headlight glare reduction
- Pedestrian sensors
- Rearward visibility enhancement
- …

Warning: Driver Attention

Zero Traffic Deaths

- Lampson's Grand Challenge:

  Reduce highway traffic deaths to zero.

  - Butler Lampson, Getting Computers to Understand, Microsoft, *J. ACM* 50, 1 (Jan. 2003), pp 70-72.

U.S Broader Research Agenda and Priorities

President's Council of Advisors on Science and Technology

Networking and Information Technology Research and Development

- PCAST/NITRD report [August 2007]
  - Dan Reed and George Scalise
  - 8 priority areas listed, with the recommendation that the first 4 get disproportionately larger funding increases.

- #1 Priority: Cyber-Physical Systems
  - Our lives depend on them.

This is Not Science Fiction

soldier in smart tank

battlefield with hidden mines

GIG

medic in MASH unit

soldier on smart stretcher with smart dogtag

medicbot

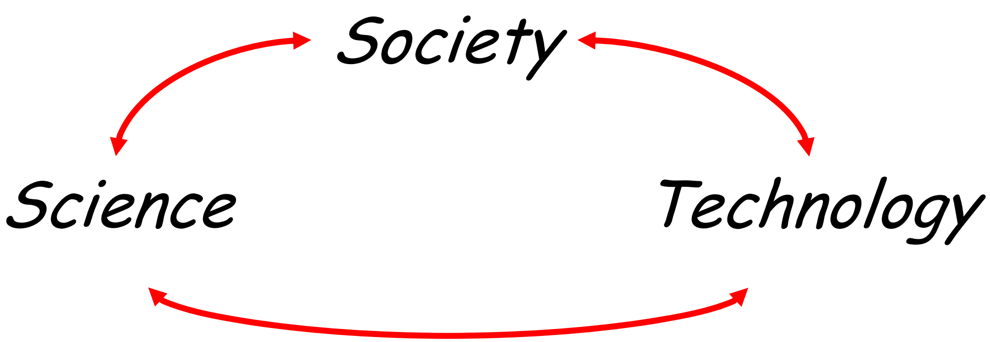
IPv6

emergency supplies station

military records administration

Research Challenges

Drivers of Computing



Users and Society

- Expectations: 24/7 availability, 100% reliability, 100% connectivity, instantaneous response, store anything and everything forever, ...
- Classes: young to old, able and disabled, rich and poor, literate and illiterate, …
- Numbers: individual → cliques → acquaintances → social networks → cultures → populations

Cyber-Physical Systems will be everywhere, used by everyone, for everything

Societal Challenge

- How can we provide people and society with cyber-physical systems they can bet their lives on?

Trustworthy:
reliable, secure,
privacy-
preserving,
usable

Important Trends in Systems

- Nature of tomorrow's systems
  - Dynamic, ever-changing, 24/7 reliability
  - Self-* (aware, diagnosing, healing, repairing, managing)

  - Two important classes converging
    - Embedded and real-time
      - Networked architecture, e.g., sensor nets (see below)
      - Safety-critical apps, e.g., medical, automotive, aero&astro
    - Pervasive and mobile
      - Focus on sensors and actuators, not just the devices and communication links
      - Prevalence of cell phones, iPods, RFIDs, …

Technical Challenge

- (How) can we build systems that interface between the cyber world and the physical world? Ideally, with predictable, if not adaptable behavior.

- Why this is hard:
  - We cannot easily draw the boundaries.
  - Boundaries are always changing.
  - There are limits to digitizing the continuous world by abstractions.
  - Complex systems are unpredictable.

Characteristics of System Complexity

Tipping points

- Stampeding in a moving crowd
- Collapse of economic markets
- "Mac for the Masses" – P. Nixon

Emergent phenomena

- Evolution of new traits
- Development of cognition,
  e.g., language, vision, music
- "Aha" moments in cognition

Predictable Behavior

- Predictable is ideal

A complicated system is a system with lots of parts and whose behavior as a whole can be entirely understood by reducing it to its parts.

A complex system is a system with lots of parts that when put together has emergent behavior.

Systems Research Challenges

- We need systems that are compositional, scalable, and evolvable.
  - Big and small components
  - One component to billions of components
  - New and old technology co-exist, e.g., from standard cars to autonomous cars, all on smarter and smarter highways
- We need ways to measure and certify the "performance" of CPS.
  - Time and space, but multiple degrees of resolution
  - New metrics, e.g., energy usage
  - New properties, e.g., security, privacy-preserving
- We need new engineering processes for developing, maintaining, and monitoring CPS.
  - Traditional ones won't work.

Software, the Great Enabler

- Good: You can do anything in software!
- Bad: You can do anything in software!

▶ It's the software that effects system complexity.

Software Research Challenges

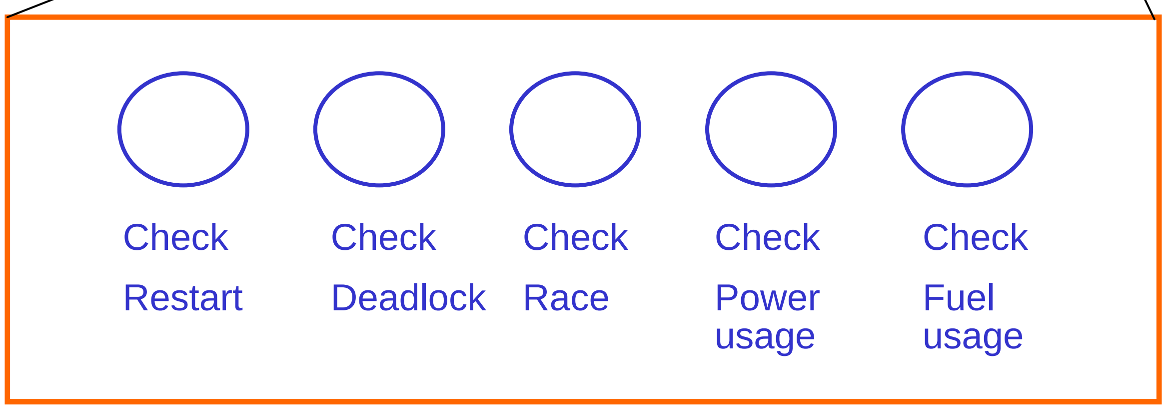
- We need new notions of "correctness".
  - Factor in context of use, unpredictable environment, emergent properties, dynamism
  - What are the desired properties of and metrics for both software (e.g., weak compositionality) and systems (e.g., power)?

- We need new formal models and logics for reasoning about cyber-physical systems.
  - E.g., hybrid automata, probabilistic real-time temporal logic
  - For verification, simulation, prediction

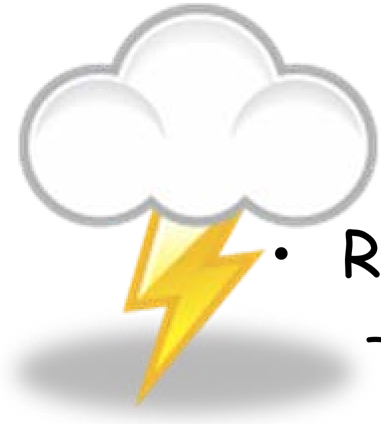
- We need new verification tools usable by domain engineers.
  - Push-button, lightweight
  - Integrated with rest of system development process

Research Vision

- To provide automotive engineers with lightweight "push-button" tools, each checking a specific application-specific property.



Fundamental Scientific Challenges



- Co-existence of Booleans and Reals
  - Discrete systems in a continuous world
- Reasoning about uncertainty
  - Human, Mother Nature, the Adversary
- Understanding complex systems
  - Emergent behavior, tipping points, …
  - Chaos theory, randomness, …

Communities Needed to Meet These Challenges

Disciplines and Sectors

- Academic Disciplines
  - Civil engineering
  - Control systems
  - Electrical engineering
  - Embedded systems
  - Formal methods
  - Human-computer interaction
  - Hybrid systems
  - Mathematics
  - Mechanical engineering
  - Probability and statistics
  - Real-time systems
  - Robotics
  - Security and privacy
  - Software engineering
  - Systems engineering
  - Usability
  - …
- Industrial Sectors
  - Aeronautics
  - Automotive
  - Buildings
  - Consumer/Home
  - Energy
  - Finance
  - Medical
  - Telecommunications
  - …

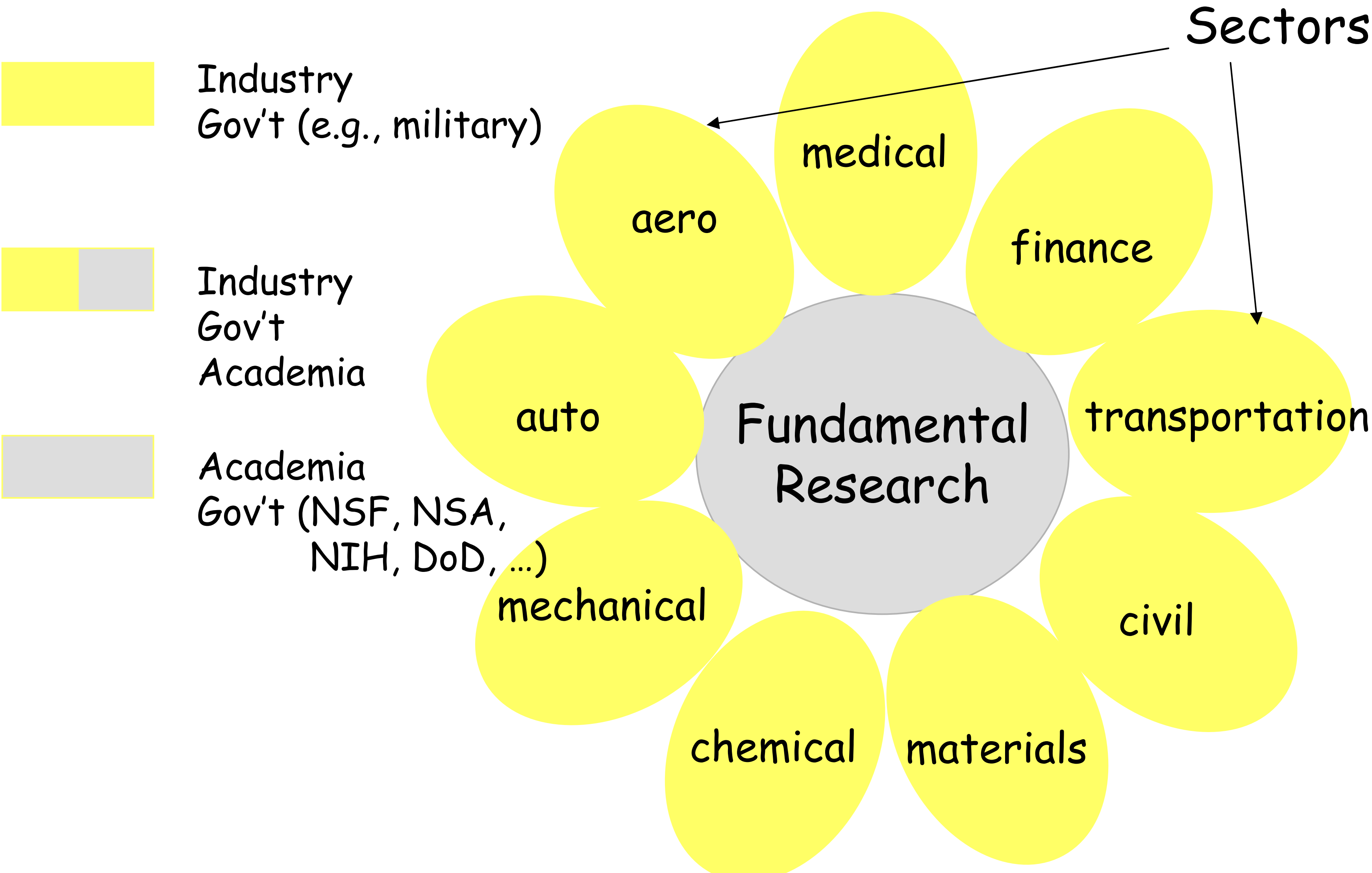
Broader Implications

- Nature of research
  - Interdisciplinary
  - Collaborative across disciplines, between industry and academia
- Education: Workforce and training
  - Discrete and continuous mathematics
  - Software, hardware, device and systems engineering
  - Need major improvements in Science, Technology, Engineering and Mathematics (STEM) education in K-12

Partnerships

- Theoreticians, experimentalists, domain experts
- Computer scientists, electrical and mechanical engineers
- Industry, Academia, Government
  - domain experts, domain problems
  - general solutions that work for specific problems

A Model for Expediting Progress



New Models for Academia-Industry-Government Partnership

- For example: Google+IBM and NSF
  - Google+IBM providing software and services on large data cluster to academic community reached by NSF. Why?
    - NSF's broad reach: all US academic institutions, all sciences and engineering
    - NSF's merit review process and infrastructure
- Other companies welcome!
- Other models of engagement welcome!

NSF's Interests in CPS

- Two directorates, CISE and ENG, working together
- Within CISE, across all three divisions
  - Foundations (CCF), systems (CNS), AI/appl'ns (IIS)
- Plans for a new FY09 initiative.
  - Please be on the lookout for our solicitation!
- Related foundation-wide initiative: Cyber-Enabled Discovery and Innovation (CDI)
  - Understanding Complex Systems

Thank you!