From Vision to Reality:
Cyber-Physical Systems

HCSS National Workshop on New Research Directions for High Confidence Transportation CPS: Automotive, Aviation, and Rail
November 18-20, 2008

Helen Gill, Ph.D.
CISE/CNS
National Science Foundation
Co-Chair, NITRD High Confidence Software and Systems Coordinating Group

Overview

- What do we mean by Cyber-Physical Systems?
- Economic context, innovation
- HCSS Actions: S&T needs, opportunities assessment
- Today: status of CPS community
- Challenge to the workshop

A Perspective on the Future: Cyber-Physical Systems

- **Cyber-physical systems** are physical, biological, and engineered systems whose operations are integrated, monitored, and/or controlled by a computational core. Components are networked at every scale. Computing is "deeply embedded" into every physical component, possibly even into materials. The computational core is an embedded system, usually demands real-time response, and is most often distributed. The behavior of a cyber-physical system is a fully-integrated hybridization of computational (logical) and physical action.

- **Examples** of cyber-physical systems include micro- and nano-scale cyber and physical materials, controlled components, cooperating medical devices and systems, next-generation power grid, future defense systems, next-generation automobiles and intelligent highways, flexible robotic manufacturing, next-generation air vehicles and airspace management, and other areas, many of which are, as yet, untapped.

Networked computers have already changed the way humans communicate and manage information. The change we envision is to the way humans manage their physical environment, including for example transportation, energy, health, and environmental quality. This change requires computing and networking technologies to embrace not just information, but also physical dynamics. The impact of this change could well dwarf that of the information revolution.

What are Cyber-Physical Systems?

- Cyber – computation, communication, and control that are discrete, logical, and switched
- Physical – natural and human-made systems governed by the laws of physics and operating in continuous time
- Cyber-Physical Systems – systems in which the cyber and physical systems are tightly integrated at all scales and levels
  - Change from cyber merely appliquéd on physical
  - Change from physical with off-the-shelf commodity “computing as parts” mindset
  - Change from ad hoc to grounded, assured development

What are Cyber-Physical Systems?

- What they are not:
  - Not desktop computing
  - Not traditional, post-hoc embedded/real-time systems
  - Not today's sensor nets
- Some defining characteristics:
  - Cyber capability in every physical component
  - Networked at multiple and extreme scales
  - Complex at multiple temporal and spatial scales
  - Dynamically reorganizing/reconfiguring
  - High degrees of automation, control loops must close at all scales
  - Unconventional computational and physical substrates (Bio? Nano?)
  - Operation must be dependable, certified in some cases
- Goals of a CPS research program
  - A new science for future engineered and monitored/controlled physical systems (10-20 year perspective)
  - Physical and cyber (computing, communication, control) design that is deeply integrated

CPS: Example at Multiple Scales

A BMW is “now actually a network of computers”

[R. Achatz, Seimens, *The Economist,* Oct. 11, 2007]

Autonomous Cars

Credit: PaulStamatiou.com

Smart Infrastructure

Credit: MO Dept. of Transportion.

Credit: Dash Navigation, Inc.

Cars as nodes in a network

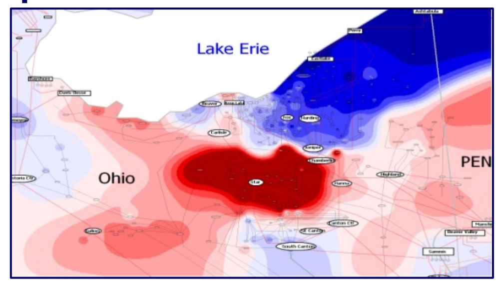
Lampson’s Grand Challenge:

Reduce traffic deaths to zero

[B. Lampson, Getting Computers to Understand, Microsoft, *J. ACM,* 50:1, pp. 70-72, Jan., 2003]

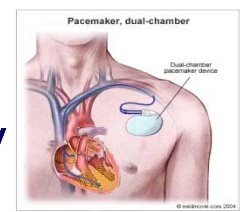
Similar Problems in Many Sectors

- **Energy**: smart appliances, buildings, power grid
  - Net-zero energy buildings
  - Minimize peak system usage
  - No cascading failures
  - Enable new, sustainable energy sources



Kindly donated by Stewart Johnston

- **Healthcare**: embedded medical devices and smart prosthetics; operating room of the future; integrated health care delivery
  - Patient records available at every point of care
  - 24/7 monitoring and treatment
  - Enable new, biocompatible technologies



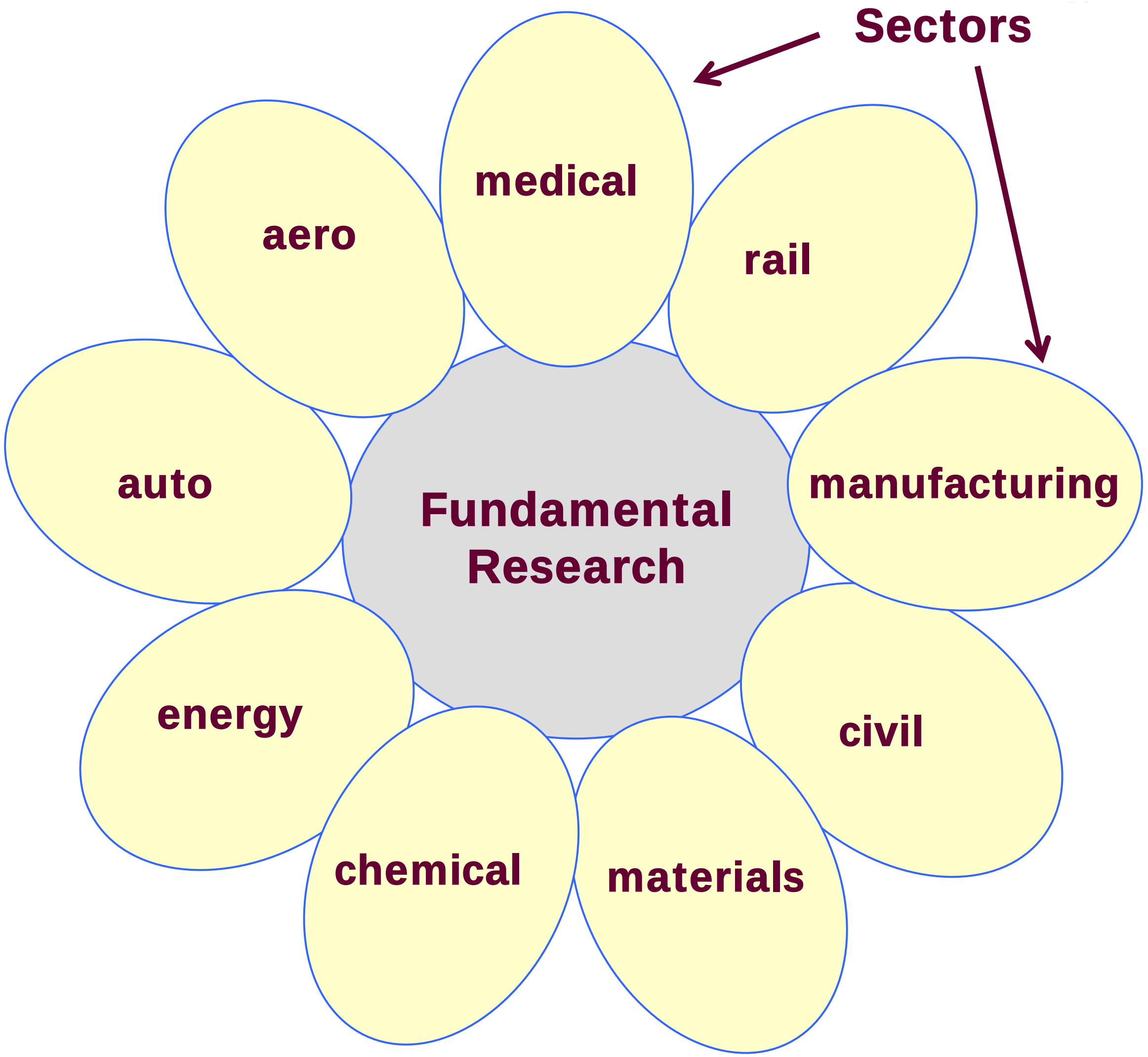
CPS – A National Research Priority

- Eight priority areas for competitiveness, with four designated as having the highest priority
  - Network and Information Technology (NIT) Systems Connected with the Physical World
  - Software
  - Digital Data
  - Networking
- NIT systems connected with the physical world (cyber-physical systems)
  - Essential to the effective operation of U.S. defense and intelligence systems and critical infrastructures
  - At the core of human-scale structures and large-scale civilian applications

President's Council of Advisor's on Science and Technology (PCAST), Computational Science: America's Competitiveness Leadership Under Challenge: Information Technology R&D in a Competitive World, August 2007.

A Model for Expediting Progress*

- A new underlying discipline
- Abstracting from sectors to more general principles
- Apply these to problems in new sectors
- Build a new CPS community



*Jeannette M. Wing
Assistant Director, CISE, NSF

Innovation through Cyber-Physical Systems

International Context (Example): EU Framework Programme 7, European Research Council, and Related Actions

- Announced November, 2006: FP7 ICT work programme; 9B€ over 2007-2013
- ARTEMIS, 3B€ over 2007-2013 (7 years)
  - Embedded systems investment
  - Backbone of European Research Area for Embedded Systems, http://www.artemis-office.org/
    - Strategic Research Agenda (SRA)
    - Joint Technology Initiative (JTI)
    - Embedded systems education and curriculum
- "High-Level Group"
  - CEOs: ABB, Airbus, Nokia, Parades, British Telecom, COMAU, Philips, Bosch, Continental Teves, Daimler/Chrysler, ST Microelectronics, Symbian, Ericsson, Finmecanicca, Telenor, Thales, IMEC, Infineon
  - Universities and national research labs: TU Vienna, CNRS/Verimag
- Joint public (EU and national) and private funding, approximately 50/50

Economic Context: Calibrating US Competitiveness

- January 2006, American Competitiveness Initiative announced:

  http://www.whitehouse.gov/stateoftheunion/2006/aci/

- National Academies study: "**Rising Above The Gathering Storm: Energizing and Employing America for a Brighter Economic Future**"

  http://www7.nationalacademies.org/ocga/testimony/Gathering_Storm_Energizing_and_Employing_America2.asp

Why Is CPS Significant?

- In automotive, avionics/aerospace, industrial automation, telecommunications, consumer electronics, intelligent homes, and health and medical equipment, electronics will reach 53% of the cost by the end of the decade[1]
  - Example: Automobiles[1]
    - 1990 – 16% of cost
    - 2003 – 52% of cost
    - 2010 – 56% of cost (projected)
  - Example: Aircraft "cyber-physical system development"[2]
    - 70's and 80's – 10% of cost
    - Current generation – nearly half of cost
    - Next generation – 50% or more of cost (projected)

- *CPS are the basic engine of innovation for a broad range of industrial sectors: This is the technology that transforms products, creates new markets and disrupts the status-quo.*

Cyber Physical Systems are the foundation of the Systems Industry

[1] Study of Worldwide Trends and R&D Programmes in Embedded Systems in View of Maximising the Impact of a Technology Platform in the Area. Prepared for the European Commission, Nov. 18, 2005.

[2] Don C. Winter, Vice President, Engineering & Information Technology, Boeing Phantom Works. Statement before a hearing on Networking and Information Technology R&D (NITRD) Program, Committee on Science and Technology, U.S. House of Representatives, July 31, 2008.

Current Concern: Weak Fundamentals?

- Economic weakness in industrial sectors
- Shrinkage of skilled engineering workforce
  - Change in nature of skills required by next-generation transportation sector
  - Concerns about mathematics, science, engineering educational pipeline; engineering/computer science disconnect; rapid loss of edge
- Globalization, multinational corporations: cost/skill equation?
- Sustained innovation requires sustained R&D and education
- Current enabling technologies are not organized for agile production, adaptation and update
- Poor convergence on cross-domain (physical/cyber) issues, per-domain vs. shared, foundational strategy, many challenges:
  - Cooperative/competitive, networked, real-time sensing and control
  - Real-time, sporadic (re-)integration of components
  - Safety and security certification
  - Open technology, open standards lack true open systems foundations
  - Fault identification, fault tolerance, failure isolation, diagnosis

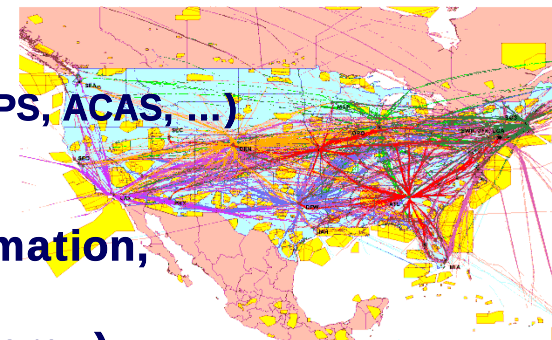
S&T Needs - Health Care and Medicine **A Better Future?**

- National Health Information Network, Electronic Patient Record initiative
  - Medical records at any point of service
  - Hospital, OR, ICU, ..., EMT?
- Home care: monitoring and control
  - Pulse oximeters (oxygen saturation), blood glucose monitors, infusion pumps (insulin), accelerometers (falling, immobility), wearable networks (gait analysis), ...
- Operating Room of the Future (Goldman)
  - Closed loop monitoring and control; multiple treatment stations, plug and play devices; robotic microsurgery (remotely guided?)
  - System coordination challenge
- Progress in bioinformatics: gene, protein expression; systems biology; disease dynamics, control mechanisms

Images thanks to Dr. Julian Goldman, Dr. Fred Pearce

S&T Needs - Aviation Industry

- **Current picture**
  - **Centralized airspace management**
    - **Limited automation (TCAS, autopilot, landing assist, ...)**
    - **Slow introduction of safety technology (RIPS, TAWS ...)**
    - **Disparate military/civilian aviation regimes; diverse constituencies**
  - **Vehicle technologies**
    - **Costly certification; recertification challenges**
    - **Barriers to introduction of safety-related technology (GPS, ACAS, ...)**



- **Better future?**
  - **NextGen (improvements in capacity, structure, automation, cooperative vehicle/airspace technologies)**
  - **Innovations in air vehicles (automotive/aviation synergy)**
    - **Platforms: smart materials and structures; fuel-efficiency, range, airspeed regimes (hypersonic, subsonic); flight regimes (HAE UAVs, VTOL)**
    - **Software-integrated systems, fly-by-wire(less) software control**
    - **Authority management, IHM, augmentation systems**
  - **Agile economic strategies to revitalize aviation sector**
    - **Air taxis, de-hub strategies, ...**
  - **Agile design for resilience, certification (vs. post hoc V&V)**
- **Perennial context: Safety, efficiency, competition, capacity**

Image thanks to C. Tomlin, UC Berkeley, J. Hansman, MIT

S&T Needs - Automotive Industry

- **Current picture**
  - Largely single-vehicle focus
  - Integrating safety and fuel economy (full hybrids, regenerative braking, adaptive transmission control, stability control)
  - Safety and convenience “add-ons” (collision avoidance radar, complex airbag systems, GPS, ...)
  - Cost of recalls, liability; growing safety culture
- **Better future?**
  - Multi-vehicle high-capacity cooperative control roadway technologies, platooning, vehicular networks
  - Energy-absorbing “smart materials” for collision protection (cooperative crush zones?)
  - Alternative propulsion and fuel technologies, “smart skin” integrated photovoltaics and energy recovery/scavenging, ...
  - Integrated operation of drivetrain, smart tires, active aerodynamic surfaces, ...
  - Safety, security, privacy certification; regulatory enforcement
- **Perennial context: Time-to-market race, cost**

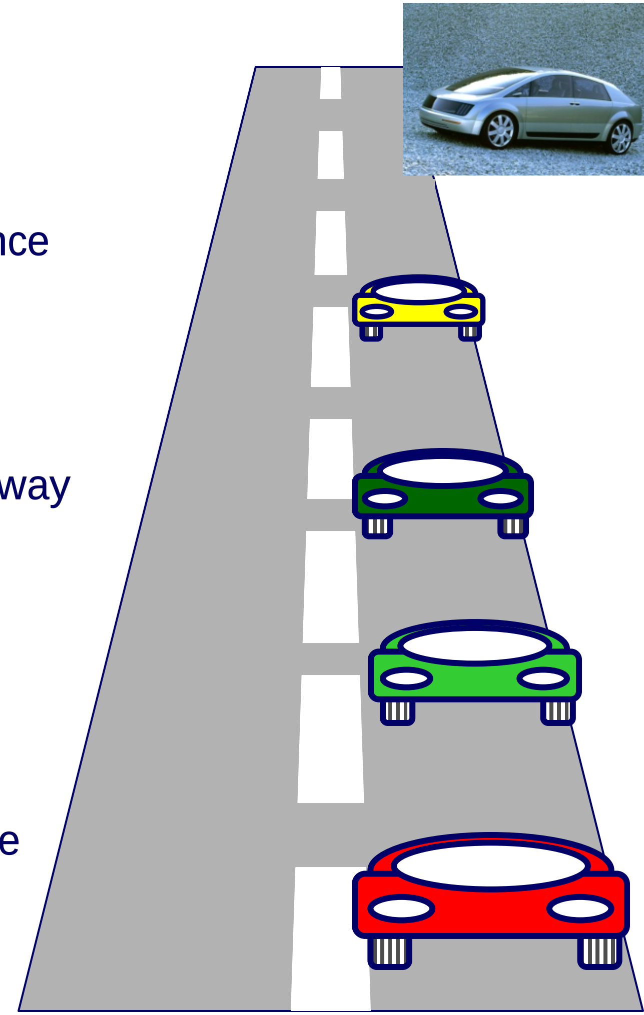
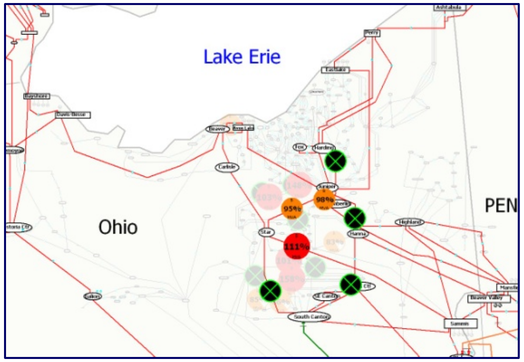
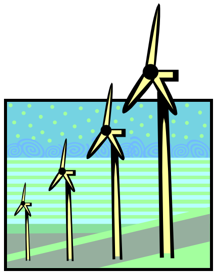


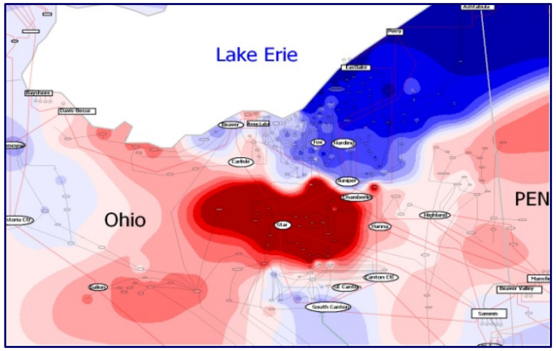
Image thanks to GMC

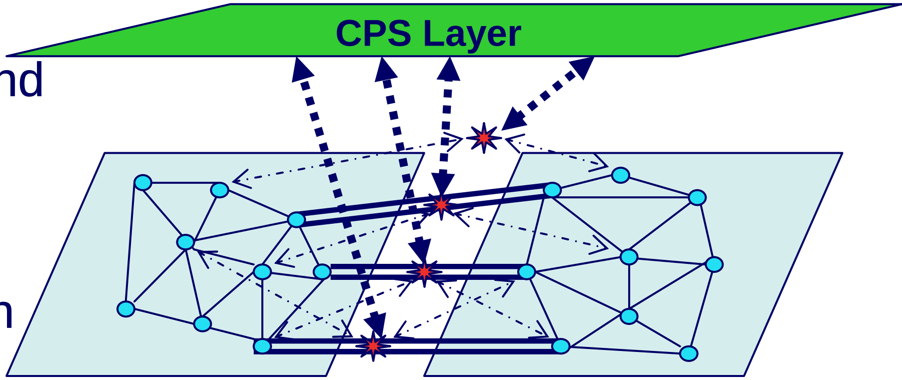
Example: Electric Power Grid

- **Current picture:**
  - Equipment protection devices trip locally, reactively
  - Cascading failure: August (US/Canada) and October (Europe), 2003
- **Better future?**
  - Real-time cooperative control of protection devices
  - Or -- self-healing -- (re-)aggregate islands of stable bulk power (protection, market motives)
  - Ubiquitous green technologies
  - Issue: standard operational control concerns exhibit wide-area characteristics (bulk power stability and quality, flow control, fault isolation)
  - Technology vectors: FACTS, PMUs
  - Context: market (timing?) behavior, power routing transactions, regulation



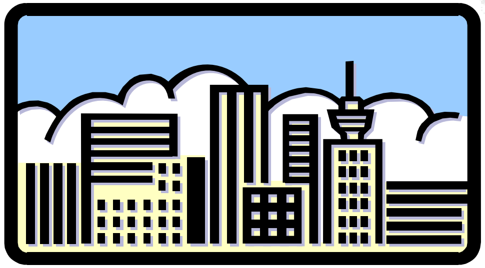






Images thanks to William H. Benders, Bruce Krogh, and Marija Ilic

S&T Needs -- Environmental Control Technologies



- Smart Buildings:
  - Today:
    - Rudimentary lighting automation
    - Zoned HVAC systems
    - Exploratory remote control of appliances
    - Consequences: Building operation consumes 40% of U.S. energy and 71% of the electricity, 12% of the water, and rapidly increasing quantities of land. Building demolition, construction and renovation generate over 35% of non-industrial waste. Buildings can also create health problems: indoor air pollutants are at concentrations typically between two and five—and occasionally more than 100—times greater than those of outdoor air. Building operation accounts for 38% of the country's carbon dioxide emissions.*
  - **Better Future?**
    - Energy conserving automation for: air quality, lighting, plumbing, water efficiency: stormwater, graywater, blackwater, household usage, irrigation; photovoltaics, daylighting
    - Co-generation (heat/energy), home-based energy generation
    - Controllable building materials and systems (e.g., smart windows); heat, light, water fixtures and plumbing,
    - Cross-system cooperative networked real-time configuration and control
  - **Challenges:**
    - Extreme, dynamic coupling of "federated" systems (e.g., open/close door)
    - Cross system energy exchange

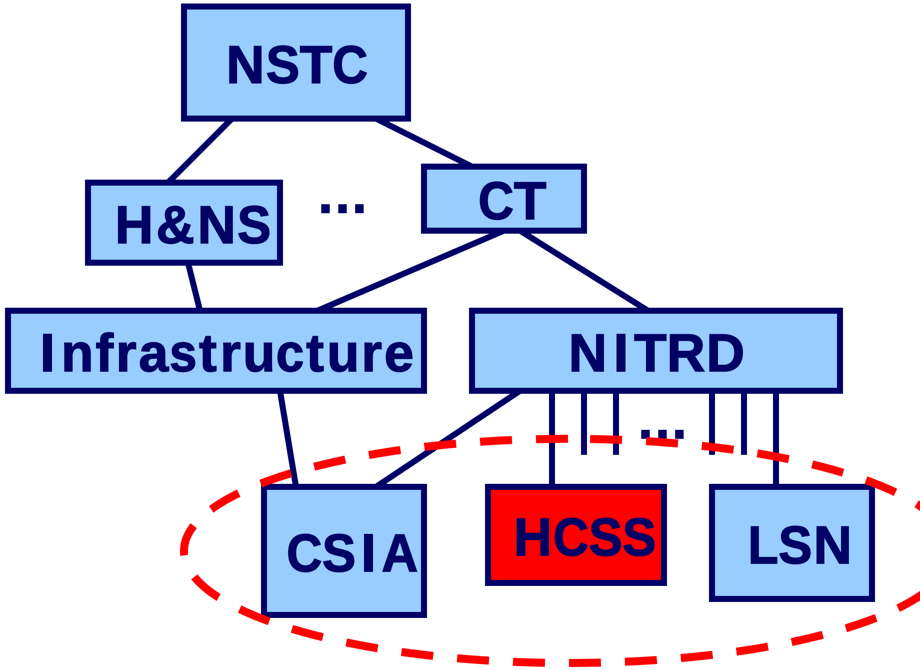
*** White paper -- RESEARCH COMMITTEE POSITION STATEMENT, U.S. Green Building Council (USGBC)**

NITRD High Confidence Software and Systems (HCSS) Coordinating Group

Research Needs Assessment

High-Confidence Software and Systems (HCSS) Agencies, 2008

- Air Force Research Laboratories*
- Army Research Office and Space and Defense Systems*
- Department of Defense/ OSD
- Defense Advanced Research Projects Agency
- Department of Energy
- Federal Aviation Administration*
- Food and Drug Administration*
- National Aeronautics & Space Administration
- National Institutes of Health
- National Institute of Science and Technology
- National Science Foundation
- National Security Agency
- Nuclear Regulatory Commission*
- Office of Naval Research*



* Cooperating agencies

NITRD/HCSS Activities towards R&D Needs Assessment

Real-time technology assessment:
Industry Non-Disclosure Briefings

"HC – RTOS" Workshop Planning Meeting

Domain-specific workshops

- **Medical Devices and Systems**
- **Aviation Systems and Certification**
- **Beyond SCADA and DCS**
- **Future Automotive Systems**
- **Future Transportation Systems**

National Workshop on New Research Directions in High Confidence Software Platforms for Cyber Physical Systems
(Nov 30 – Dec 1, 2006)

Workshop on Composable Systems Technologies for Cyber Physical Systems
(July 9-10, 2007)

National Academies Study
Software for Dependable Systems: Sufficient Evidence?

Verification Grand Challenge

Research Needs Assessment: Resources

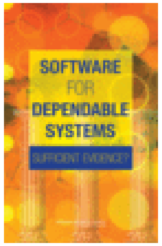
Domain-specific workshops

- High Confidence Medical Device Software and Systems (HCMDSS),
  - Planning Workshop, Arlington VA, November 2004, http://www.cis.upenn.edu/hasten/hcmdss-planning/
  - National R&D Road-Mapping Workshop, Philadelphia, Pennsylvania, June 2005, http://www.cis.upenn.edu/hcmdss/
  - Joint Workshop On High Confidence Medical Devices, Software, and Systems (HCMDSS) and Medical Device Plug-and-Play (MD PnP) Interoperability, Boston, MA, June 25-27, 2007, http://rtg.cis.upenn.edu/hcmdss07/index.php3
- National Workshop on Aviation Software Systems: Design for Certifiably Dependable Systems, (HCSS-AS) (NSF, AFRL, NASA, FAA)
  - Planning Workshop, Seattle, WA, November 9-10, 2005, http://chess.eecs.berkeley.edu/hcssas/previousMeetings.html
  - National R&D Road-Mapping Workshop, Alexandria, Virginia, October 5-6, 2006, http://chess.eecs.berkeley.edu/hcssas/index.html
- High Confidence Critical Infrastructures: "Beyond SCADA: Networked Embedded Control Systems" (NSF, NIST, NSA)
  - US Planning Workshop, Washington, DC, March 14-15, 2006, http://www.truststc.org/scada/march06_plan.html
  - US National R&D Road-Mapping Workshop, Pittsburgh, Pennsylvania, November 8-9, 2006, http://www.truststc.org/scada/
- High Confidence Automotive Cyber-Physical Systems
  - Planning meeting: RTSS, Tucson, December 3, 2007
  - National meeting: April 3-4, 2008, Troy, MI, http://varma.ece.cmu.edu/auto-cps/

CPS Website: http://varma.ece.cmu.edu/summit/Workshops.html

Research Needs Assessment, cont'd.

- "New Research Directions in Composition and Systems Technology for High Confidence Cyber Physical Systems" – July 9-10, 2007, Arlington, VA, draft report, http://ike.ece.cmu.edu/twiki/bin/view/CpsReports/WebHome



- National Academies study: "Sufficient Evidence? Design for Certifiably Dependable Systems," http://www7.nationalacademies.org/cstb/project_dependable.html
  - Kickoff workshop, April 2004, "Software Certification and Dependability" (report)
  - Report released, October 23, 2007

- CPS Workshop, Austin, TX October 16-17, 2006, draft report, http://ike.ece.cmu.edu/twiki/bin/view/CpsReports/WebHome

- RT GENI Workshop, Reston, VA, February 6-7, 2006, http://www.geni.net/GDD/GDD-06-32.pdf

- Open Verification Initiative
  - Response to Hoare Verification Grand Challenge: Open verification technology for industrial-strength system and software analysis and composition, VSTTE 2005, Zurich, Switzerland, http://qpq.csl.sri.com/vsr/vsi.pdf, http://qpq.csl.sri.com/vsr/manifesto.pdf

- Science and Engineering Indicators 2008, http://www.nsf.gov/statistics/seind08/

Upcoming HCSS Actions

- Transportation Systems CPS workshop (THIS WORKSHOP)
  - November 18-20, 2008, Sheraton Premiere Hotel, Vienna, VA
  - Challenges spanning transportation modalities: capability, capacity, safety, security
    - Automotive
    - Aviation
    - Rail
    - Maritime

- Future Energy Systems workshop
  - Date TBD, Winter-Spring 2009
  - NSF ENG and CISE directorates, HCSS agencies

- Net-Zero Energy Buildings workshop?

Overall CPS Assessment: WHERE ARE WE TODAY?

(NSF View)

2005-2007
NITRD/HCSS Interagency Workshops,
Strategic Planning: HCSS CPS

Oct. 2006
NSF Cyber-Physical Systems Workshop

Oct. 2006
NSF Real-Time GENI Workshop

May 2007
NSF Industry Roundtable

CPSWEEK 2008
NSF CPS Summit
CCC: CPS Theme

August, 2007
PCAST Report:
NIT for Resilient Physical Systems

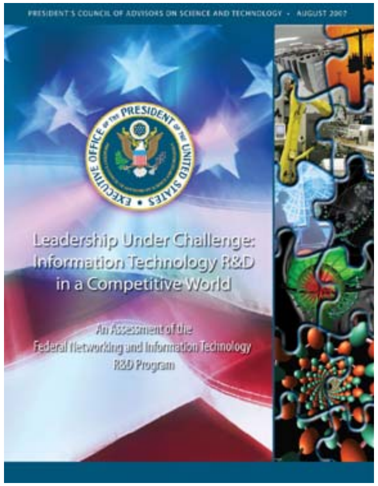
National Academies Study
Software for Dependable Systems: Sufficient Evidence?

Verification Grand Challenge 2006-8
-> VSTTE IFIP Working Conferences
-> Evidential Tool Bus
-> Open Verification Platform

NSF Actions
FY 2007: CPS seedling
FY 2008: CPS-T & CPS-E
FY 2009: CISE & ENG
Cross-cutting program
NSF-08-611

Remember:
CPS – A National Research Priority

- Eight priority areas for competitiveness, with four designated as having the highest priority
  - Network and Information Technology (NIT) Systems Connected with the Physical World
  - Software
  - Digital Data
  - Networking
- NIT systems connected with the physical world (cyber-physical systems)
  - Essential to the effective operation of U.S. defense and intelligence systems and critical infrastructures
  - At the core of human-scale structures and large-scale civilian applications



President's Council of Advisor's on Science and Technology (PCAST), Computational Science: America's Competitiveness Leadership Under Challenge: Information Technology R&D in a Competitive World, August 2007.

Workshop Challenge

- **NITRD Strategic Planning process is currently underway: inform it!**

- Imagine “the better future”

- Use this workshop to identify the “60% common” science and technology (and the CPS R&D) needed to enable a 21^{st} century transportation sector

- Seek research directions that will provide people and society with cyber-physical systems they can bet their lives on

- Think about organizational constructs that may be useful for research, transition (industry/university/government, agency/agency, international)

- Don’t forget education

Thank you