A Continuing Vision:

Cyber-Physical Systems

Fourth Annual Carnegie Mellon Conference on the Electricity Industry
FUTURE ENERGY SYSTEMS: EFFICIENCY, SECURITY, CONTROL

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Overview

- What do we mean by Cyber-Physical Systems?
- Economic context, motivation
- S&T Needs, opportunities
- Interagency actions, status of CPS

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.

Cyber Physical Systems

- Two major types of computing systems
  - Desktops - servers, PCs, and notebooks
  - Embedded
- The next frontier
  - Mainframe computing (60's-70's)
    - Large computers to execute big data processing applications
  - Desktop computing & Internet (80's-90's)
    - One computer at every desk to do business/personal activities
  - Embedded computing (21st Century)
    - "Invisible" part of the environment
    - Transformation of industry

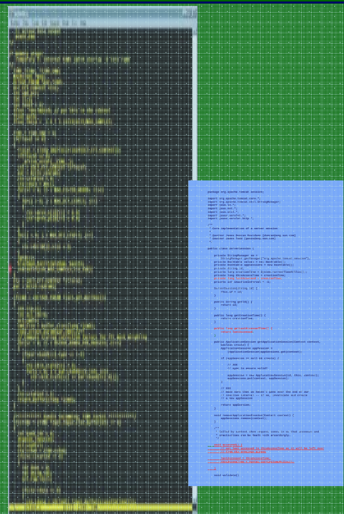
- Number of microprocessor units per year
  - Millions in desktops
  - Billions in embedded processors
- Applications:
  - Automotive Systems
    - Light and heavy automobiles, trucks, buses
  - Airspace Systems
    - Airplanes, space systems
  - Consumer electronics
    - Mobile phones, office electronics, digital appliances
  - Health/Medical Equipment
    - Patient monitoring, MRI, infusion pumps, artificial organs
  - Industrial Automation
    - Supervisory Control and Data Acquisition (SCADA) systems for chemical and power plants
    - Manufacturing systems
  - Defense
    - Source of superiority in all weapon systems

What are Cyber-Physical Systems?

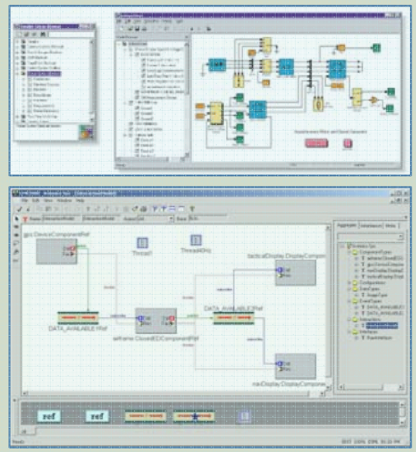
- What they are not:
  - Not desktop computing
  - Not traditional, post-hoc embedded/real-time systems
  - Not today's sensor nets
- Some defining characteristics:
  - Cyber capability in every physical component
  - Networked at multiple and extreme scales
  - Complex at multiple temporal and spatial 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

Why is CPS Hard?

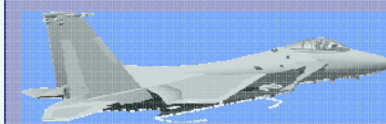
Software

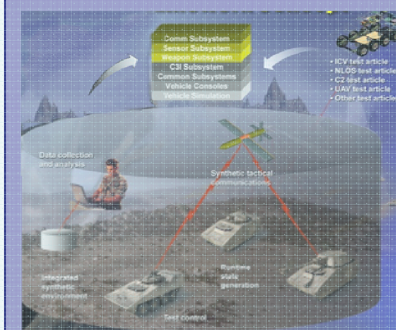


Control



Systems





Crosses Interdisciplinary Boundaries

- Disciplinary boundaries need to be realigned
- New fundamentals need to be created
- New technologies and tools need to be developed
- Education needs to be restructured

Why Is CPS Significant?

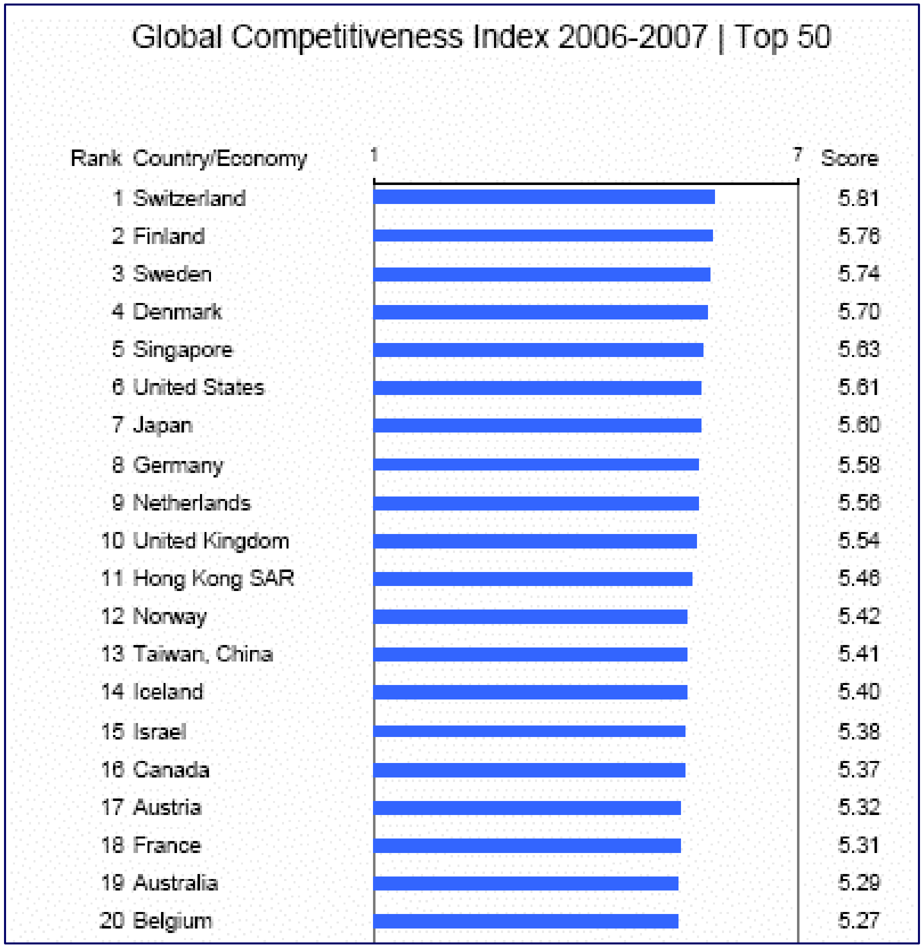
- Building systems that integrate computational and physical objects requires new systems science foundations.
  - Fusion of physical and computational sciences
- Expected share of value of embedded computing components in the next five years:
  - Automotive and airspace systems 30-40%
  - Health/Medical equipment 33%
  - Industrial automation 22%
  - Telecommunications 37%
  - Consumer electronics and Intelligent Homes 41%
- *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

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: Recent Data



World Economic Forum Report
October, 2006

- US dropped from first to sixth
- Twelve out of the first twenty are EU member states
- The first four are EU member states
- EU increases 75% of R&D investment in Information and Comm. Technology research by 2013

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

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

Innovation through Cyber-Physical Systems

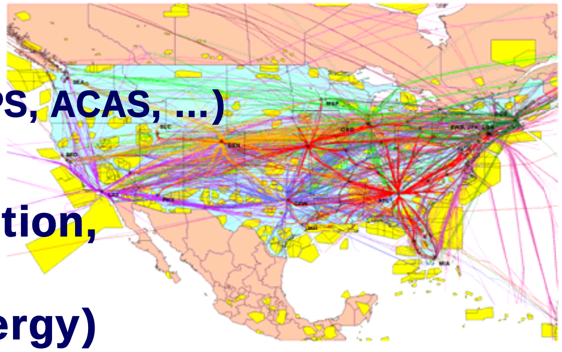
S&T Needs - Health Care and Medicine

- 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

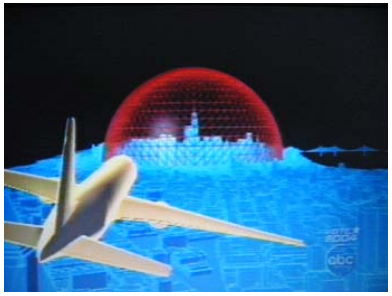
Images thanks to Dr. Julian Goldman, Dr. Fred Pearce

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?**
  - **NGATS (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 certification (vs. post hoc V&V)**



- **Perennial context: Safety, efficiency, competition, capacity**

Image thanks to C. Tomlin, Stanford, 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**

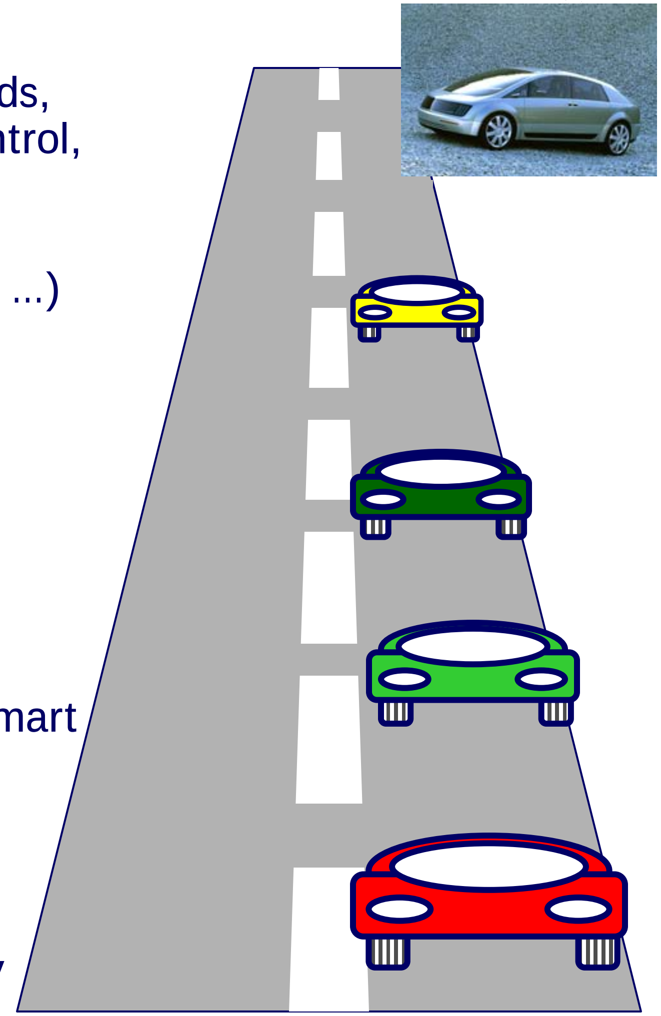
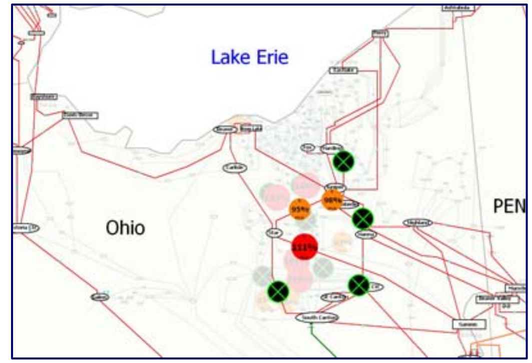
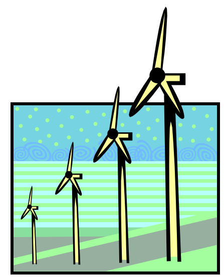


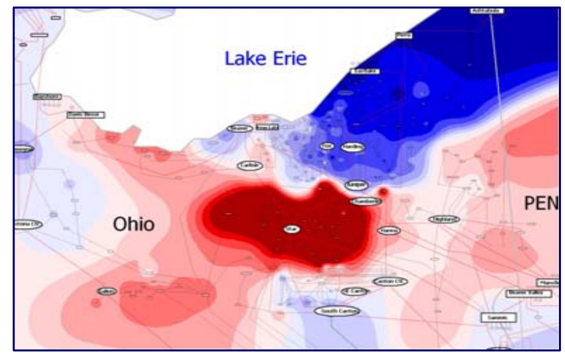
Image thanks to Sushil Birla, GMC

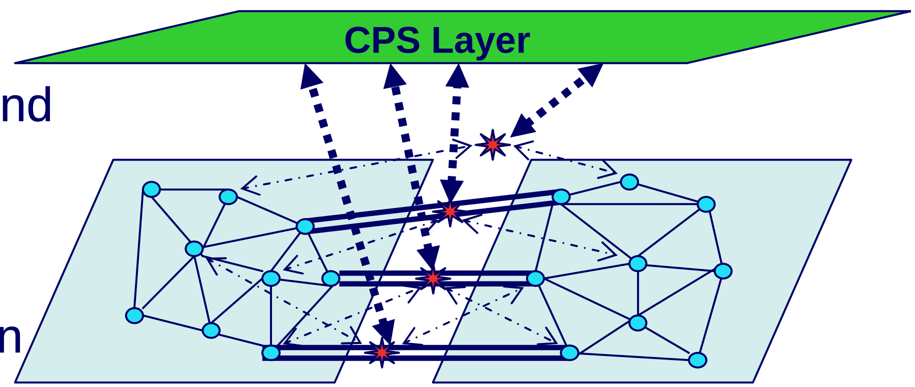
Example: Electric Power Grid

- **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



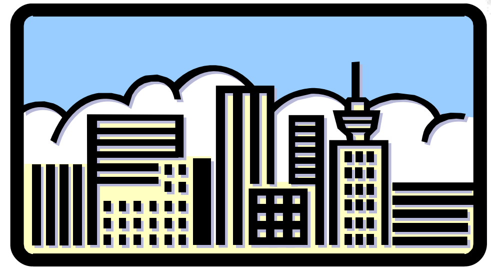






Images thanks to William H. Sanders, Bruce Krogh, and Marija Ilic

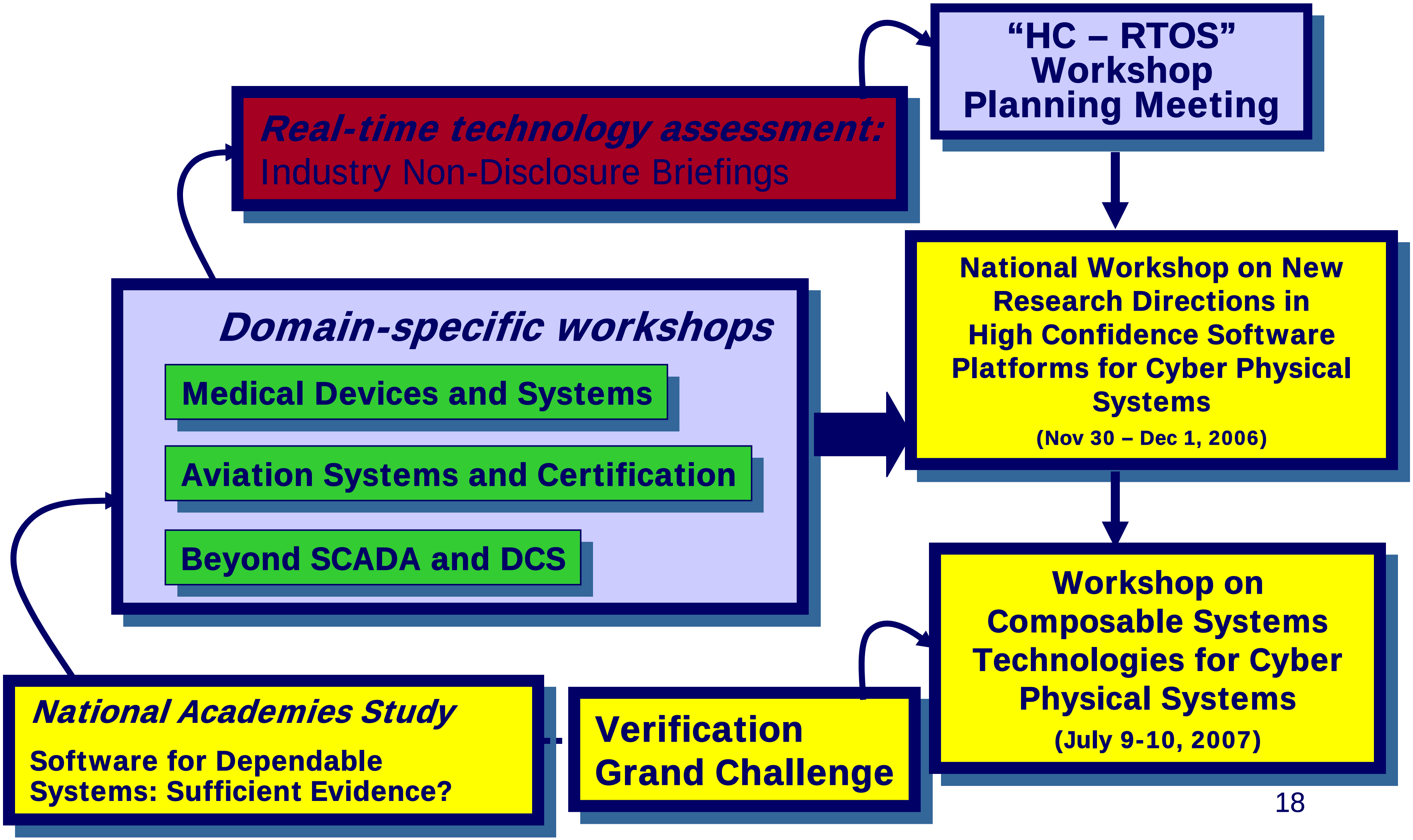
S&T Needs -- Environmental Control Technologies



- 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.*
  - **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

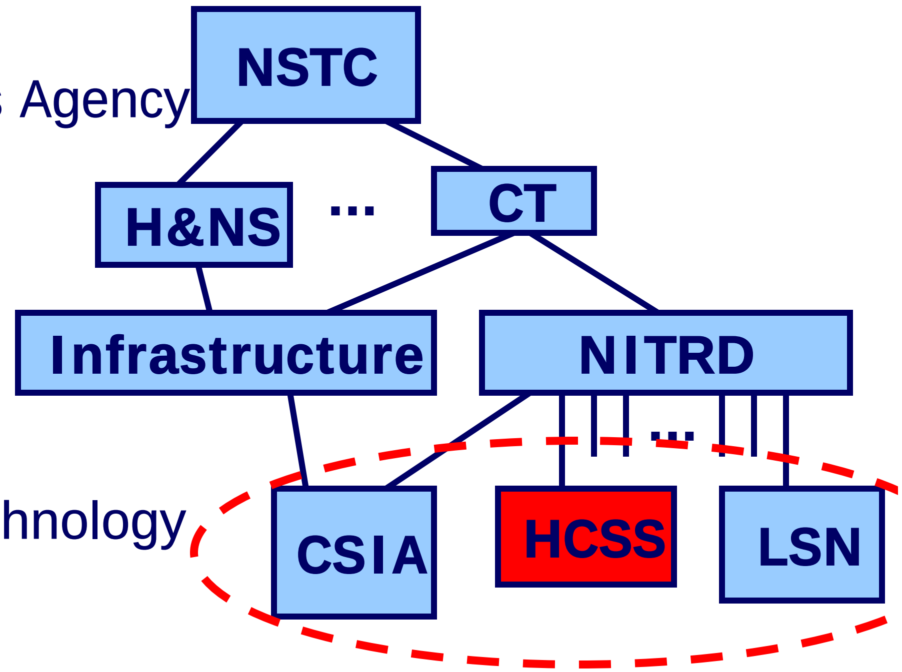
*** White paper -- RESEARCH COMMITTEE POSITION STATEMENT, U.S. Green Building Council (USGBC)**

NITRD/HCSS Activities towards R&D Needs Assessment



High-Confidence Software and Systems (HCSS) Agencies, 2007

- 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 Air & Space Administration
- National Institutes of Health
- National Institute of Science and Technology
- National Science Foundation
- National Security Agency
- Office of Naval Research*



* Cooperating agencies

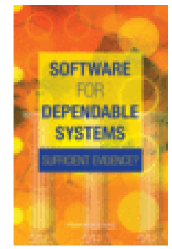
Research Needs Assessment - Resources

- HCSS Workshops on domains of high economic importance:
  - 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/

Domain-specific workshops

Research Needs Assesment, 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/

Emerging Federal R&D Context and Potential Impact

- President's Council of Advisors on Science and Technology (PCAST)
  - Priorities for future R&D investment in Networking and IT R&D
  - PCAST Networking and IT (NIT) subcommittee report:
    - Pre-release briefing: **http://www.ostp.gov/PCAST/agendas/Apr-07/Reed-Scalise_PCAST_Apr07.pdf**
    - Final Report: Leadership Under Challenge: Information Technology R&D in a Competitive World

Priority Area for increased funding:

NIT for resilient physical systems

"The National Science and Technology Council should develop a Federal Plan for a coordinated multiagency R&D effort to maximize the effectiveness of Federal investments and ensure future U.S. competitiveness in this area"

Overall CPS Assessment: WHERE ARE WE TODAY?

2005-2007
NITRD/HCSS Interagency
Workshops, reports
Coming soon: HCSS-CPS?

NSF Cyber-Physical Systems
Workshop
(Oct 16-17, 2006)

NSF Real-Time GENI
Workshop, Oct. 2006

Industry Roundtable
May 17, 2007

PCAST Report:
NIT for Resilient
Physical Systems
August, 2007

National Academies Study

Software for Dependable Systems:
Sufficient Evidence? (released)

Verification Grand Challenge 2006-7
-> VSTTE IFIP Working Conference
-> Evidential Tool Bus
-> Open Verification Platform

FY 2007: CPS seedling

FY 2008: CPS-T & CPS-E

CPS TODAY:
FY 2009 and Beyond?

Upcoming Actions

- Automotive systems workshop
  - Planning meeting: RTSS, Tucson, December 3, 2007
  - National meeting: April 3-4, 2008, Troy, MI
    - USCAR co-sponsor with NSF, HCSS
- Future (green) power systems workshop
  - Date TBD, late summer early autumn?
  - NSF ENG and CISE directorates, HCSS
- Net Zero Energy Buildings workshop?
- May 20, 2008 GSA/HCSS Expedition (at NSF): "*Potentials and Realities of Certification in Light of Open Technology Development …*"

  To explore the conducive conditions for certification within and across multiple critical cyberinfrastructures that share a common need for high confidence software and systems that advance national preparedness, public safety, and economic growth. How are technical advances, sources of supply, and interdependencies measuring up or falling short of national demands for high confidence in critical technologies and cyberinfrastructures? Have certification programs to mitigate risk kept pace with technology advances? If not, what needs to be done? Given the continuum of open systems architecture, what does the landscape for dependable software approaches look like today?

CPS At NSF

- Thanks to CMU!:
  - Jeannette Wing, Assistant Director of the NSF for Computer and Information Science and Engineering (CISE Directorate)
  - Bruce Krogh, CISE scientific advisor on CPS
  - Marija Ilic, Raj Rajkumar, research community leadership
- CPSWeek 2008 IEEE/ACM: RTAS, HSCC, IPSN, http://www.cpsweek.org/
- CPS Funding Opportunities
  - FY 2007, exploratory CSR theme, NSF 07-504
  - FY 2008, expanded CSR exploration, NSF 08-538, http://www.nsf.gov/pubs/2008/nsf08538/nsf08538.htm
    - CPS-T – technology base for cyber-physical systems
    - CPS-E – exploratory, experimental research
  - FY 2009 – *Under Construction*, expected summer 2008

CISE CPS Academic Summit, St. Louis, April 25, 2008

Thank You

Back-up

CPS Scientific Challenge