Cyber-Physical Systems Initiative: NSF & Beyond
(NSF 08-611)

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National Science Foundation

CPS Transportation Workshop
19 November 2008

What are Cyber-Physical Systems?

- CPS deeply integrate **computation, communication, and control** into **physical** systems
- CPS exploit pervasive, networked computation, sensing, and control, i.e., “Internet of [**controlled]** things”
- “CPS will transform how we interact with the physical world just like the Internet transformed how we interact with one another.” *

* CPS Summit Website:
http://varma.ece.cmu.edu/summit/index.html

Computing is Becoming Ubiquitous

- 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)

[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.

A Few *Example* Opportunities*

Transportation	▪ Faster and more energy efficient aircraft ▪ Improved use of airspace ▪ Safer, more efficient cars	
Energy and Industrial Automation	▪ Homes and offices that are more energy efficient and cheaper to operate ▪ Distributed micro-generation for the grid	
Healthcare and Biomedical	▪ Increased use of effective in-home care ▪ More capable devices for diagnosis ▪ New internal and external prosthetics	
Critical Infrastructure	▪ More reliable and efficient power grid ▪ Highways that allow denser traffic with increased safety	

* Cyber-Physical Systems Executive Summary, CPS Steering Group, March 6, 2008. Available on-line: http://varma.ece.cmu.edu/summit/

CPS: An 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

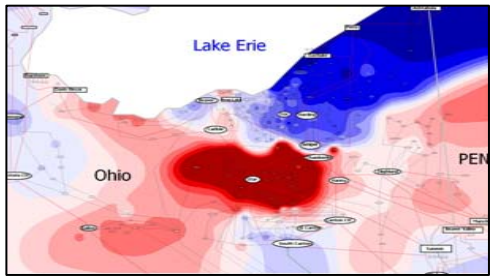
Lampson's Grand Challenge:

Reduce traffic deaths to zero

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

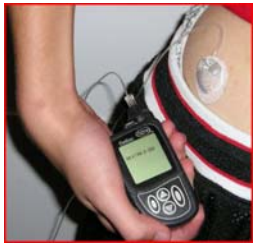
Similar Problems in Many Sectors

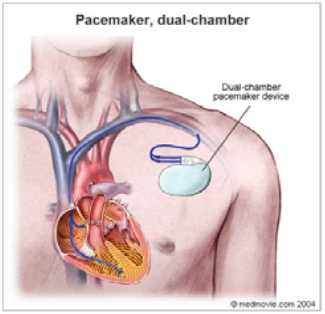
- **Energy**: smart appliances, buildings, power grid
  - Net-zero energy buildings
  - Minimize peak system usage
  - No cascading failures



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





Selected Workshops on CPS

- High-Confidence **Medical Device Software and Systems** Workshop, June 2005, Phila., PA
- **Aviation Software Systems**: Design for Certifiably Dependable Systems, Oct. 2006, Alexandria, TX
- Beyond SCADA: **Networked Embedded Control** for Cyber Physical Systems, Nov. 2006, Pittsburgh, PA
- High-Confidence **Software Platforms** for Cyber-Physical Systems, Nov. 2006, Alexandria, VA
- Joint Workshop On High-Confidence Medical Devices, Software, and Systems and **Medical Device Plug-and-Play** Interoperability, June 2007, Boston, MA
- **Composable and Systems Technologies** for High-Confidence Cyber-Physical Systems, 2007, Arlington, VA
- High-Confidence **Automotive** Cyber-Physical Systems, April 2008, Troy, MI
- **CPS Summit**, CPS Week, April 2008, St. Louis, MO
- **Robotics** and Cyber-Physical Systems Special Session at IROS, Sept. 2008, Nice, FRANCE
- Transportation Cyber-Physical Systems: **Automotive, Aviation, and Rail**, November 2008, Vienna, VA

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

CPS Challenges

- Societal challenge – How can we provide people and society with cyber-physical systems they can bet their lives on?
- Technical challenge – How can we build systems that interface between the cyber world and the physical world, with predictable, or at least adaptable, behavior
  - We cannot easily draw the boundaries
  - Boundaries are always changing
  - There are limits to digitizing the continuous world by abstractions
  - Complex systems are unpredictable
  - Current cyber + physical systems are overly conservative in their design

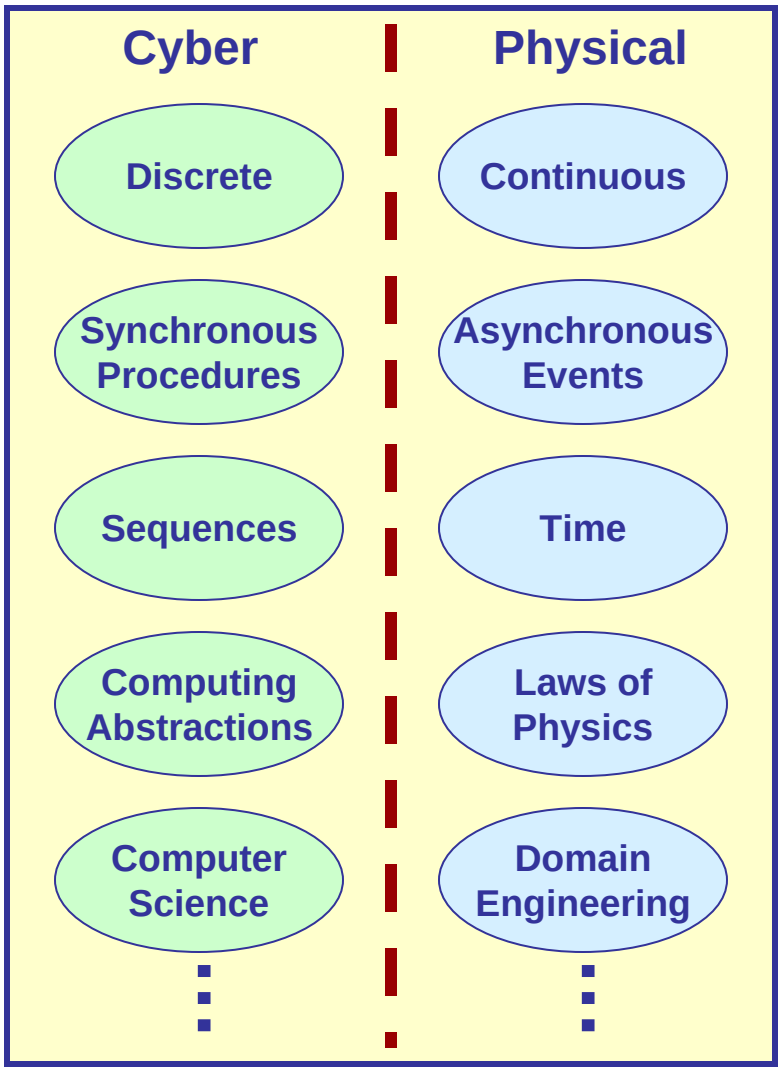
Systems Research Challenges (1)

- 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
- We need ways to measure and certify the “performance” of cyber-physical systems
  - Time and space, but multiple degrees of resolution
  - New metrics, e.g., energy use
  - New properties, e.g., security, privacy-preserving
- We need new engineering processes for developing, maintaining, and monitoring CPS
  - Traditional methods will not work or are too costly

Systems Research Challenges (2)

- 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 software (e.g., weak compositionality), hardware (e.g., power), and systems?
- We need new formal models and logics for reasoning about cyber-physical systems
  - Such as 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

CPS Research Gaps

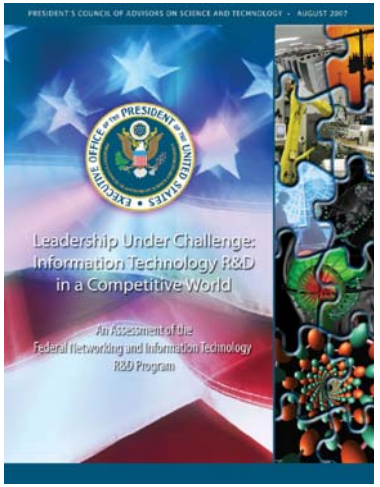


Research Gaps

- Composition
- Design automation
- System integration
- Certification
- Security and privacy
- Education and work force

CPS – A National Research Priority

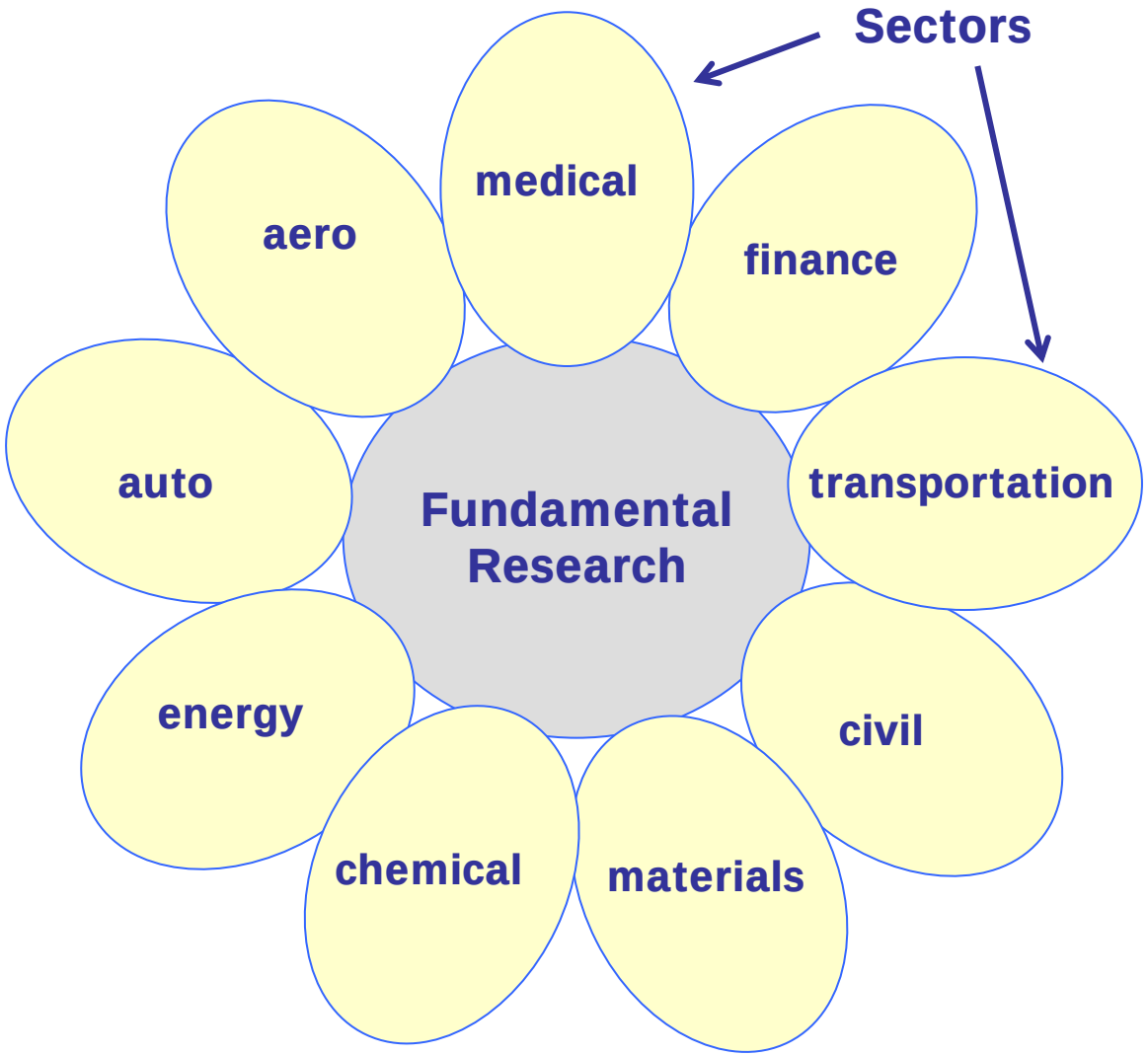
- Eight priority areas for competitiveness, with four designated as having the highest priority
  - Network and Information Technology (NIT) Systems Connected with the Physical World
  - Software
  - Digital Data
  - Networking
- NIT systems connected with the physical world (cyber-physical systems)
  - 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.

NSF 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

X Impacting CPS

- *X* has some principles of cyber-physical integration, focused on particular structures/state-spaces – *Can you abstract this?*
- *X* may solve certain problems (sensor fusion, situational awareness, multi-agent planning, real-time scheduling, control over networks, etc.) – *Can the same methods be generalized?*
- *X* may be pushing the envelope in certain CPS grand challenge areas – *What can you offer to solving other problems (such as common architectures)?*
- *X* may have nascent CPS tendencies unto itself – *How do you engage in the larger CPS effort? Who do you team with?*
- **Expand *X*, Rethink *X***

CPS Impacting *X*

What could you do with …

- A science of CPS?
- A method to optimize designs over cyber and physical components cohesively?
- An infrastructure for networked, real-time control (that was as easy to build your applications upon as it is to build applications that run over TCP/IP on the Internet)?
- Students and colleagues that were trained in CPS fundamentals?

CPS Solicitation (NSF 08-611)

- Joint initiative of Directorate for Computer and Information Science and Engineering (CISE) and Directorate for Engineering (ENG)
- Proposals due February 27, 2009
- Total funding of up to about $30M, up to 40 awards
- Continuation in future years is expected

http://www.nsf.gov/funding/pgm_summ.jsp?pims_id=503286

Type of CPS Projects

- *Small Projects –* individual or small-team efforts that focus on one or more of the three defined CPS themes (up to $200,000/year for up to three years)
- *Medium Projects –* span one or more CPS themes and may include one or more PIs and a research team of students and/or post-docs (up to $500,000/year for up to three years)
- *Large Projects –* multi-investigator projects addressing a coherent set of research issues that cut across multiple themes or that explore a particular theme in great depth (up to $1,000,000/year for up to five years)
- *CPS-Virtual Organization –* facilitate and foster collaboration and information exchange (R2R, R2I)

Three CPS Themes

- *Foundations –* develop new scientific and engineering principles, algorithms, models, and theories for the analysis and design of cyber-physical systems
- *Research on Methods and Tools –* bridge the gaps between approaches to the cyber and physical elements of systems through innovations such as novel support for multiple views, new programming languages, and algorithms for reasoning about and formally verifying properties of complex integrations of cyber and physical resources
- *Components, Run-time Substrates, and Systems –* new hardware and software infrastructure and platforms and engineered systems motivated by grand challenge applications

CPS Information Day

- When?: December 15, 2008
- Where?: Westin Arlington Gateway, Arlington, VA (also a webcast)
- What?:
  - CPS solicitation information from the NSF (morning)
  - Workshop: Challenges for a CPS Community (afternoon)

http://varma.ece.cmu.edu/InfoCPS/

(Registration Required!)

Solicitation 08-611: NSF Team

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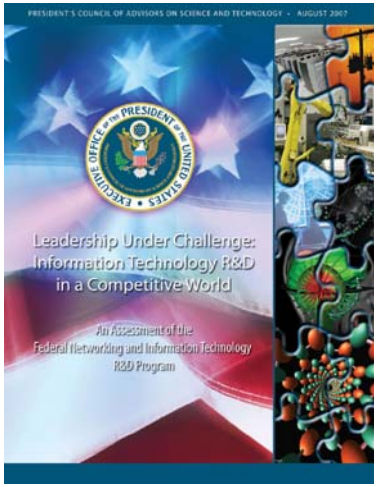

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CPS Virtual Organization

- Proposals with innovative, effective strategies/mechanisms to:
  - facilitate and foster interaction and exchanges among CPS PIs and their teams, and between CPS researchers and industry
  - enable sharing of artifacts and knowledge generated by the projects with the broader engineering and scientific communities
- Strategies/mechanisms could include, but are not limited to:
  - creating and maintaining a web-based repository and collaborative platform to facilitate the open exchange of research results, tools, and educational materials among CPS researchers and the broader community
  - hosting tutorials and workshops to promote community interest, understanding, and the use of new methods
  - identifying effective mechanisms for technology transfer
  - creating a consortium of small businesses with interests in CPS innovations
  - collecting and disseminating CPS challenge problems from industry
- Funding up to $200,000/year for up to five years, for **at most one**

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 pervasive computing to add sensing+control
  - Change from ad hoc to grounded, assured development