Cyber Physical Systems

Looking Into the Future

Dr. Ty Znati, Division Director
Computer Systems and Networks
Computer and Information Science and Engineering
National Science Foundation

GRC/SRC Summer Study
La Quinta, CA 92253

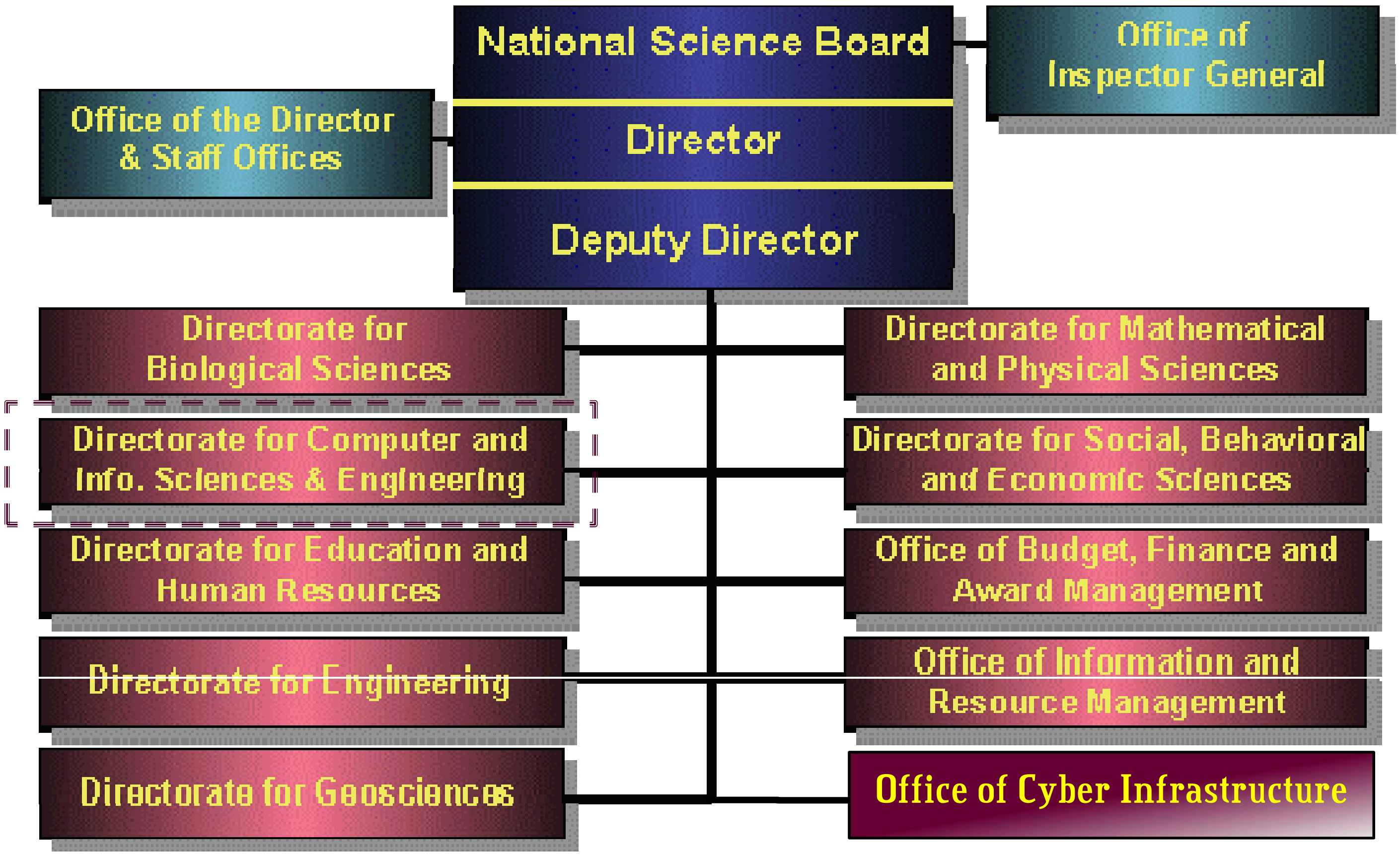
Outline

- Cyber-Physical Systems
  - Characteristics and Properties
- CPS Challenges and Design Approaches
  - Research Directions
- NSF Response
  - Cyber Physical Systems Initiative
- Concluding Remarks

National Science Foundation Vision and Goals

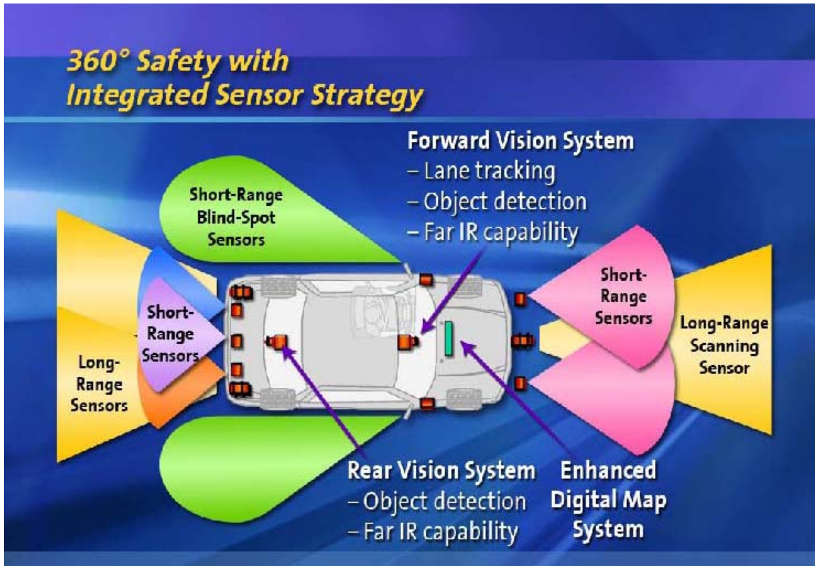
- Advancing discovery, innovation and education beyond the frontiers of current knowledge, and empowering future generations in science and engineering.
  - **Discovery** – Advancing frontiers of knowledge
  - **Learning** – World-class science and engineering workforce and scientific literacy of all citizens
  - **Research Infrastructure** – Advanced instrumentation, facilities, cyberinfrastructure, and experimental tools
  - **Stewardship** – Supporting excellence in science and engineering research and education

National Science Foundation



Computing Technology **Re**volution

Smart Cars


360° Safety with
Integrated Sensor Strategy
Forward Vision System
– Lane tracking
– Object detection
– Far IR capability
Short-Range
Blind-Spot
Sensors
Short-
Range
Sensors
Long-Range
Scanning
Sensor
Short-
Range
Sensors
Long-
Range
Sensors
Rear Vision System
– Object detection
– Far IR capability
Enhanced
Digital Map
System


OnStar
by GM
Front Sensors
Cellular Antenna
Sensing Diagnostic Module
(SDM)
Side Sensors
OnStar
Module

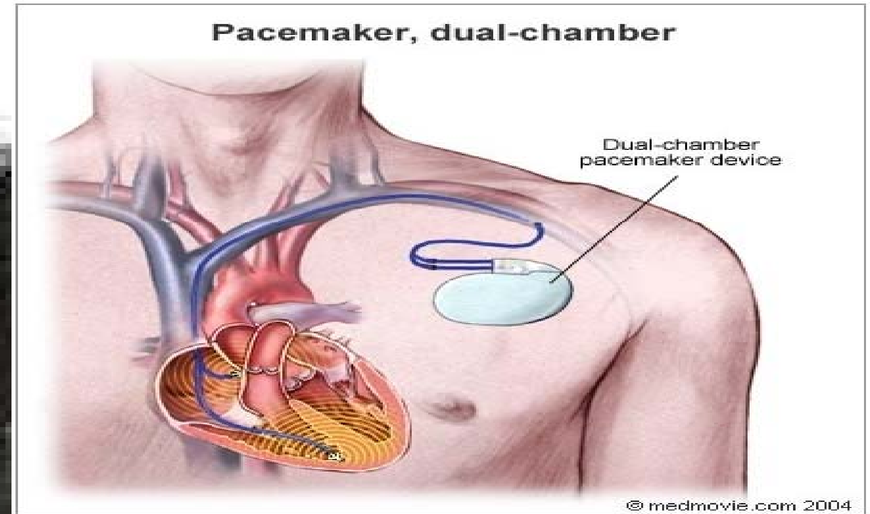

REAR-PASSENGER FLAT-PANEL DISPLAYS
COMMAND SYSTEM WITH PCMCIA SLOT
GPS NAVIGATION
DVD PLAYER
LED LAMP CLUSTER
HEAD-UP DISPLAYS
DASHBOARD-INSTRUMENT CLUSTER
TELEMATIC SYSTEM
CLIMATE CONTROL
ELECTRONIC POWER-ROOF SYSTEM
RADAR SENSOR
TRANSMISSION CONTROL
COLLISION AVOIDANCE
ADAPTIVE CRUISE CONTROL
HID HEADLAMP
MEMORY SEAT/MIRROR/STEER
AIR-BAG CONTROL AND
SATELLITE CRASH SENSORS
ACTIVE STEERING
BODY CONTROL
SUSPENSION CONTROL
POWER WINDOWS
REMOTE KEYLESS ENTRY
SEAT MASSAGE/HVAC
ADAPTIVE BRAKE LIGHTS
PARKING SENSORS
REAR-VIEW CAMERA
BATTERY MANAGEMENT
POWER SEATS
THROTTLE CONTROL
ENGINE CONTROL UNIT
FOLDING DOOR MIRRORS
ELETROCHROMIC REAR-VIEW MIRRORS
CAR RADIO
ANTILOCK-BRAKING SYSTEM/ELECTRONIC-
STABILITY PROGRAM
TIRE-PRESSURE-MONITORING SYSTEM (TPMS)


Emissions System
Air Bag System
Antilock Braking System
OnStar System
MAINTENANCE INFORMATION
Remaining Oil Life: 10%
Mileage: 6,503
Tire Pressure Monitoring: Low
OnStar Subscription
Hands-Free Calling

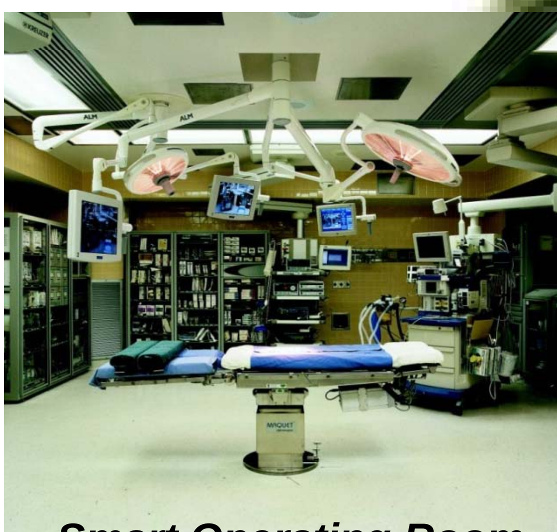
Embedded Medical Devices

Infusion Pump

Tetherless Patients

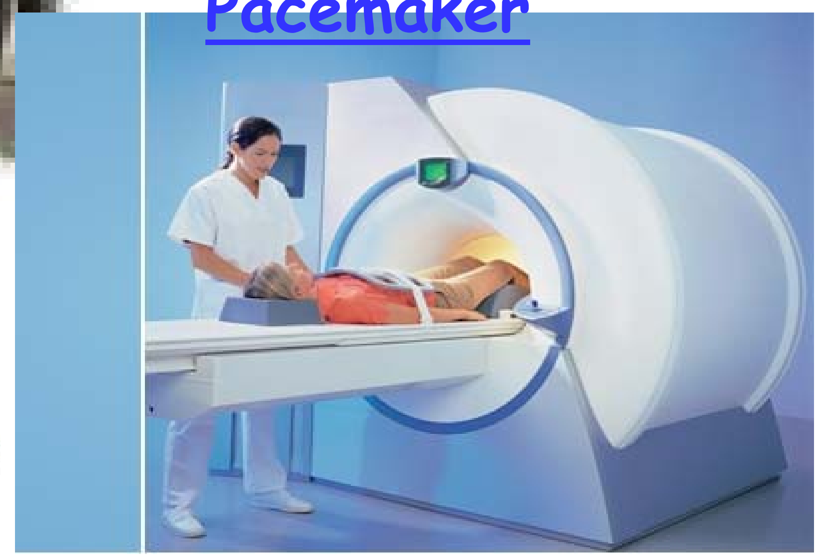


[Pacemaker]



Smart Operating Room

Automated External Defibrillator



Scanner

Sensors Everywhere

Sonoma Redwood Forest

Hudson River Valley

Smart Buildings

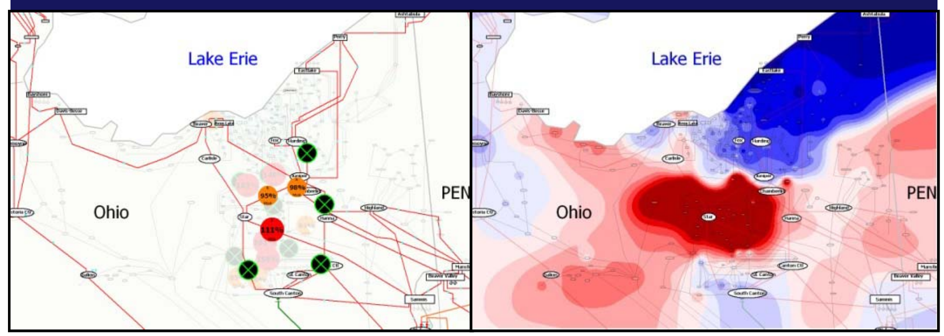
Smart Bridges

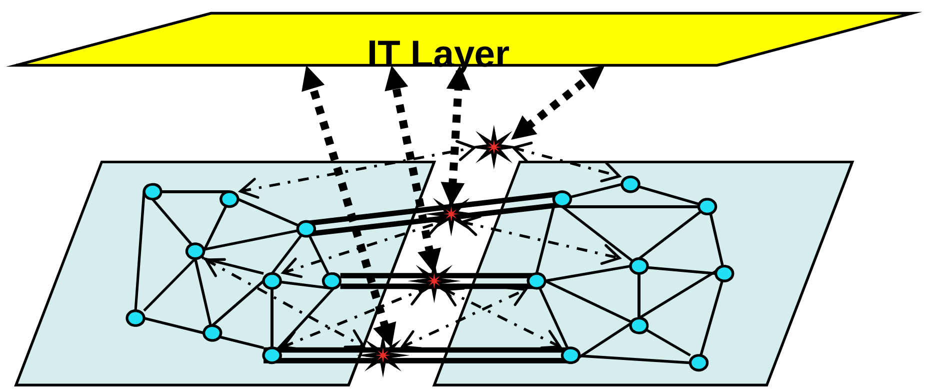
Smart Grids

- ❑ **Real-time cooperative control of protection devices**
  - ▪**Bulk power stability and quality, flow control, fault isolation**

- ❑ **Self-healing -- (re-)aggregate islands of stable bulk power**

- ❑**Ubiquitous green technologies**





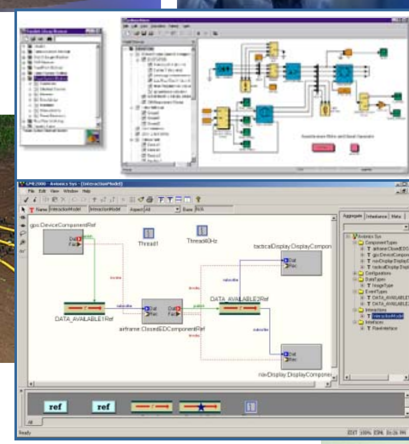
A Complex Ecology Socio-Technical IT Infrastructure

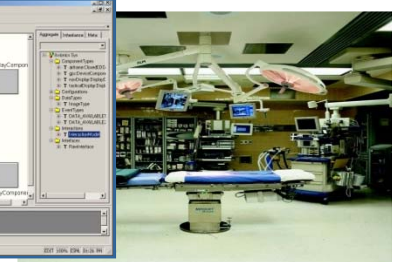
People, Cyber and Physical Networked Together

From simple computing devices to a **complex ecology** of **Cyber Physical Systems** – **people** and **deeply-embedded intelligent devices** networked together, communicating "**naturally**" with **each other** and with the **physical environment**, getting **services**, creating **content** and sharing **knowledge**, over **ubiquitous** and **pervasive** networks

Cyber Physical Systems

Cyber Physical Systems are natural and engineered physical systems that are integrated, monitored and controlled by a computational core.



What’s Particular About CPSs?

- **Tight integration of computational processing and physical processes**
  - It becomes nearly impossible to identify what causes behavioral attributes: Computational, Physical or a combination of both
- **Major system’s characteristics and functionality are defined by and the product of computational and physical interaction**
  - Computing devices themselves have their own physical properties which contribute to the overall system behavior

CPS Challege!

- The trend in CPS is to rely less and less on human intervention and decision-making and more and more on the **intelligence** as embodied in the **computational** core.

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

CPS Characteristics and QoS Requirements

- Deeply-embedded, possibly mobile, deployed over extended areas, and expandable,
- They need to be scalable, rapidly configurable, adaptive, responsive, reactive, self-configuring, coordinated and synchronized,
- They need to be fault-tolerant, reliable, robust, predictable, trustworthy and usable with high-confidence,
- They need to be affordable and cost-effective, user-friendly, efficient and long-lived

CPS are Complex Systems

Complicated Systems

- A complicated system is one that is composed of a large number of parts, and whose behavior can be entirely understood by reducing it to its parts.

Complex Systems

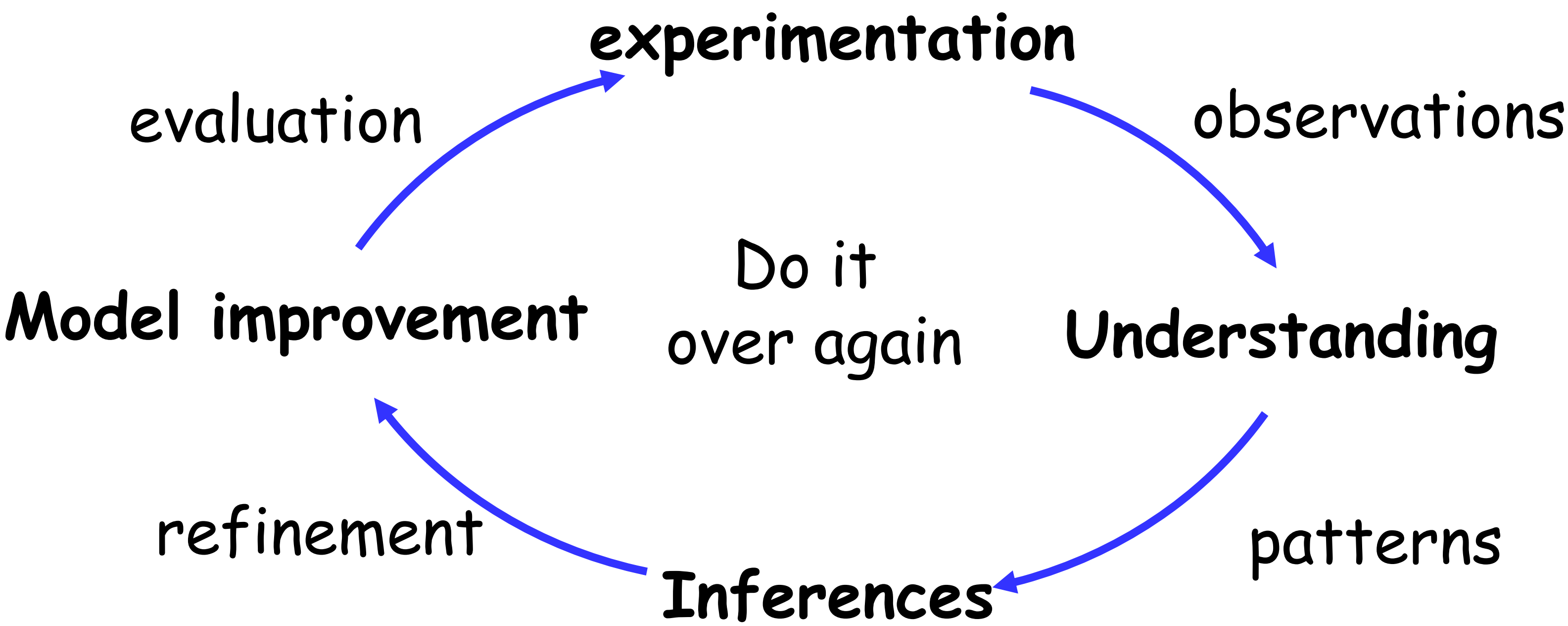
- A complex system consists of a large number of components whose interactions lead to rich dynamics with patterns and fluctuations on many scales of space and time.

Complex Systems Properties

- **Phenomenon of emergence**
  – Non-linear interactions among system components that lead to unanticipated, emergent behaviors
    - Hard to control complex systems with strategies derived from simple deduction or linear reasoning
  – Unintended and unanticipated consequences of changes in complex systems lead to unexpected failures
    - Dynamics, Oscillations, Instabilities
- **Various degrees of resolution**
  – "Traditional" methods are no longer applicable
    - Difficult to capture essential relationships between entities
    - Limited ability to reason about the overall behavior

Fundamental tradeoffs, invariance, global behavior, asymptotic remain a challenge to deal with

“Classical” Approach to Science



Assumes some level of specification

Knowledge and Abstraction

- Complexity brings about a marked shift in our concerns with knowledge, our perceptions of problems and attempts at their solutions
  - Hard to determine what can be “known” and how “knowledge” can be achieved in the presence of emergent behaviors
- If abstraction forming is a basic tool for coping with large-scale system design, is it still possible to capture global behavior under uncertainty?

Fundamental Question

- Is there a **science** for understanding the complexity of our systems such that we can **engineer** them to have predictable behavior, … or at least an adaptable one?
  - To what extent does there exist a “structure” that gives rise to the properties of large-scale complex systems?
  - Are there “universal laws” that govern the structure and consequently the behavior of complex networked systems?
  - Can a theory be developed to assess the vulnerabilities and fragilities inherent in complex networked systems to better understand their behaviors?

How can this knowledge be used to design, organize, build, and manage complex networked systems?

Current State of the Art Computational Side

- **Effective methods and tools have been developed for computational systems, but they largely ignore physical systems**
  - Dominant abstractions in programming languages typically avoid explicit representation of time and other aspects of physical world
    - Treated as “non-functional” requirements

Current State of the Art Physical Side

- Engineering of physical systems often ignores intrinsic properties of computing and communication platforms, such as scheduling, resource management, network delays, computational failures
  - Often regarded as “Software” issues or secondary implementation issues

"Separation of Concern" is a primary design principal in dealing with multi-objective design problems"

It breaks down, as design views in CPS are not necessarily orthogonal due to complex interactions between the components

Separation of Computational and Physical is unsustainable if we were to build CPS our lives depend upon

Future Research Directions

CPS Abstractions Computational Models

- **Existing abstractions and computational models need to be fundamentally rethought**
  - Needed are resource- and environment-aware computational models and novel forms of real-time cyber-physical concurrency models.
    - Abstractions that will allow the synthesis of computations with physical properties and physical systems dynamics

New Compositionality Paradigms

- In most cases, the software provides much of the intelligence of the computational core
  - Our current computing models violate the compositionality requirement – the ability to easily infer system-level behavior from component local properties and behaviors
- CPS are likely to exhibit properties that will make compositionality expensive or impractical
  - New paradigms must be developed to achieve predictability assuming partially compositional properties

Operating under Uncertainty

- **Robustness, Safety and Security of CPSs**
  - Uncertainty in the environment, security attacks, and errors in physical devices and in cyber systems make how to ensure overall system robustness, security and safety.
    - Needed is a set of useful coherent metrics that capture different (cyber and physical) models of uncertainty, errors, faults, failures and security attacks.

Certification

- **Current certification methods impose requirements on the development process and require testing-based evidence**
  - Does not scale and is costly
- Compositional certification as alternative
  - Works well in physical systems, but breaks down when cyber and physical are seamlessly integrated

CPS Engineering Challenges

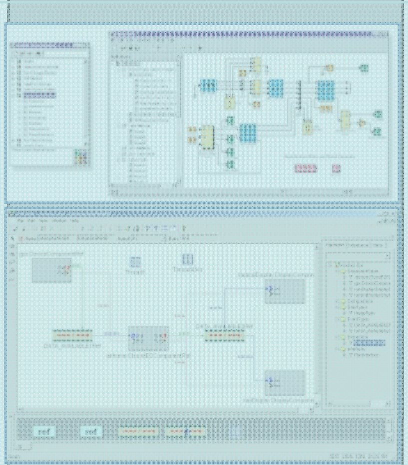
- The need for scientific and engineering foundation to iteratively develop both the system structure model and the system behavior model.
- Analytical capability to map behavior onto structure and vice versa
  - What parts of behavior will be performed by which specific parts of structure?
- Integrated quantitative models for trade-off analysis focused on the constraints of the cyber, physical and humans.
- Model-based system and software design and integration tools and technologies
  - Deep analysis of underlying abstractions and their interactions.

New Control Frameworks

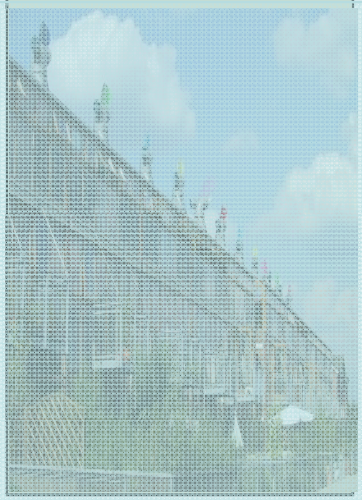
- Conventional Control System Design are limited
  - CCSD assumes an I/O structure.
    - In CPS, the identity of input/output signals is context dependent
  - *CCSD assumes command-driven performance measures*
    - *CPS must consider the intent of the user*
  - *CCSD assumes only information feedback*
    - *CPS must include physical feedback*
  - *In CCSD embedded components close local “inner” feedback loops*
    - *CPS must enhance and leverage nature physical feedback at all levels.*

A Cross-Disciplinary Effort for Sustainable CPS

Software

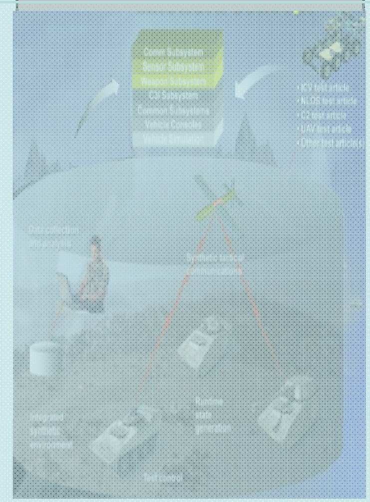


Control



Systems

Security

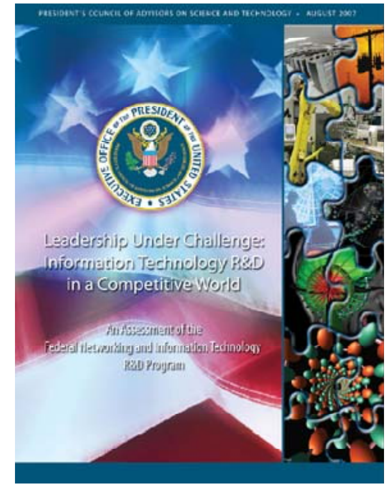


- We need to realign disciplinary boundaries
- We need to re-structure education

CPS@NSF

CPS – A National Research Priority

- Eight priority areas, 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
- In response, NSF put forth a solicitation



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.

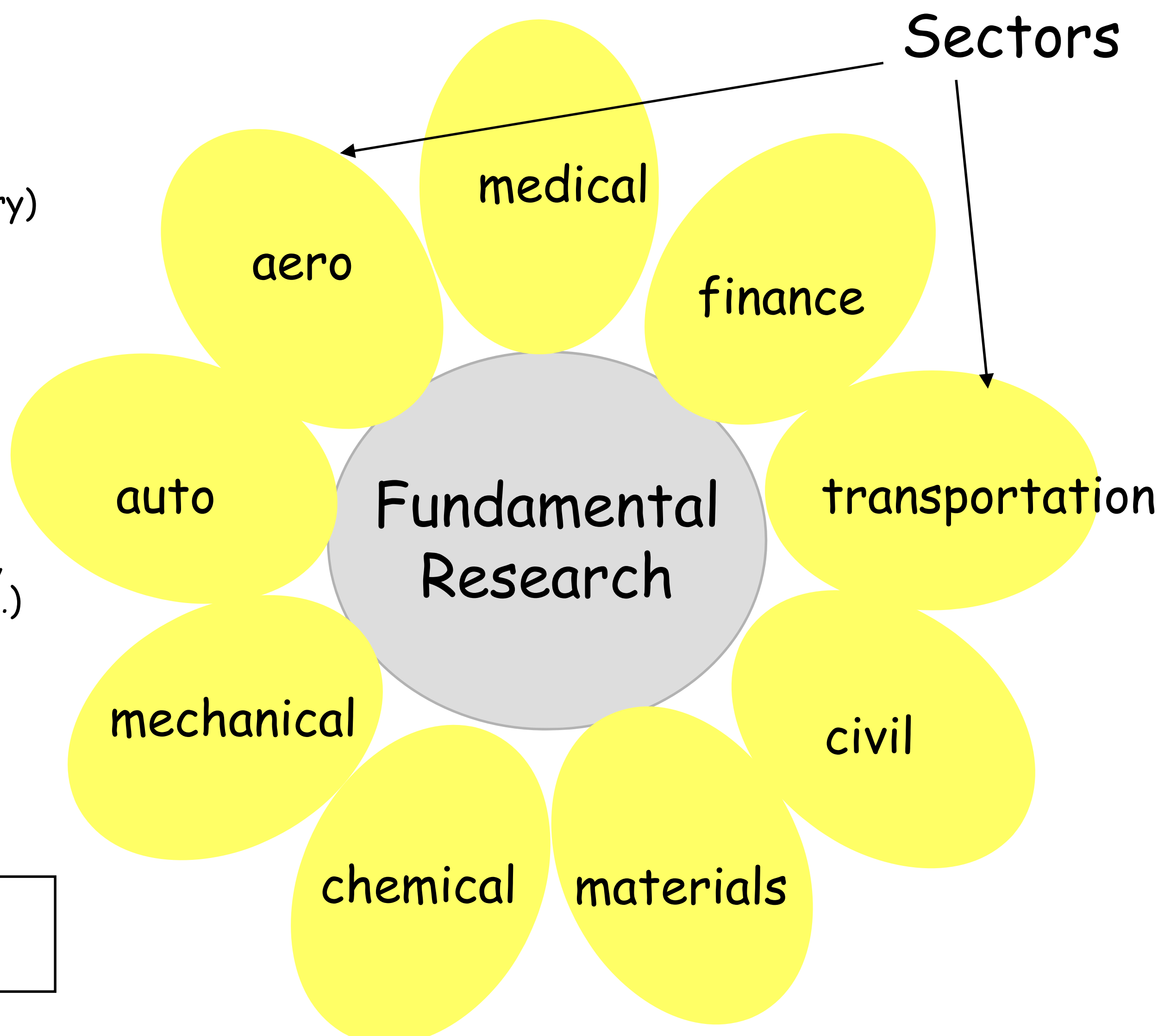
Pre-release briefing: **http://www.ostp.gov/PCAST/agendas/Apr-07/Reed-Scalise_PCAST_Apr07.pdf**
Final Report: Leadership Under Challenge: Information Technology R&D in a Competitive World

A Model for Expediting Progress

Industry
Gov't (e.g., military)

Industry
Gov't
Academia

Academia
Gov't (NSF, NSA, NIH, DoD, …)



Jeannette Wing presentation, CPSWEEK, April 2008

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

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)
- Possible CPS-Virtual Organization (CPS-VO)

Program Goals

- **Promote** *bold, ambitious, transformative* research that explores new scientific frontiers which promise disruptive innovations to help define the future of computing
  - **Catalyze** far-reaching research in the computing and information fields motivated by hard, emerging problems and/or compelling applications that benefit society
  - **Inspire** current and future generations of Americans (esp., underrepresented groups) to pursue CISE careers
  - **Stimulate** significant research and education outcomes that promise scientific, economic, and/or societal benefits through effective knowledge transfer

Concluding Remarks

CPS applications will dwarf the 20^{th} century IT revolution!

The foundational challenges of CPS require top-to-bottom rethinking of computation

Edward Lee, Professor UC Berkeley, 2007

Thank You!

Acknowledgement: J. Wing, NSF NeteSE Group, NSF CPS Group, CPS steering group and Organizing Committee, NSF CDI Group and NSF Expedition Group.

Questions and Feedback