General CPS Architecture Concepts

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CPS Architectures: Generalities

- **Architecture** : key ingredient of any system

  -- "Much abused" word

- **Architecture** : description of structure and behavior components of a system together with their configuration and interfaces and interconnections

- **Architecture for CPS** is challenging :

  Must account for both the physical and cyber constraints – e.g. physical and material laws as well as geometric laws will guide the physical part

CPS Architectures: Generalities

- **Various concepts of time and their constraints**: Extensions of current distributed architectures for computers at all scales, including both digital and analog components need to be considered

- Interplay between the principles and rules of architectures from the physical and cyber sides need to be considered and brought to harmony

- Overall technical goals: develop principles, languages and a taxonomy of CPS architectures

Architect and Architecture
(Buildings)

- **Architect** - Αρχιτέκτων -- "master builder"

- from αρχι – "chief" -- first + τέκτων -- tekton – "builder"

- **ARCHITECTURE** – ΑΡΧΙΤΕΚΤΟΝΙΚΗ: *The art and science of designing and erecting buildings and other physical structures*

Arch. for religion & esthetics

Arch. for acoustics

Add computer controlled electronic amplifiers and sound amplification
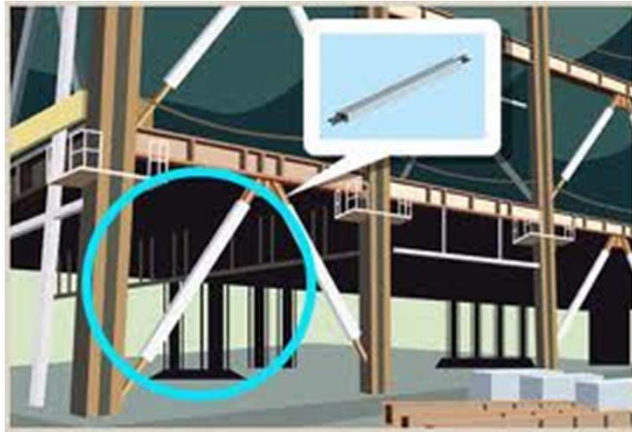*How to integrate?*
Joint architecture?

Fidias -- the Parthenon

Polykleitos - Epidaurus

Arch. for water

Add computer controlled pumps and valves, flow control, distribution
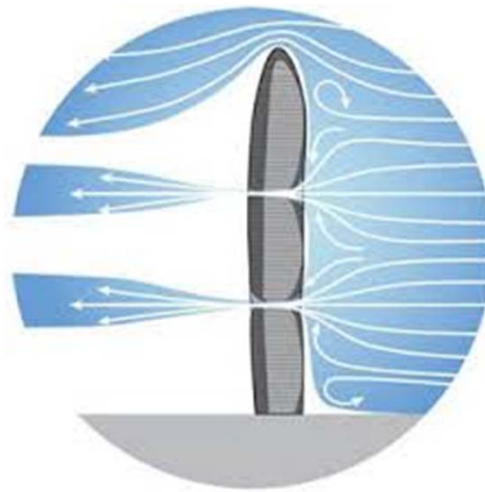*How to integrate?*
Joint architecture?

Roman aqueducts

CPS Architecture: Buildings

Architecture for earthquake resistance
Add computer controlled sensors, shock absorbers, material properties
CPS architecture?

Architecture for energy efficiency

Add computer controlled sensing, HVAC, etc.
CPS architecture?
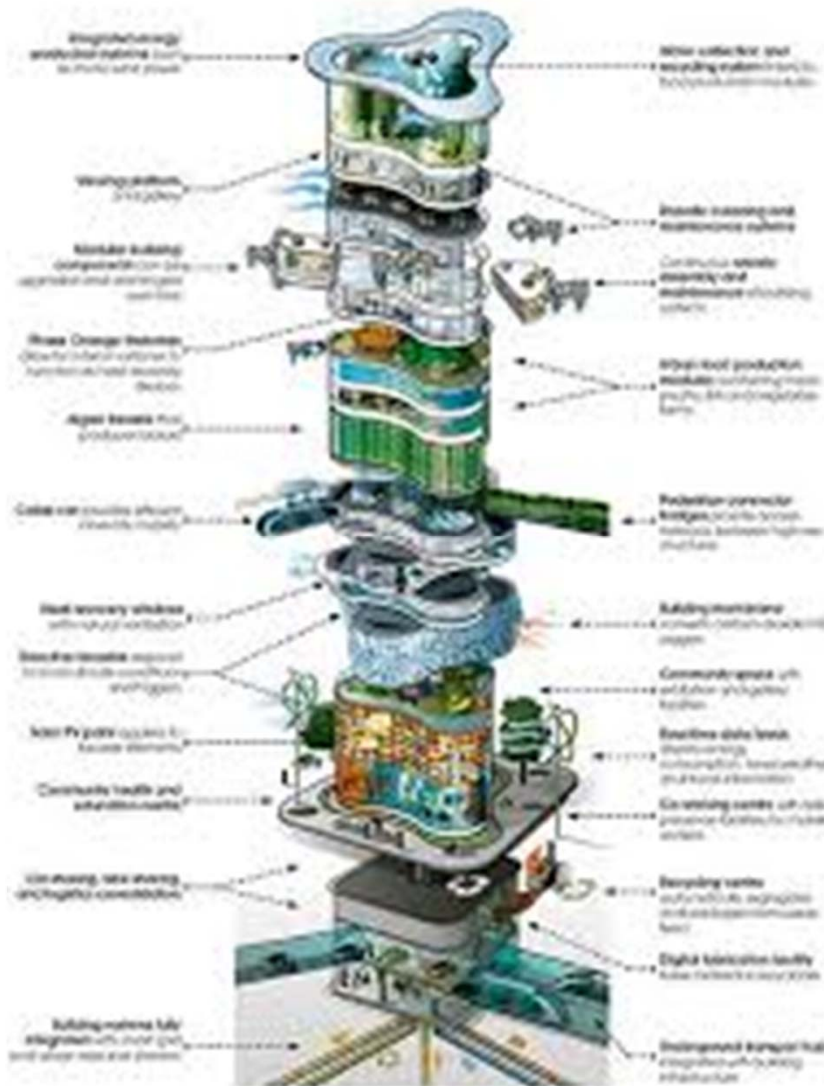
Pearl River Tower Complex, Guangzhou

CPS Architecture:
"Smart" and Energy Efficient Buildings

Architecture for??

*The* Institute for **Systems** Research

Arup 2050: *It's Alive!*

"smart" "thinking" buildings:

- on-site power generated by algae, wind, or photovoltaic paint
- phase-changing and self-healing materials
- farms that use recycled water for irrigation;
- flying robots that maintain the building and add and delete functional units;
- heat-sensing walls and windows
- preprogrammed to recognize you
- adjusts the lights to your liking,
- turns on your favorite music

**Integrated evolvable CPS architecture?
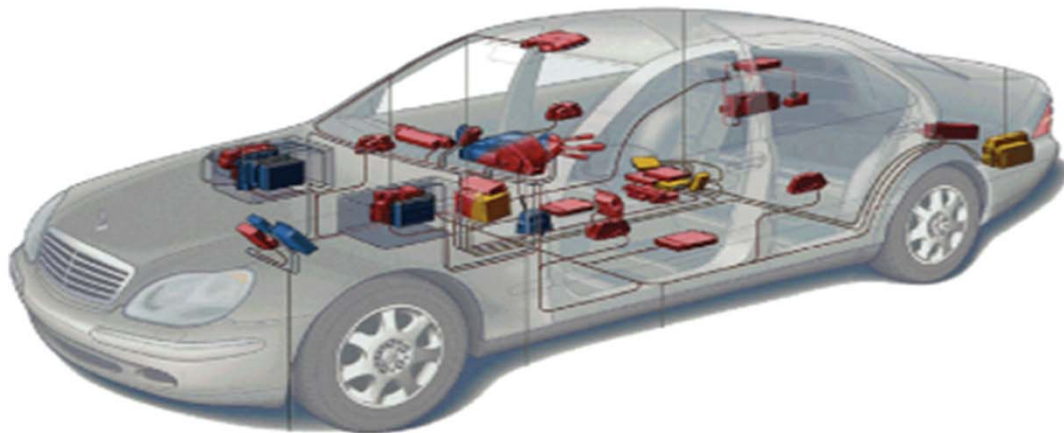What is "C" and what is "P" here?**

CPS Architectures: Automotive
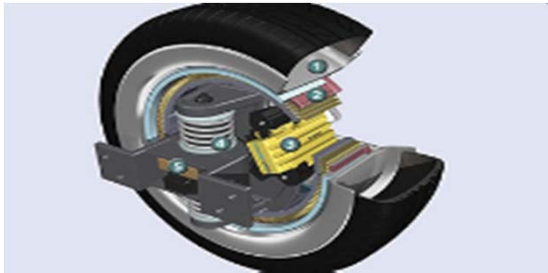
From components,
to subsystems,
to systems,
to system of systems

- **Compositionality and Composability**
- **Separation of concerns vs integration and adaptability via programmability**
- **Greater variability**
- **Safety**
- **Security**
- **Performance**
- **Human**
- **Validation and Verification and Testing**

Architecture for???

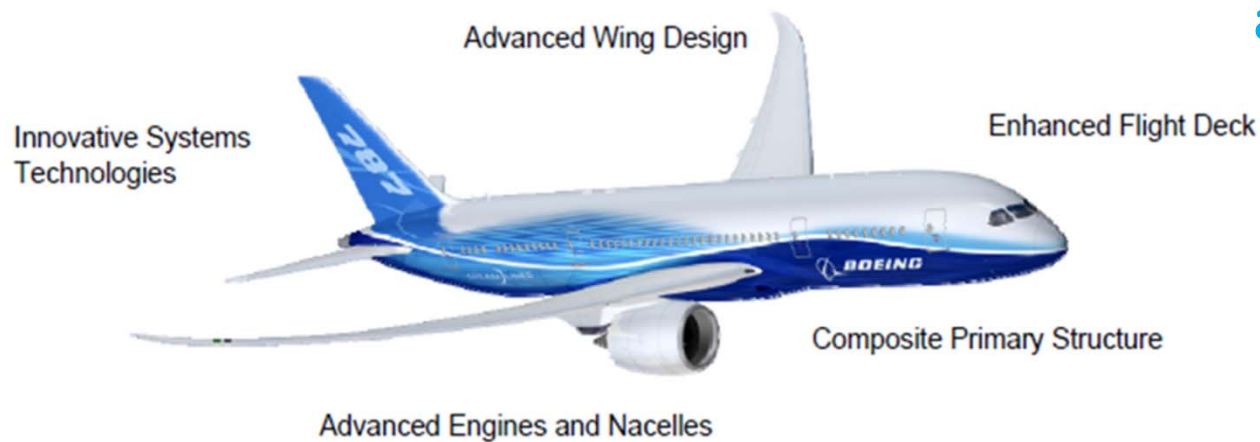# CPS Architecture: Materials-Geometry-Controls

The 787 Dreamliner delivers:

$20\%^{*}$ reduction in fuel and CO_2

28% below 2008 industry limits for NOx

$60\%^{*}$ smaller noise foot print

*Relative to the 767

Architecture Logics, their Representation and Integration

Advanced Wing Design

Innovative Systems Technologies

Enhanced Flight Deck

Composite Primary Structure

Advanced Engines and Nacelles

Composite wing – new control algorithms
All-electric platform – new aircraft VMS

Smart suit – improve physical endurance & energy harvesting

CPS Architecture:
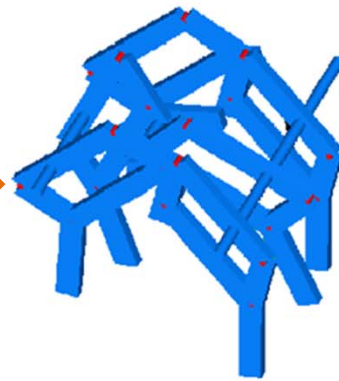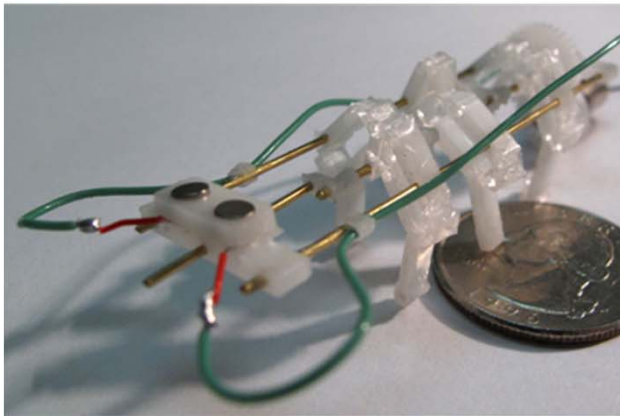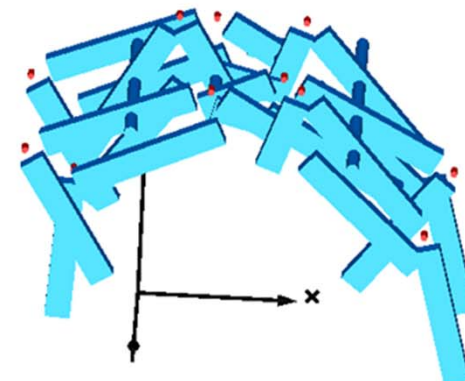# Materials-Geometry-Controls

Modularity?
Evolvable modularity?
What is "C"?
What is "P"?
Architecture for ??

Robotic lizards – new motion-material-geometry
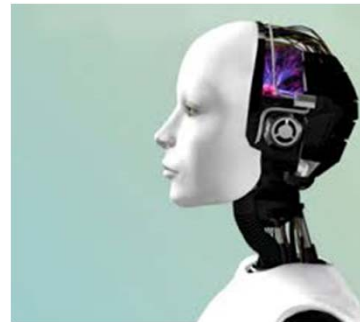
old   new

*Fast micro-robots – new joint design
of geometry-material-controls –
More stable and faster running*

CPS Architecture: Perception-Cognition and Co-Robots

The "pressure" of "P" on "C"
The return of analog computation?
Non-von Neumann Architectures?
Physics of computation?
Beyond Turing?
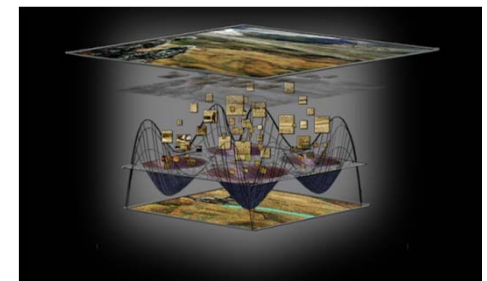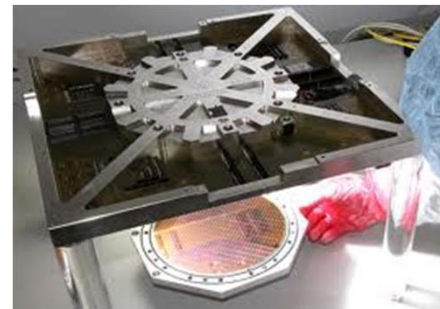
Cognition and knowledge generation from sensory perception –
communicating with humans – *collaboration*
Not just obeying commands – *the inverse problem*
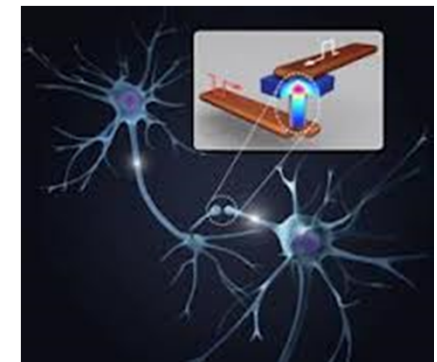
Networked CPS
Architecture: Wireless Sensor Networks

Wireless Sensor Networks (WSN) for infrastructure monitoring

- Environmental systems
- Structural health
- Construction projects
- Energy usage
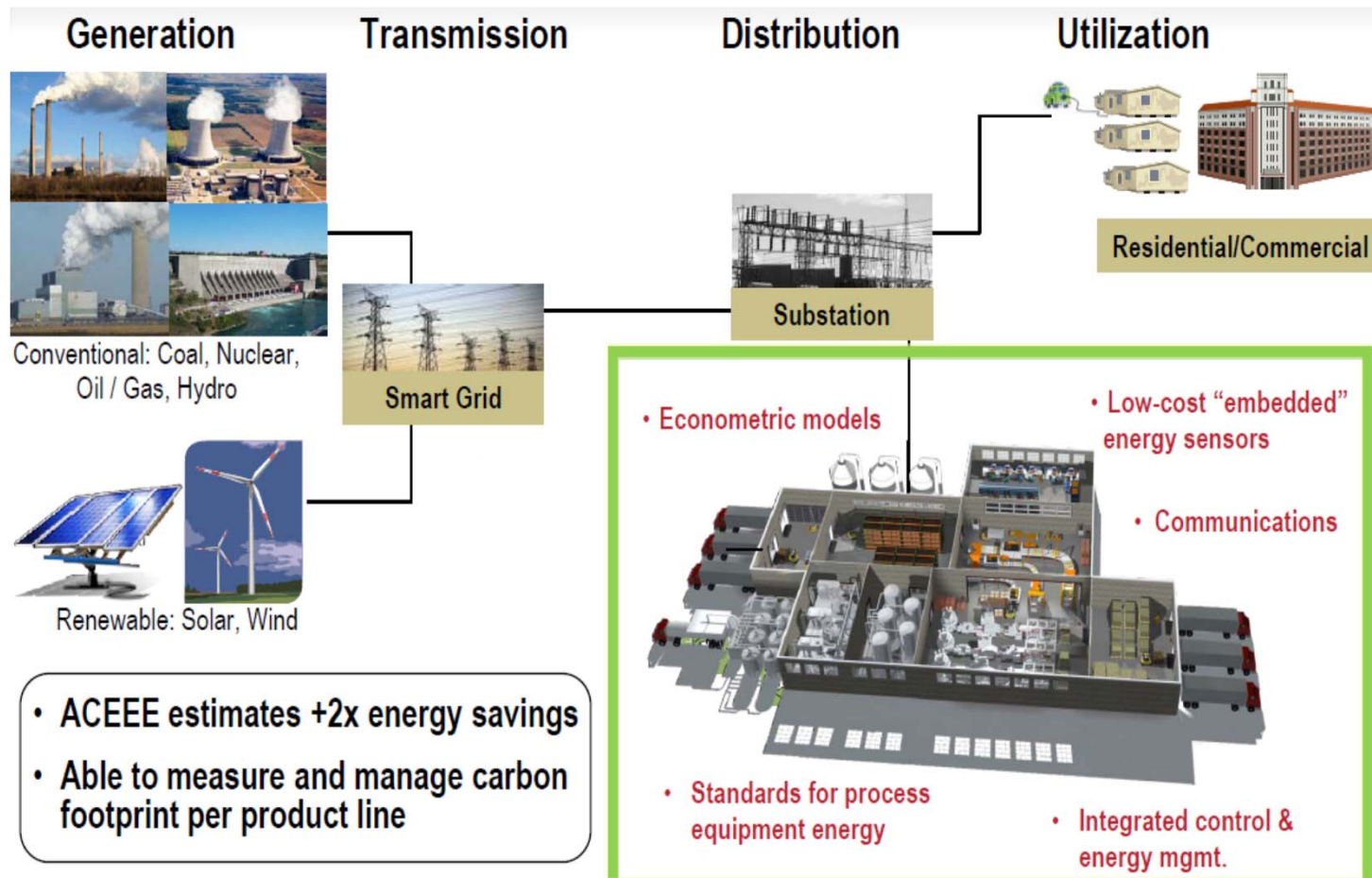
Bridges

Snowpack

Soil liquefaction

Smart buildings

Traffic

Vineyards

Architecture for??

Networked CPS
Architecture: Smart Grids

- ACEEE estimates +2x energy savings
- Able to measure and manage carbon footprint per product line

Generation — Transmission — Distribution — Utilization

Conventional: Coal, Nuclear, Oil / Gas, Hydro

Renewable: Solar, Wind

Smart Grid

Substation

Residential/Commercial

- Econometric models
- Low-cost "embedded" energy sensors
- Communications
- Standards for process equipment energy
- Integrated control & energy mgmt.

Architecture for??

Rockwell

Architecture for??

Networked CPS Architecture: FAA NextGen
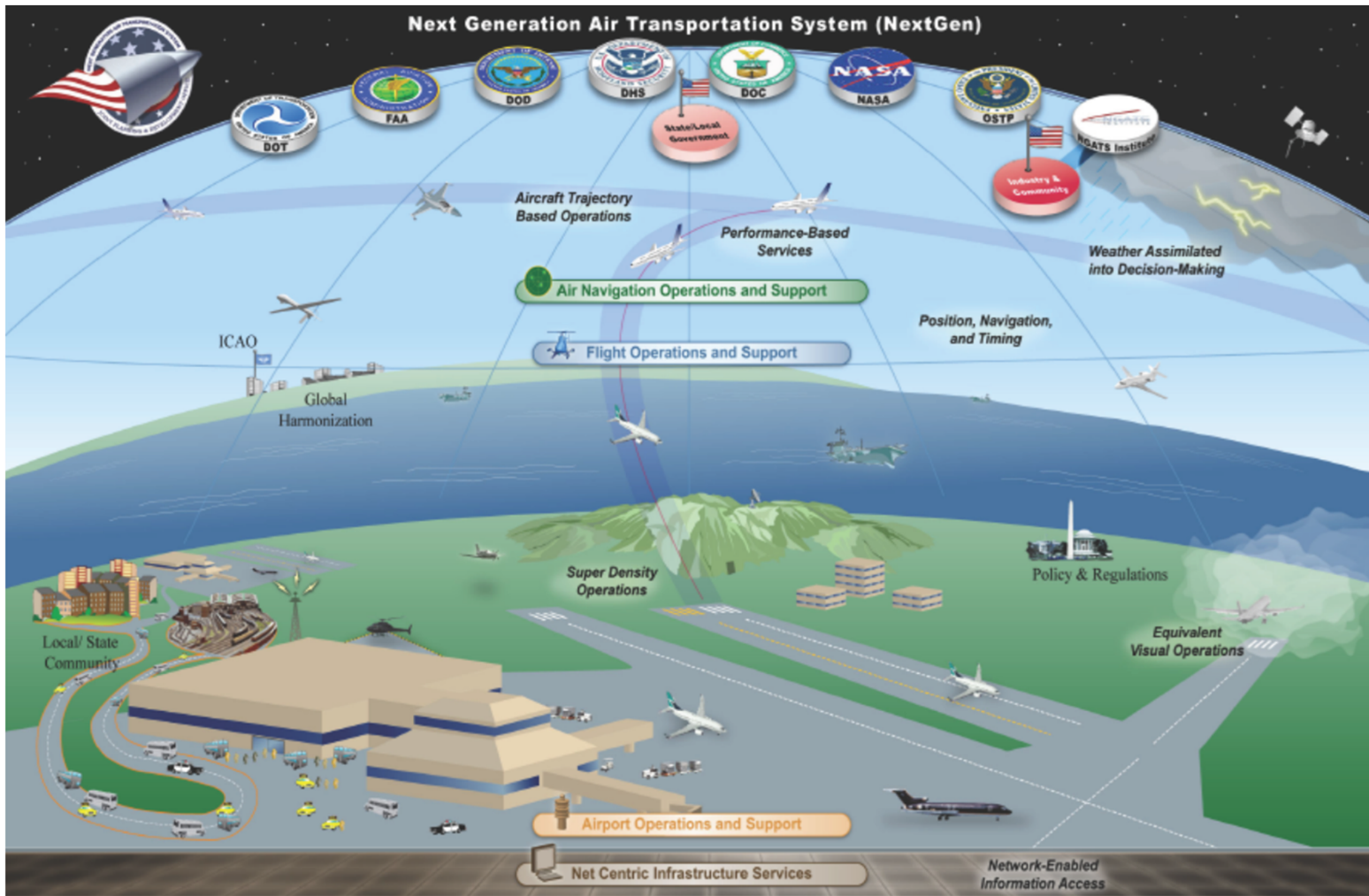
Architecture for??

Networked CPS
Architecture: Autonomous Swarms

- **Component-based Architectures**
- **Communication vs Performance Tradeoffs**
- **Distributed asynchronous**
- **Fundamental limits**

Architecture for??

Networked CPS
Architecture: Multiple Interacting Multigraphs

- Multiple Interacting Graphs
  - *Nodes*: agents, individuals, groups, organizations
  - Directed graphs
  - *Links*: ties, relationships
  - Weights on links : value (strength, significance) of tie
  - Weights on nodes : importance of node (agent)
- **Value directed graphs with weighted nodes**
- **Real-life problems: Dynamic, time varying graphs, relations, weights, policies**

Information network

$j : w_j^S$

w_{ij}^S $i : w_i^S$

$k : w_k^I$ w_{kl}^I $l : w_l^I$

Communication network

$m : w_m^C$ w_{mn}^C $n : w_n^C$
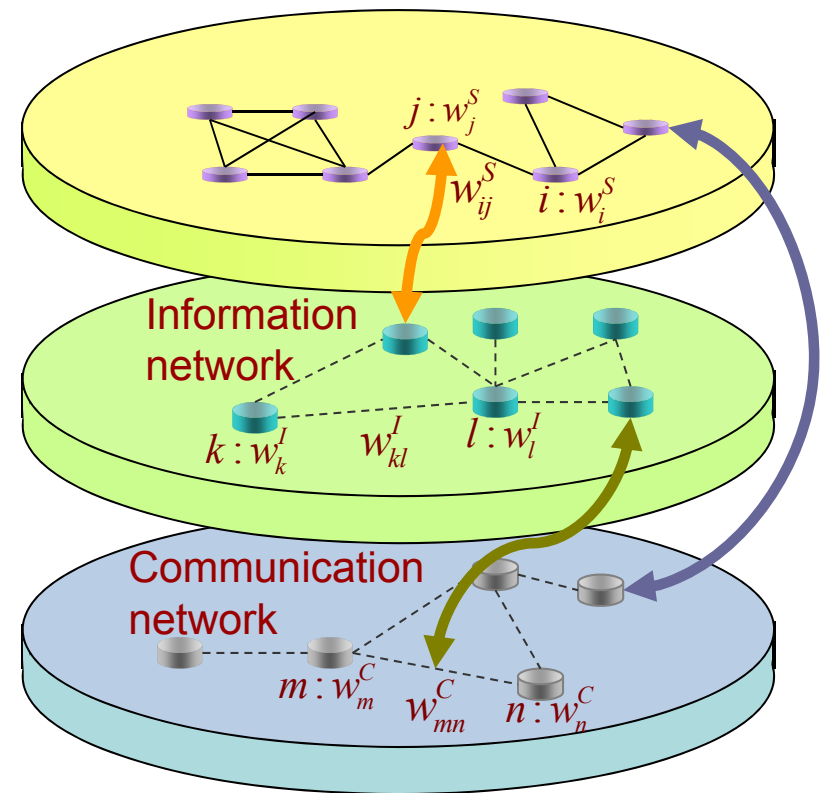
Networked System architecture & operation

Modularity vs Performance
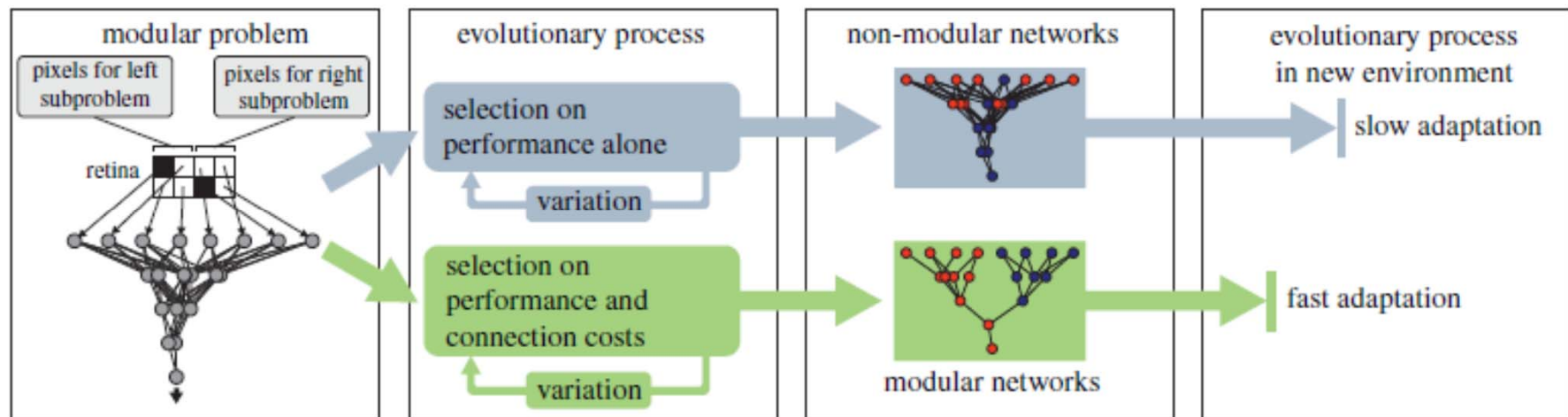
- **Optimize only on performance – poor adaptivity**
- **Add cost of communications – improved adaptivity**
- **Communication motifs**
- **Evolvable modularity for some CPS??**

Evolutionary Robotics:
from programmed structure to function
feedback on structure

Structural design & tuning

Predictions

Evolutionary robotics → Computational neurosciences → Experimental neuroscience

New building blocks

Experimental data

Autonomous robots

Brain models

Animal experiments

CPS Architectures: Observations
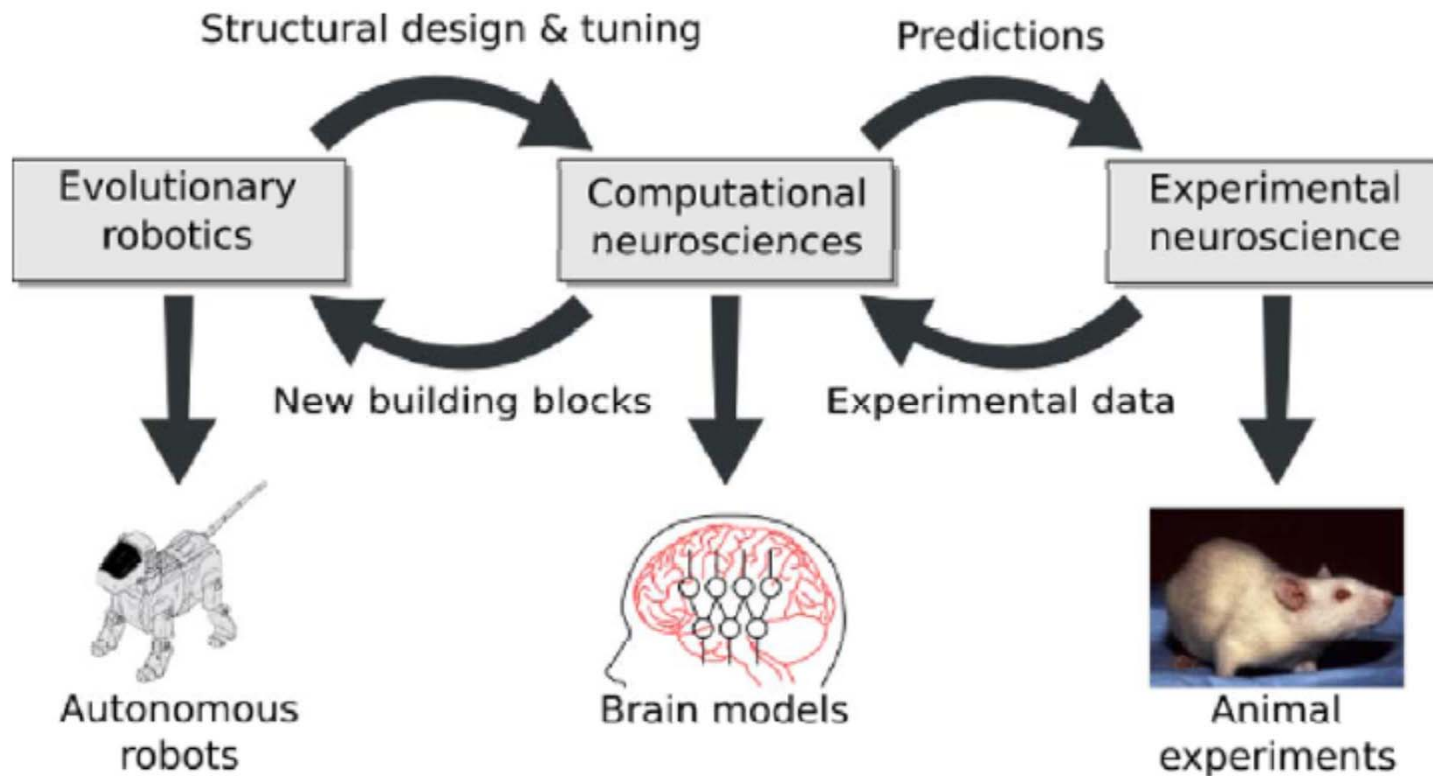
- Generically we have Architectures for …

- Properties that can drive architecture design and specification: safety, performance, security, system development time and cost

- We have used successfully some notional abstractions in the past: hardware vs software, source vs channel, plant-controller separation, separation of estimation and control. Are there analogs for CPS and networked CPS?

CPS Architectures: Observations/Research Topics

- **There will be classes (types) of CPS Architectures**

- **Various types of Architectures: Functional, Logical, Technical, Physical, Cyber**

- **Key notions: modularity, compositionality, composability, homogeneity, heterogeneity**

- **Must introduce formal and rigorous methods including formal requirements capture and analysis, layers of abstraction, formal verification, synthesis and optimization, formal verification**

- **Can we develop a taxonomy based on principles?**

- **Can we link types/classes to CPS domain ontologies?**

- **Are there Architectural Patterns?**

- **How to handle multiple domains: multiple physics, electrical, mechanical, control, communication, computing,…**

CPS Architectures:
Some Research Questions

1) Examples of physical system architectures strongly influenced by the physical laws of the components, including material and geometry laws and principles.

2) Examples of system cyber architectures where the physical layer and heterogeneous engineering components played a critical role.

3) Do we need specific architecture description languages for CPS?

4) What is the current state of the art in industry sectors like automotive, aerospace, power grids, where CPS thinking has already started?

5) Visions about some generic architectures set-up like the various planes in complex communication and computer networks. Is such a generic framework appropriate or even feasible for CPS? Is it possible to develop a taxonomy of CPS architectures? Examples?

CPS Architectures: Some Research Questions

6) There are pervasive cross-cutting concerns across classes of CPS, like security-resilience and robustness. How should these requirements be reflected in CPS architectures?

7) Is there a need for standards development as we work towards a taxonomy of CPS architectures? How important are such developments for interoperability and design of CPS?

8) What should the role and principles be of CPS architectures with respect to validation and   verification at the system level?

9) What is the role and principles for CPS architectures from the perspective of composability and compositionality?

10) CPS exist at various scales from macro to nano and even at multiple scales within the same system. What are the challenges for CPS architectures emanating from this multi-scale reality?

Thank you!

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Questions?