INTEGRATED CONTROL FOR CYBER PHYSICAL SYSTEMS A RESEARCH AGENDA

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Shonan Meeting No. 52 — Sep 7-10, 2015
Engineering Adaptive Software Systems

University of Victoria

CALL TO ACTION

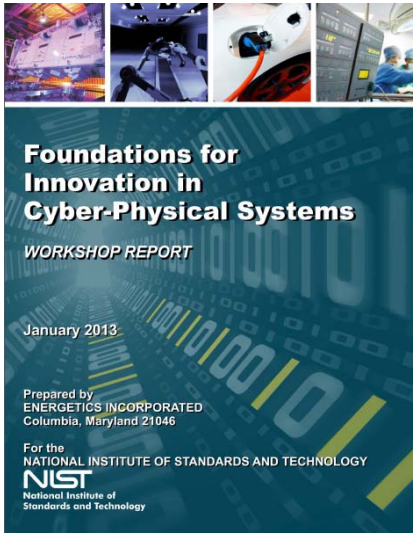
- Self-adaptive systems (SAS) researchers ought to drive the cyber physical systems research agenda
- CPS R&D affords spectacular and transformative opportunities
- As software engineering and SAS researcher be a leader, inject your expertise, and exploit these opportunities

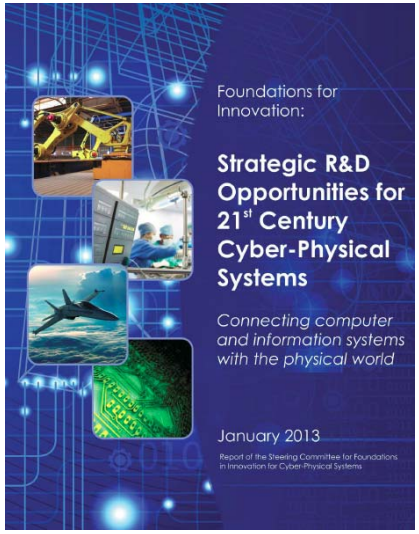
CPS SOCIETAL IMPACT

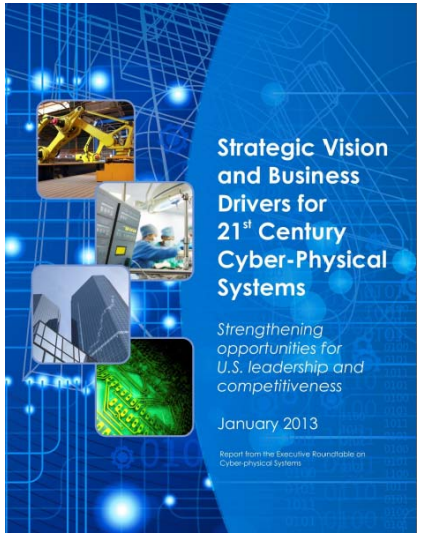
- Virtually every engineered system is affected by advances in the networked and cloud capabilities of CPS
- Future CPS applications are expected to be more transformative than the IT revolution of the past three decades
- Enormous funding opportunities
- CASCON Workshop on CPS Mylopoulos, Litoiu, Müller

NIST REPORTS ON CPS

- Distilled perspectives on CPS from experts from industry, academia and government
- Future CPS will sweeping impacts on how we live, work and do business







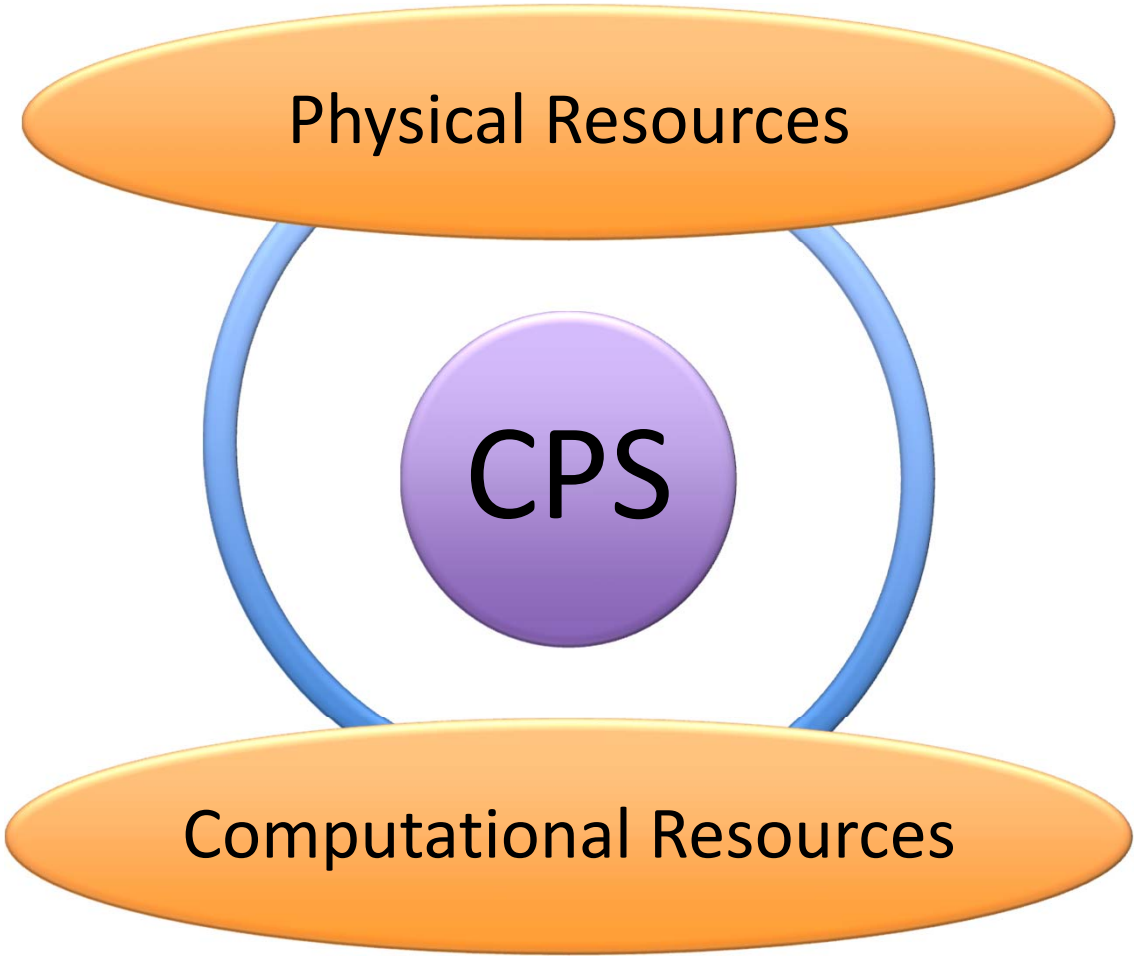
http://www.nist.gov/el/isd/cps-020613.cfm

CPS

- Smart systems that encompass computational and physical components, seamlessly integrated and closely interacting to sense the context of the real world
- Physical and engineered systems whose operations are **monitored, coordinated, controlled and integrated** by a computing, communication and control core
- Tight integration and coordination between computational and physical resources
- Add capabilities to physical systems
- Exceeds today's systems in adaptability, autonomy, efficiency, functionality, reliability, resiliency, safety and usability

CPS

Tight integration and coordination between computational and physical resources



CPS

Smart systems that encompass computational and physical components, seamlessly integrated and closely interacting to sense the context of the real world

CONFLUENCE OF SENSORS, NETWORKS, CLOUDS, DEVICES, AND APPS

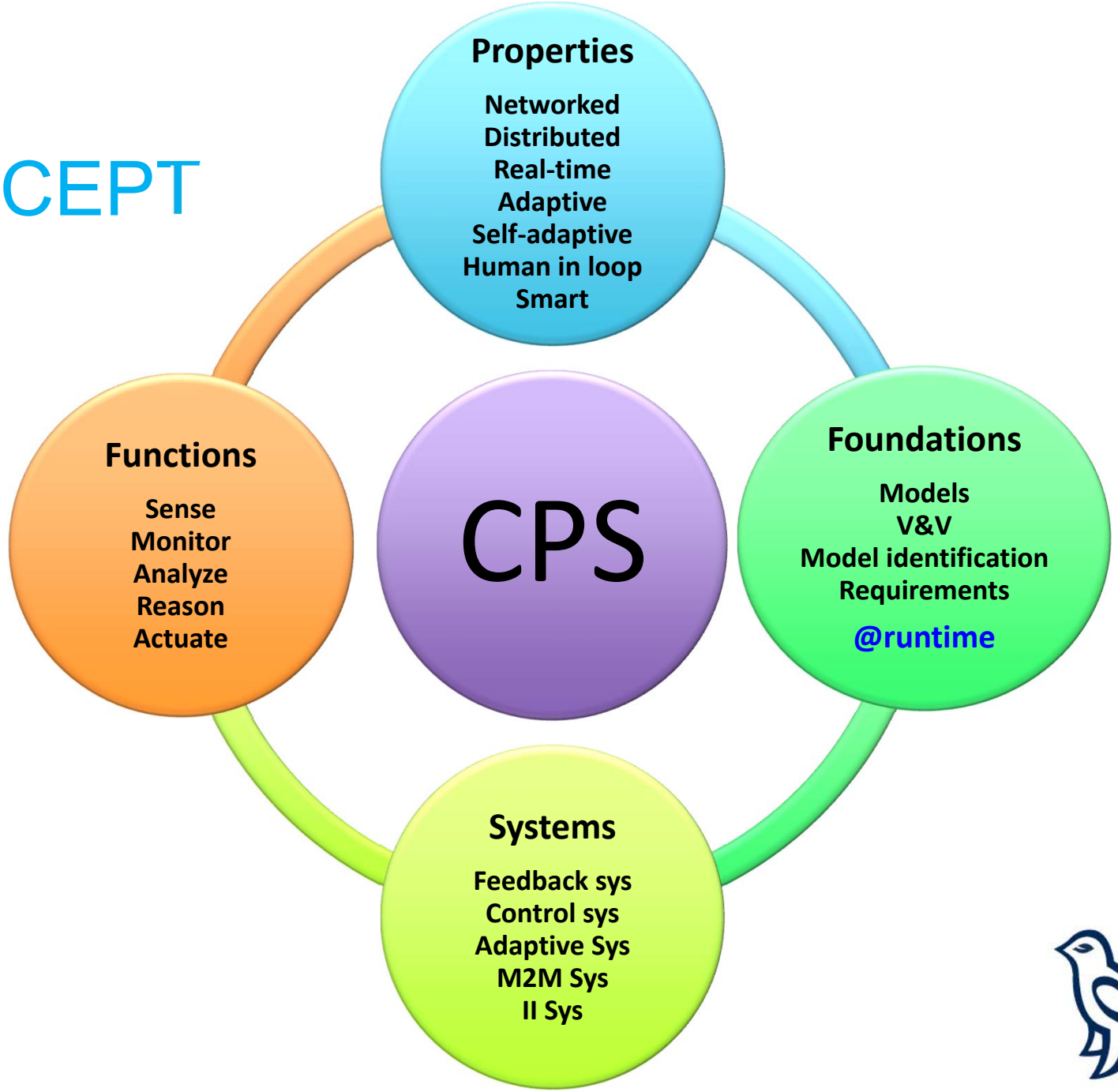
Convergence of analytical and cognitive capabilities, real-time and networked control, pervasive sensing and actuating, as well as compute and storage clouds

EXERCISE

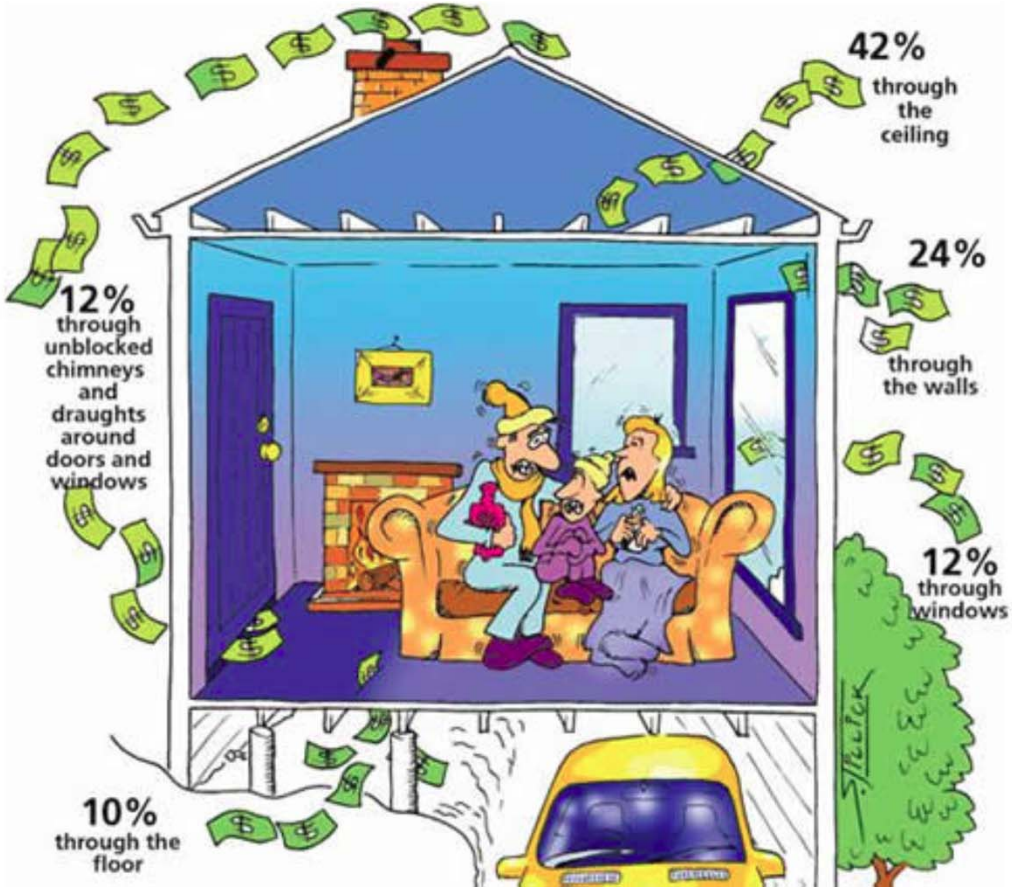
What is the difference between the CPS and IoT?

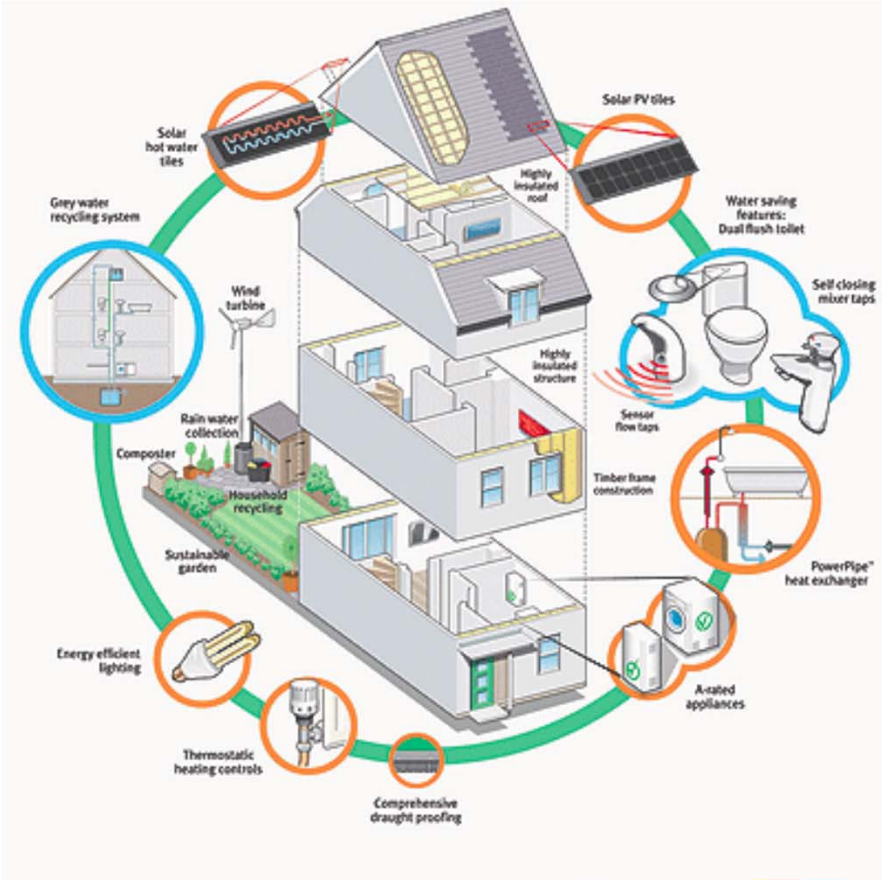
Convince each other that there is a difference.

CPS CONCEPT MAP

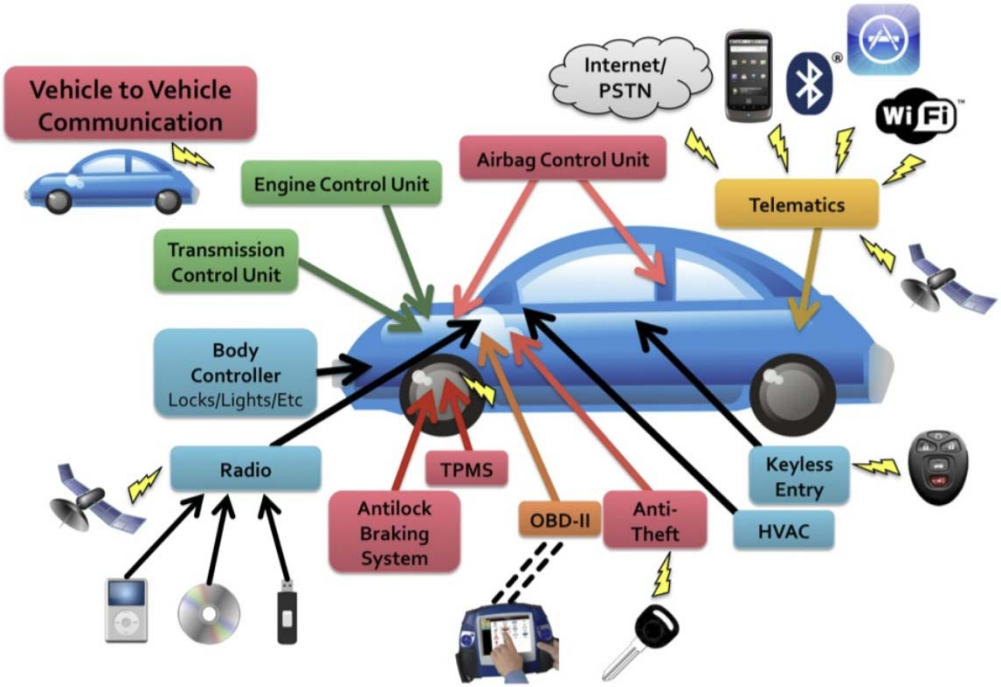


SMART BUILDINGS





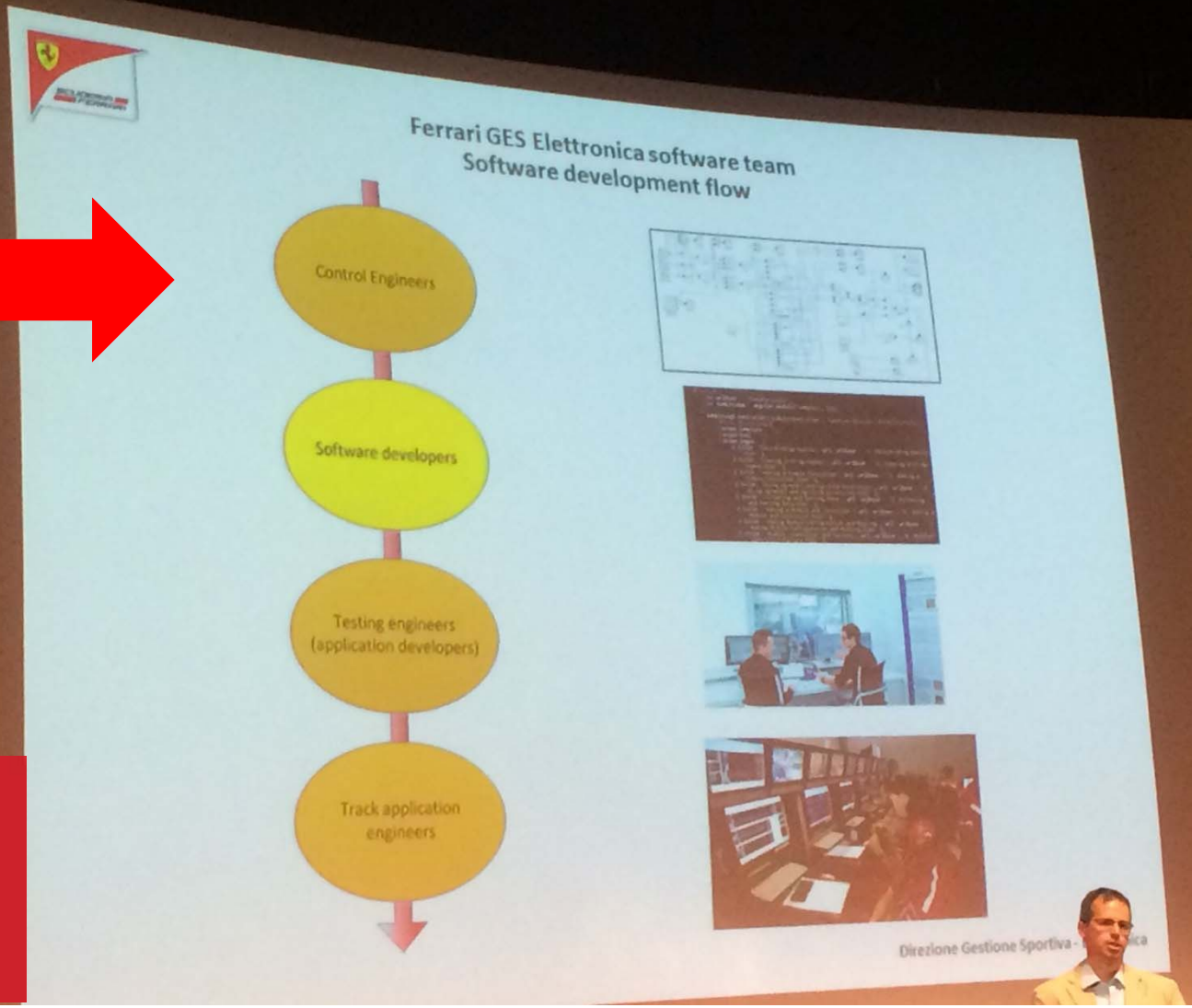
CONNECTED CARS



AUTONOMOUS VEHICLES

FERRARI KEYNOTE ICSE 2015

2015.icse-conferences.org/program/keynotes



CAN WE BUILD SUCH AMAZING CPS SYSTEMS?

MINDBOGGLING SITUATION AWARENESS

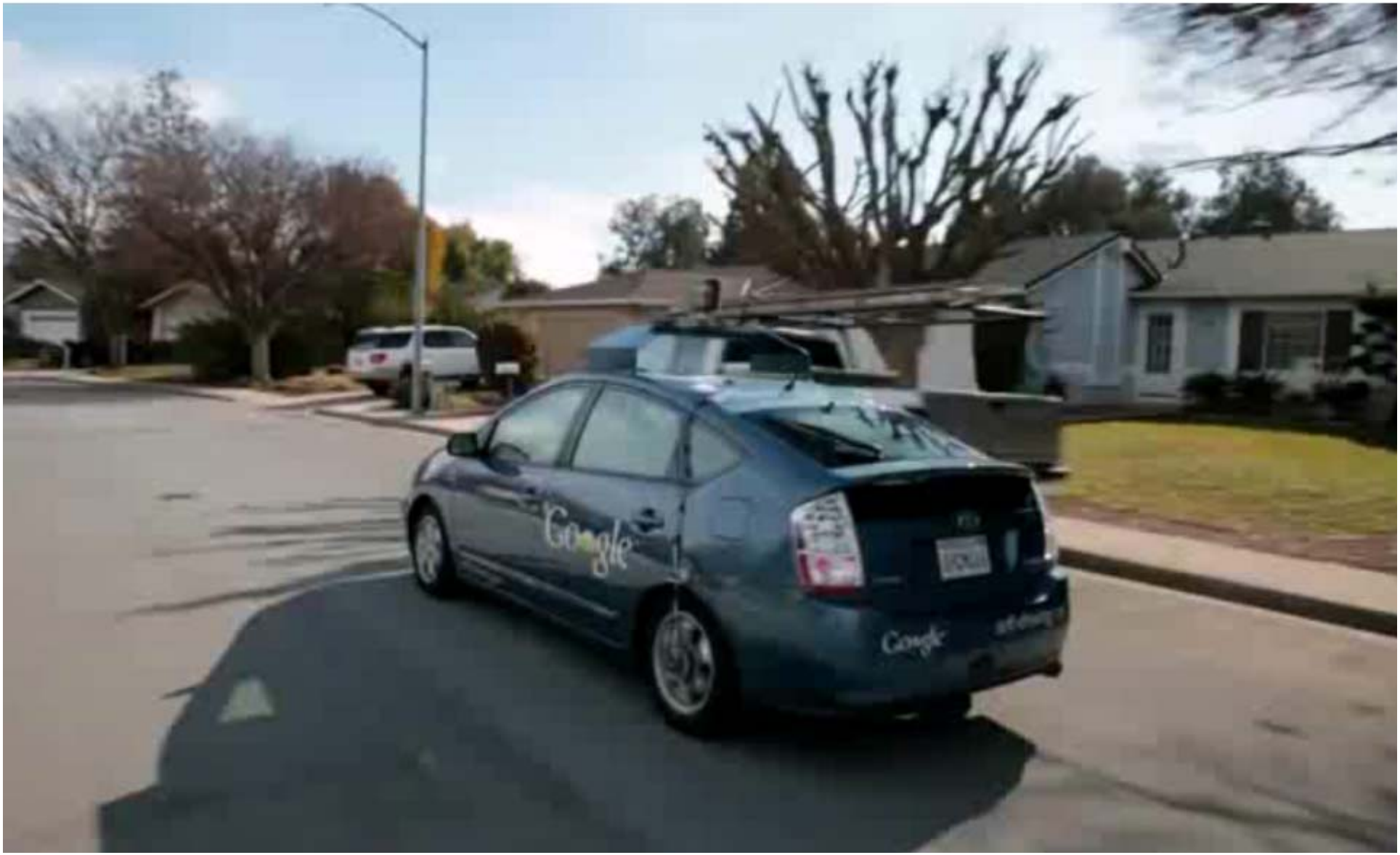
Tolyo, Japan

HUMANS ARE AMAZINGLY ADAPTIVE

Who thinks this experiment is possible right now?

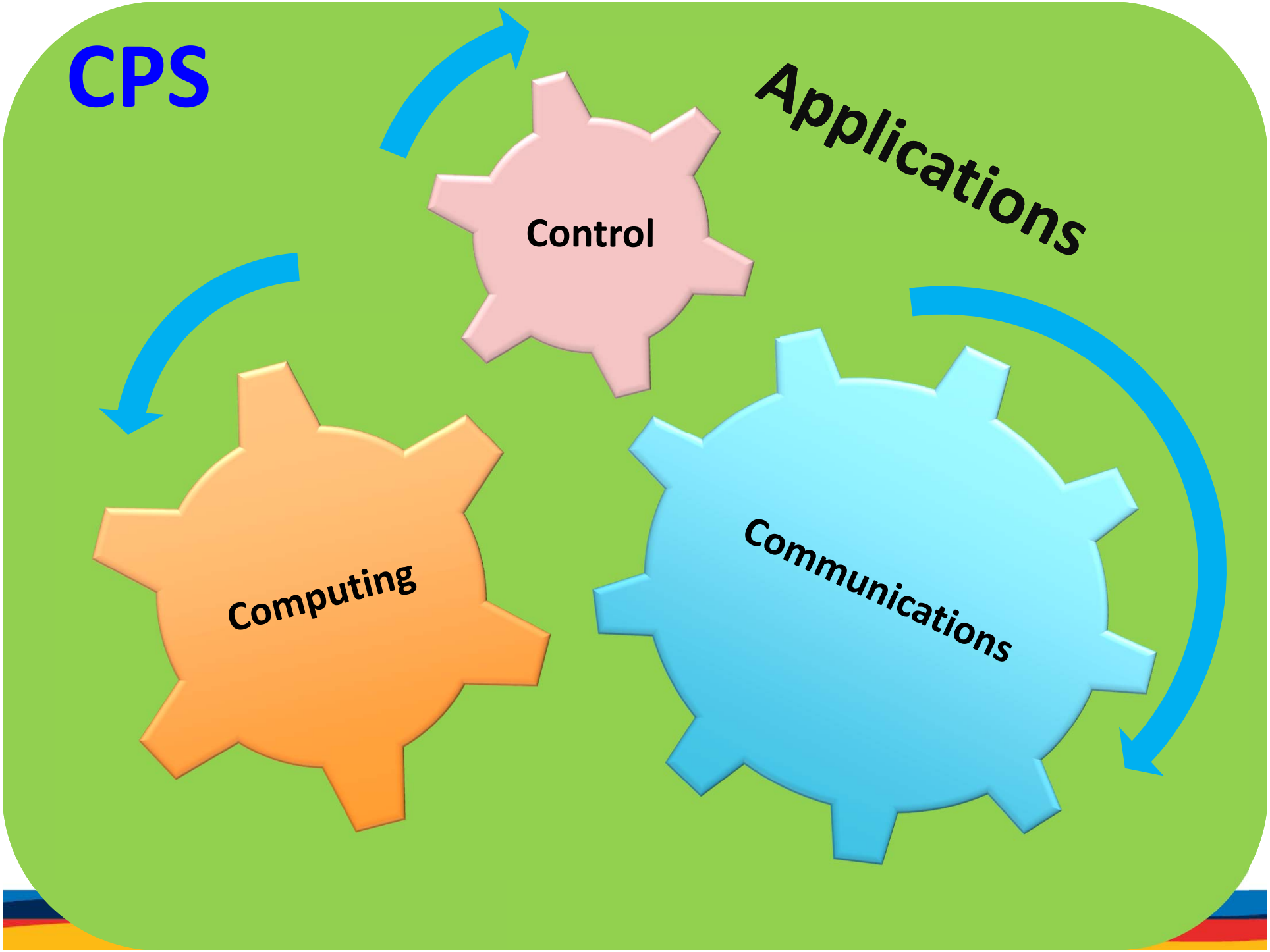
GOOGLE DRIVERLESS CAR — 2:07 MINS

LICENSED IN CALIFORNIA, NEVADA AND FLORIDA



CPS NURSE LOG

It is critical to educate engineers and scientists in cyber physical systems to reap the competitive advantages of developing and mastering advanced CPS.


CPS
Applications
Control
Computing
Communications

SELECTED CPS APPLICATIONS

Energy

Computing

Environment

Vehicles

CPS Foundations

Computing, Communications, Control

University of Victoria

SELECTED CPS APPLICATIONS

Energy

Computing

Environment

Vehicles

University of Victoria

SELECTED CPS APPLICATIONS

Energy	Computing	Environment	Vehicles
Smart Grid	Smart shopping and elderly web tasking	Smart Ocean	UAVs
Smart Buildings	Digital Ecosystems	Tidal Energy	Connected Cars
Green Computing	Wearable Computers	Smart water	Smart Transport

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SELECTED CPS FOUNDATIONS

- Adaptive Systems and MART
- Cloud Computing and Cyber Security
- Analytics and Machine Learning

Computing

- Wireless and Mobile Networks
- Wireless Sensor Networks (WSN)
- Software Defined Networks (SDN)

Communications

- Networked and Distributed Control
- Model Adaptive and Predictive Control
- Autonomic Computing

Control

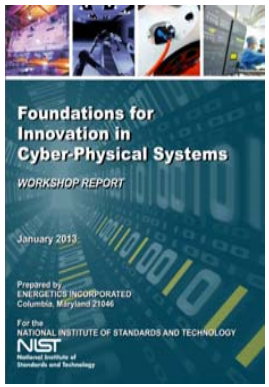
University of Victoria

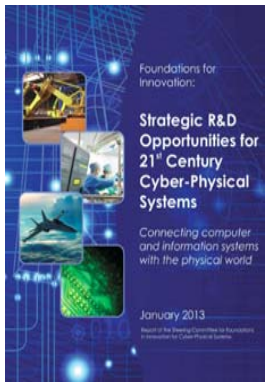
EXERCISE

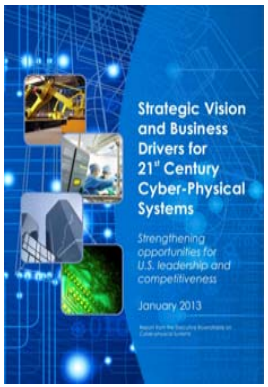
- Why is it so important to educate engineers and scientists in the foundations of CPS?

CONTROL AND SYSTEMS SCIENCE FOR CPS

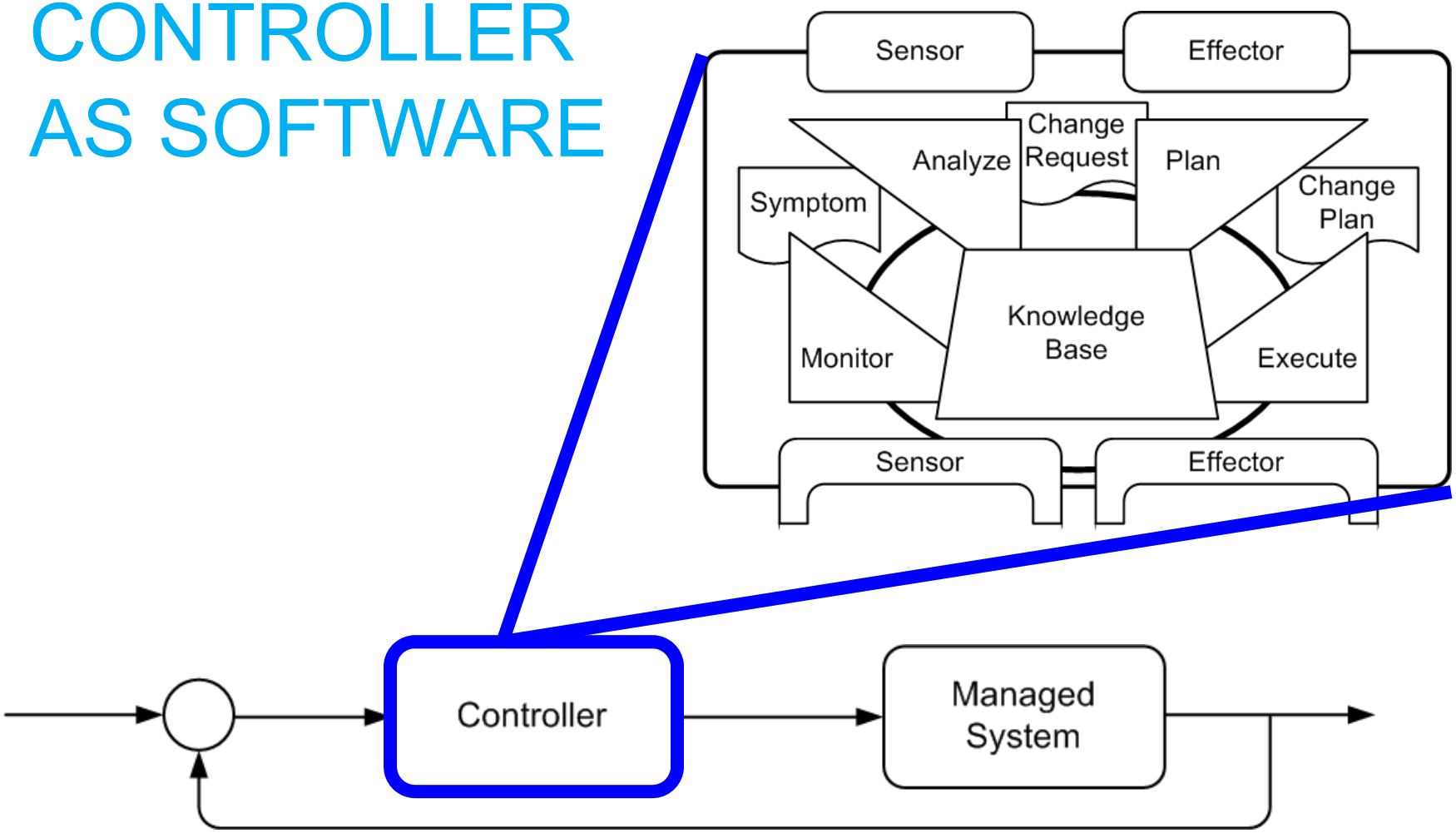
- Abstraction infrastructure to bridge digital and physical system components
  - Integrated and networked control
  - Adaptive and predictive control
  - Composition of control
  - Reference models
- Characterizing problems & guaranteeing solution quality
  - Utility function policies and optimization
  - Uncertainty characterization and quantification
- Assurance at runtime
  - Models at runtime
  - V&V at runtime





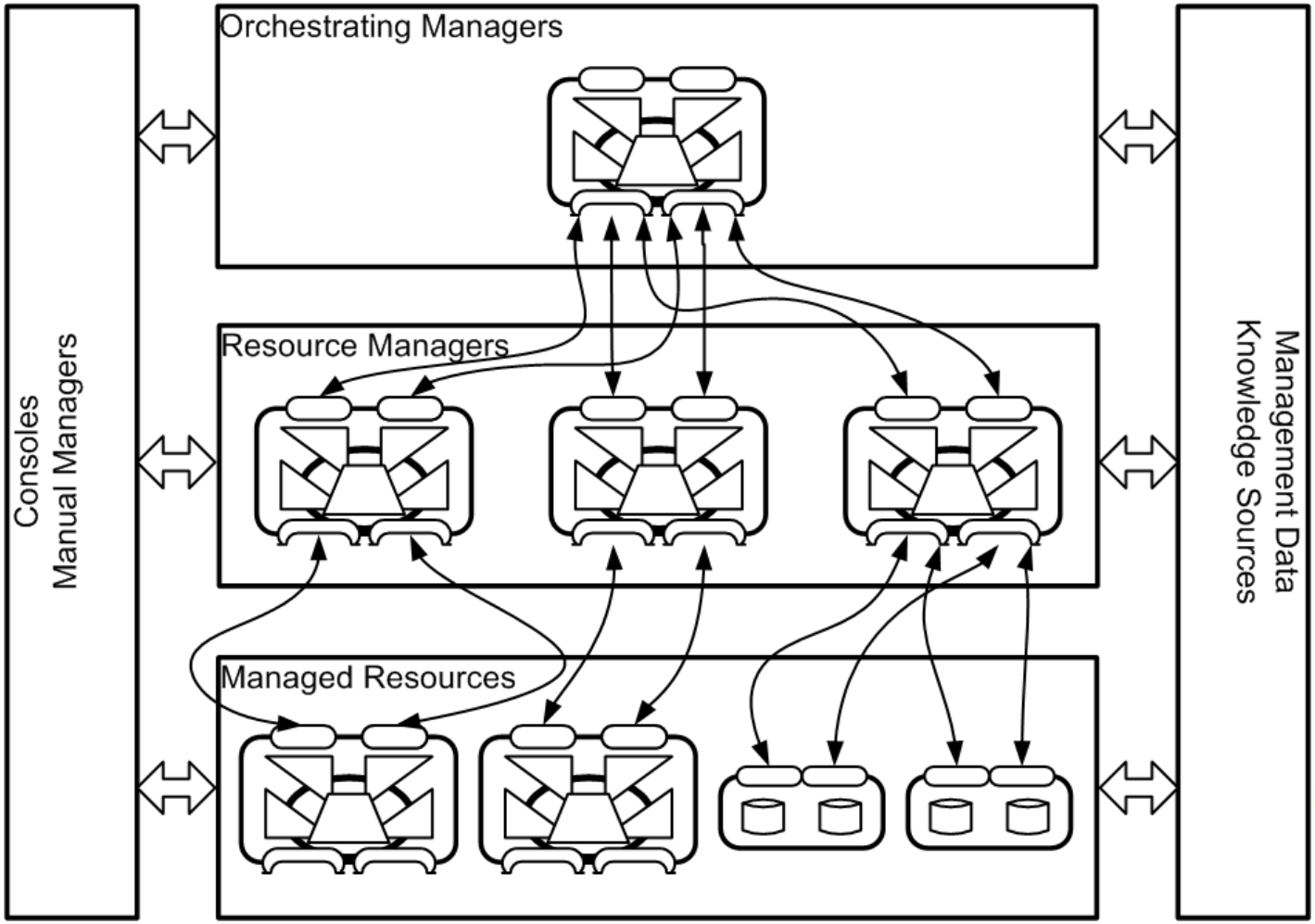


CONTROLLER AS SOFTWARE



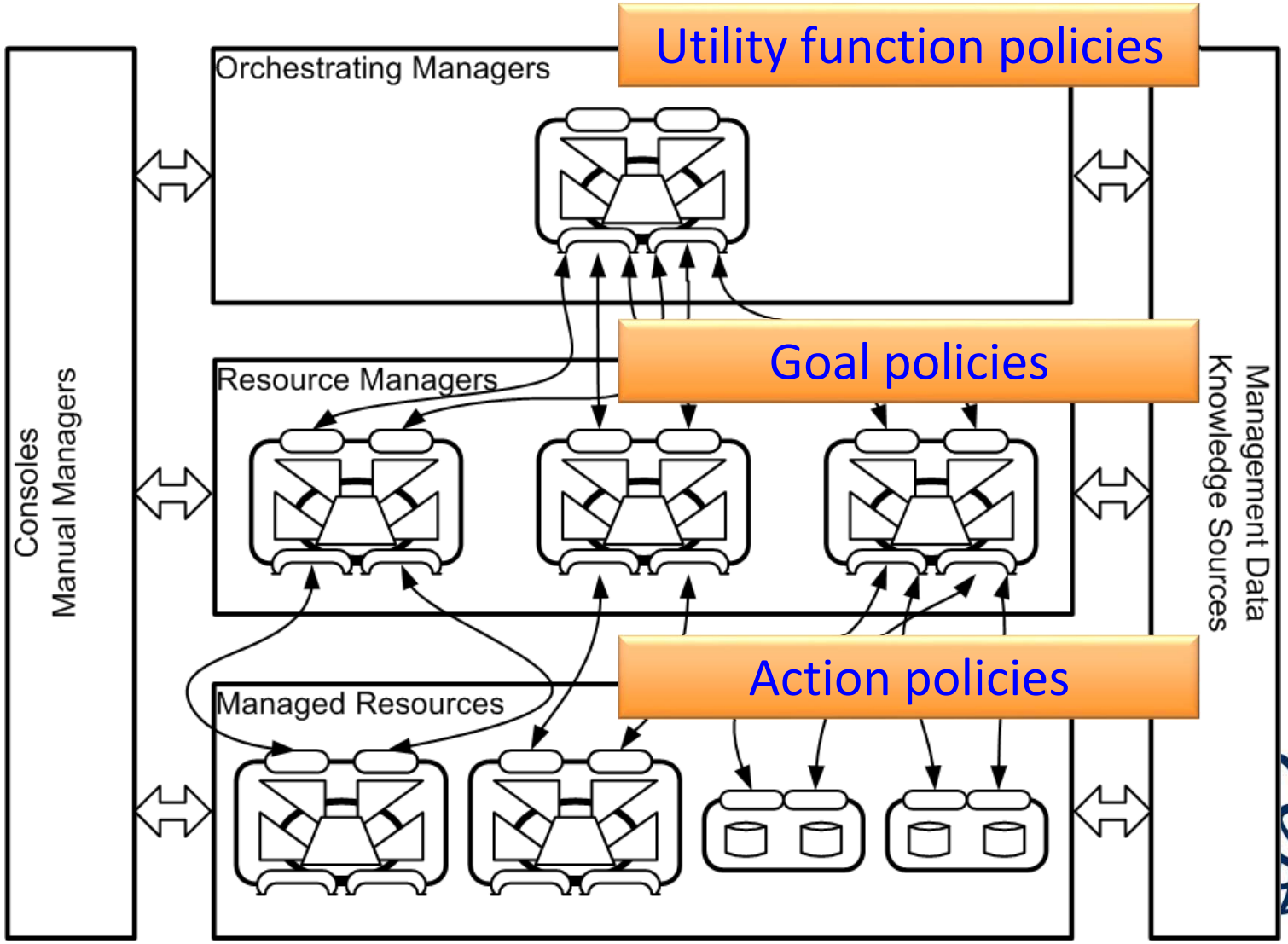
ACRA

AUTONOMIC COMPUTING REFERENCE ARCHITECTURE



AUTONOMIC COMPUTING REFERENCE ARCHITECTURE (ACRA)

HIERARCHY OF CONTROLLERS



POLICY TYPES FOR CPS

- Action policies
  - **If-then action rules** specify exactly what to do under a condition
  - Rational behaviour is compiled in by the designer
  - Basis for reflex agents
- Goal policies
  - Requires self-model, planning, conceptual knowledge representation
- Utility function policies
  - It chooses the actions to maximize its utility function
  - Finer distinction between desriability of different states than goals
  - Numerical characterization of state
  - Needs methods to carry out actions to optimize utility

CPS systems embody a combination of policy types.

UTILITY THEORY

- Utility theory with service level agreements
- One cost objective function
- Optimization

John Wilkes, HP Labs
Utility functions, prices, and negotiation
HP Tech Report and Slides, 2008.

John Wilkes, Google
formerly HO Labs

ADAPTIVE CONTROL

- Adaptive control is the idea of “redesigning” the controller while online, by
  - looking at its performance and
  - changing its dynamic in an automatic way
- Motivated by aircraft autopilot design
  - Allow the system to account for previously unknown dynamics
- Adaptive control uses feedback to observe the process and the performance of the controller and reshapes the controller closed loop behavior autonomously.

ADAPTIVE CONTROL

- Modify the control law to cope by changing system parameters while the system is running
- Different from Robust Control in the sense that it does not need *a priori* information about the uncertainties
  - Robust Control includes the bounds of uncertainties in the design of the control law.
  - Therefore, if the system changes are within the bounds, the control law needs no modification

CHARACTERISTICS OF THREE-TIER HIERARCHICAL INTELLIGENT CONTROL SYSTEMS

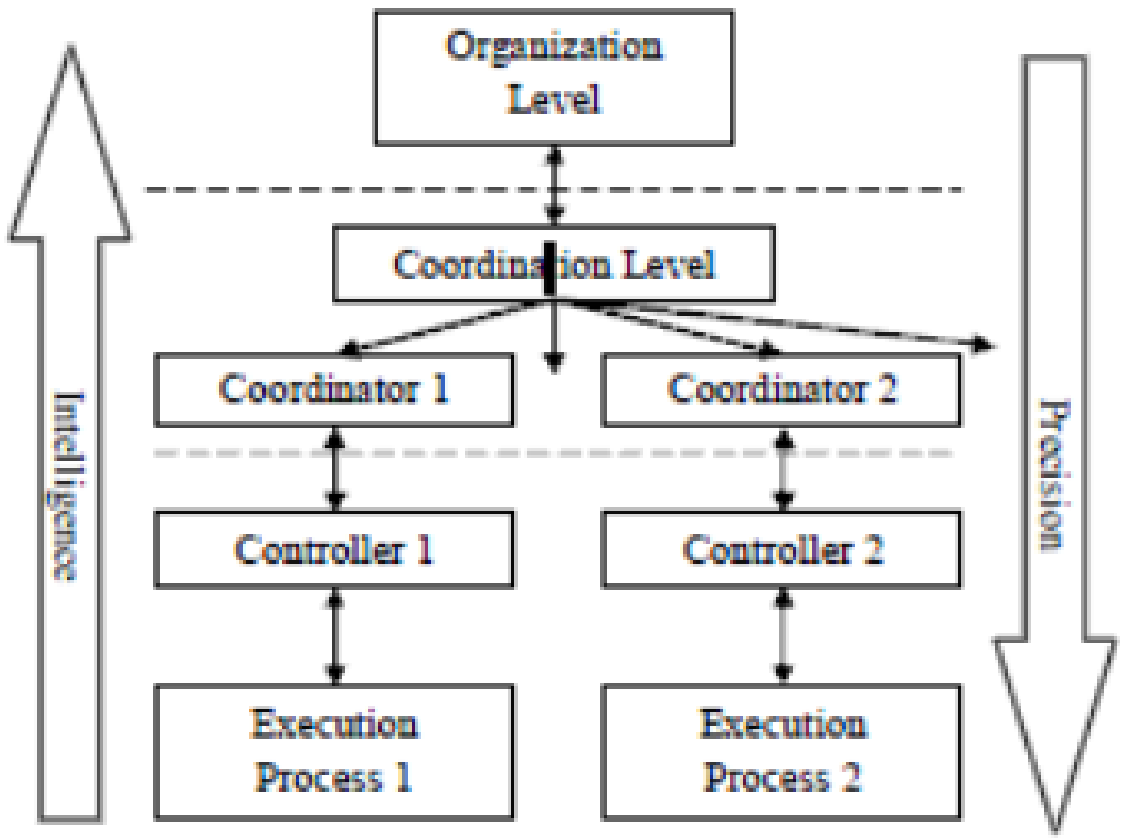
- The three-tier architecture is prevalent
  - service-oriented software systems
  - automation systems
  - decision-support systems
  - many other types of adaptive and self-managing systems
- Three layers
  - separate concerns (e.g., three-tier web architecture where the presentation and data tiers are separated by an application or business logic tier)
  - Impose a hierarchy along a dimension where such a dimension represents an extra-functional requirement or quality criterion as outlined
    - performance, internal state, goals, policies, plan sophistication, “intelligence”, or quality of service
  - The scales depend on the actual requirement or criterion of the dimension
    - from specific goals to general goals
    - from high precision to low precision
    - from fast performance to slow performance
    - from stateless to memory of the past and predictions of the future
    - from hard-wired policies to utility-function policies (i.e., trade-off analysis)
  - Rationale for three tiers is usually not explicitly stated, but frequently a natural fit

HIERARCHICAL INTELLIGENT CONTROL

- AI and robotics communities generated several closely related three-layer reference control architectures:
  - R. A. Brooks: A Robust Layered Control System for a Mobile Robot, *IEEE Journal on Robotics and Automation* RA-2(1), March 1986.
  - R.J. Firby: *Adaptive Execution in Dynamic Domains,* PhD Thesis, TR YALEU/CSD/RR#672, Yale University, 1989.
  - E. Gat: *Reliable Goal-directed Reactive Control for Real-world Autonomous Mobile Robots,* Ph.D. Thesis, Virginia Polytechnic Institute and State University, Blacksburg, Virginia, 1991.
  - E. Gat: Three-layer Architectures, Artificial Intelligence and Mobile Robots, MIT/AAAI Press, 1997.
  - T. Shibata & T. Fukuda: Hierarchical Intelligent Control for Robotic Motion, *IEEE Trans. On Neural Networks* 5(5): 823-832, 1994.

HIERARCHICAL INTELLIGENT CONTROL SYSTEM (HICS) ARCHITECTURE

1986-94

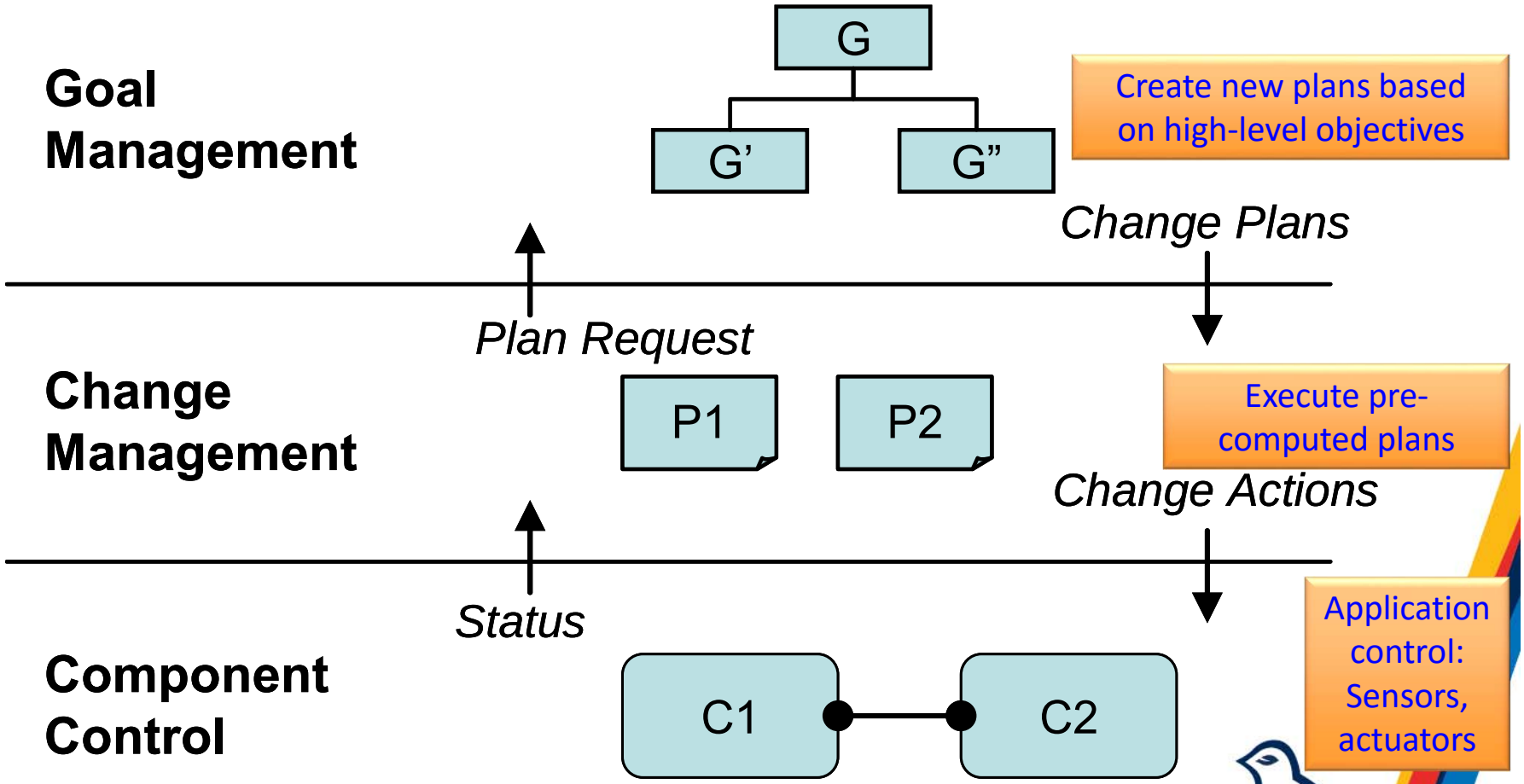


T. Shibata & T. Fukuda: Hierarchical Intelligent Control for Robotic Motion, *IEEE Trans. On Neural Networks* 5(5): 823-832, 1994

HICS ARCHITECTURE

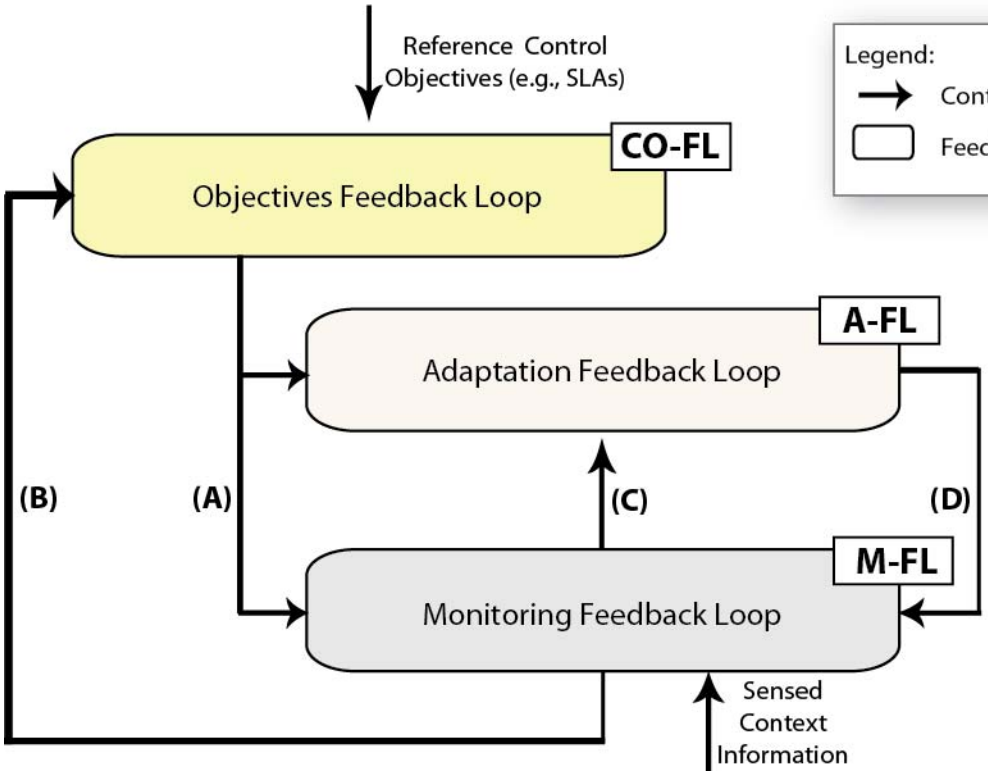
- Hierarchical Intelligent Control System (HICS)
- HICS is probably the most general reference architecture emerging from AI and robotics
- Three HICS layers (from bottom to top)
  - Execution
  - Coordination
  - Organization Level
- The complexity of reasoning (i.e., intelligence) increases from the execution to the organization level
- The flexibility of policies decreases from organization to execution (i.e., the precision of increases).

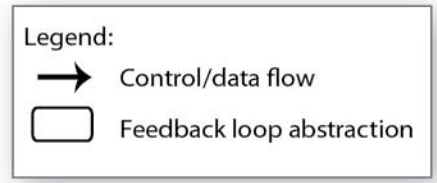
ROBOTICS INSPIRED THREE-LAYER ARCHITECTURE MODEL



Kramer, Magee: Self-Managed Systems—An Architectural Challenge, Future of Software Engineering (FoSE 2007), ICSE 2007.

The DYNAMICO Reference Model





Q3: How to maintain context-awareness?

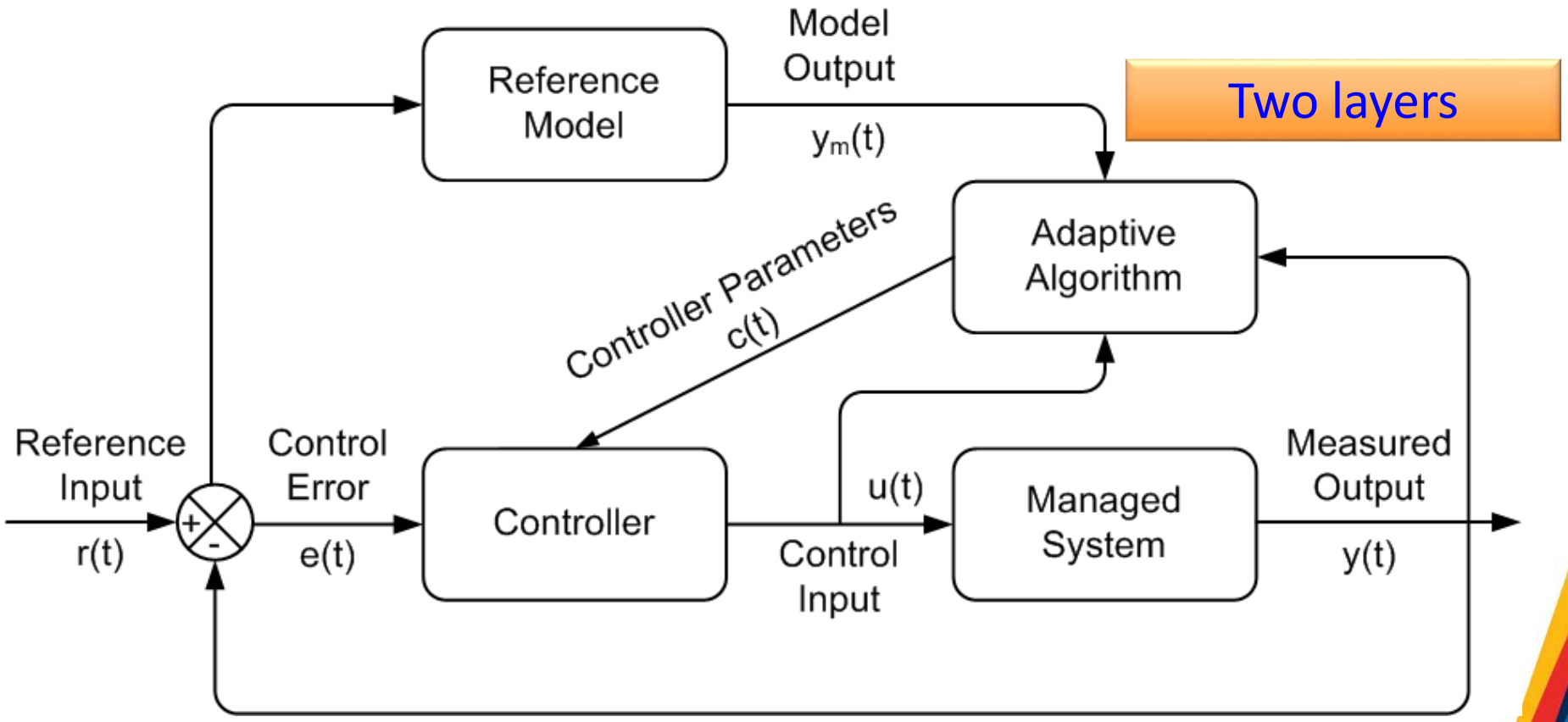
Q4: How to apply dynamic monitoring to runtime V&V?

- Guides the design of highly dynamic self-adaptation mechanisms
- Manages uncertainty due to changing requirements
- Preserves context-awareness in self-adaptation

Villegas, Tamura, Müller, *et al.*: *DYNAMICO: A Reference Model for Governing Control Objectives and Context Relevance in Self-Adaptive Software Systems* (Springer 2013)

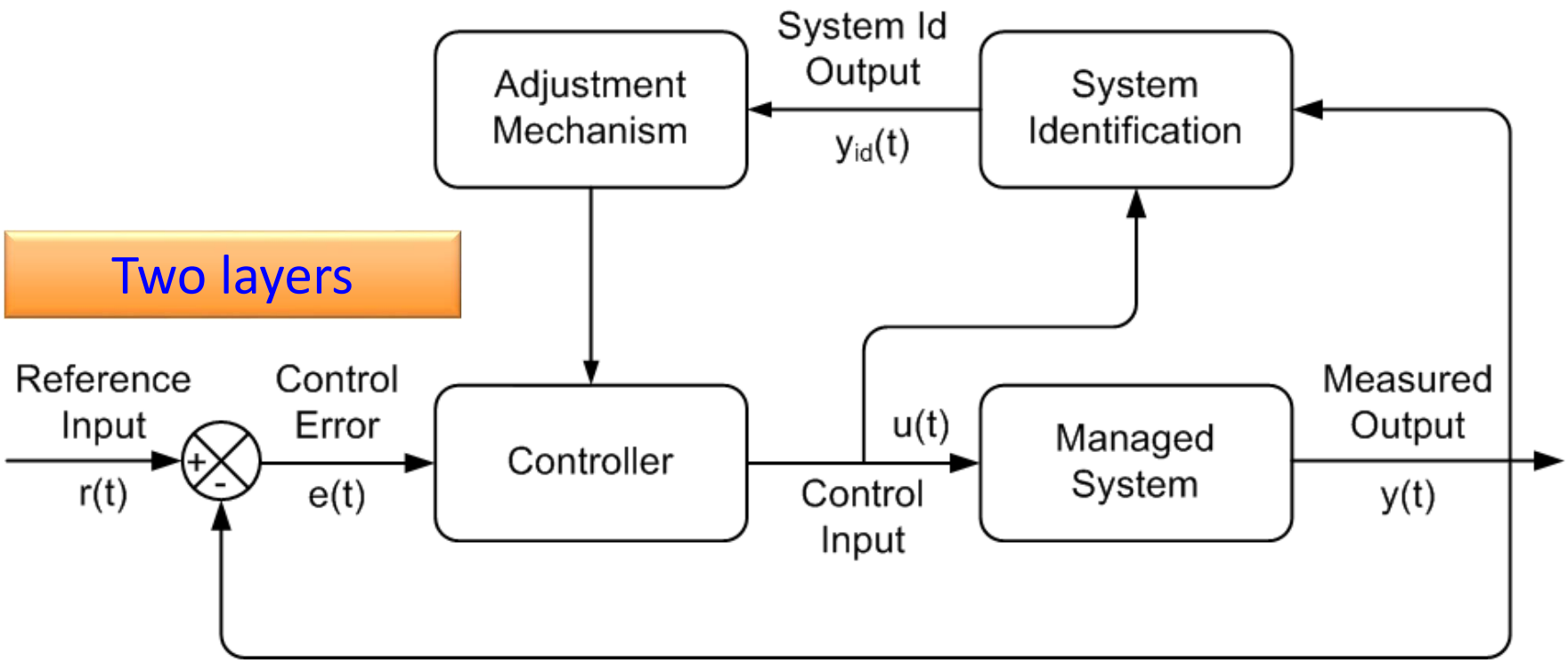
ADAPTIVE CONTROL—MRAC

MODEL REFERENCE ADAPTIVE CONTROL



ADAPTIVE CONTROL—MIAC

MODEL IDENTIFICATION ADAPTIVE CONTROL



Two layers

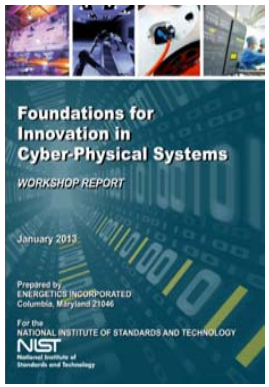
Müller and Villegas: Runtime evolution of highly dynamic software, in Evolving Software Systems, Mens, et el. Springer, pp. 229-264 (2014)

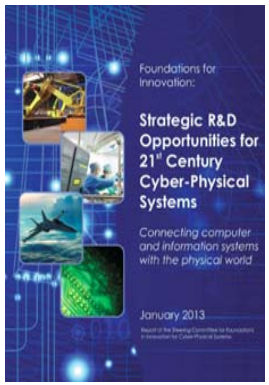
MODEL PREDICTIVE CONTROL (MPC)

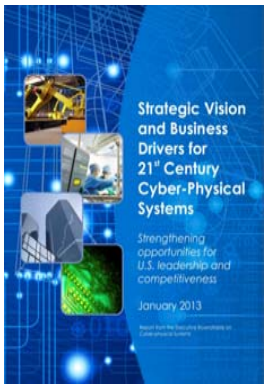
- Two-level controllers like controllers for adaptive control
- Model predictive controllers rely on dynamic models of the managed system
- Most often linear empirical models obtained by system identification
- The main advantage of MPC is the fact that it allows the current timeslot to be optimized, while taking future time slots into account
- Optimize a finite time-horizon, but only realize the current timeslot
- MPC has the ability to anticipate future events and can take control actions accordingly
- Generic PID controllers do not have predictive abilities

CONTROL AND SYSTEMS SCIENCE FOR CPS

- Abstraction infrastructure to bridge digital and physical system components
  - Integrated and networked control
  - Adaptive and predictive control
  - Composition of control
  - Reference models
- Characterizing problems & guaranteeing solution quality
  - Utility function policies and optimization
  - Uncertainty characterization and quantification
- Assurance at runtime
  - Models at runtime
  - V&V at runtime



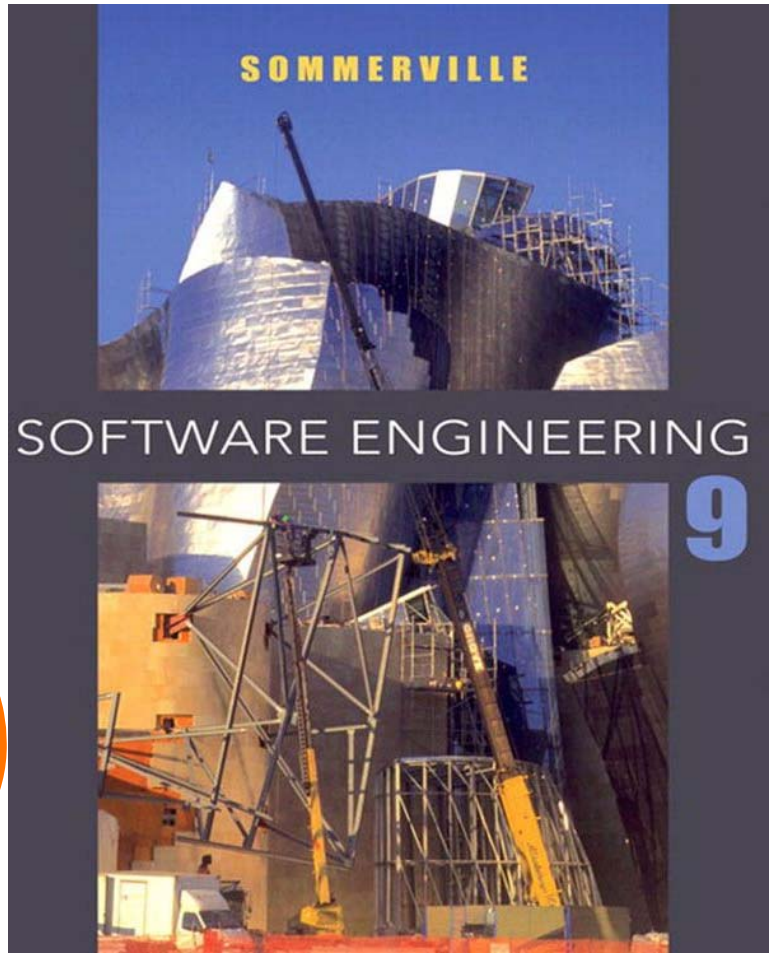




HOW SHOULD WE TEACH THE CONCEPTS OF HIGHLY DYNAMICAL SOFTWARE SYSTEMS IN THE AGE OF CONTEXT?

How do we integrate these topics into computing science and software engineering curricula?

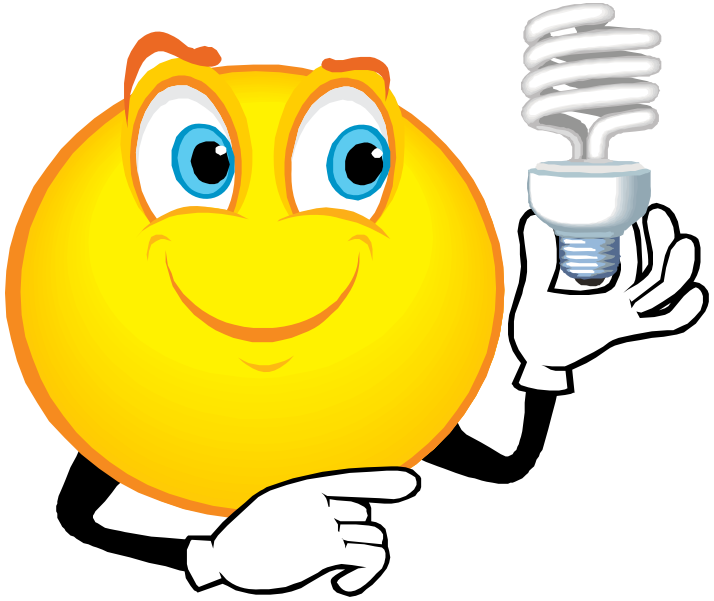
IAN SOMMERVILLE SOFTWARE ENGINEERING 9TH EDITION 2010



Contents at a Glance

We need a new discipline

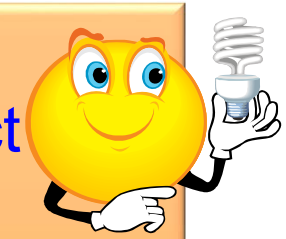
SOFTWARE ENGINEERING @ RUNTIME



SOFTWARE ENGINEERING @ RUNTIME

- Requirements@runtime
- Models@runtime
- Monitoring@runtime
- V&V@runtime
- Adaptation@runtime
- Analysis@runtime
- CM@runtime
- Assurance@runtime

- Profound impact on SE and CS
- Rethink software design and evolution for highly adaptive software systems
- Feedback loops and control theory are key



Boundary between development-time and run-time is disappearing

Baresi, Ghezzi: The disappearing boundary between development-time and run-time.
In: *FSE/SDP Workshop on Future of Software Engineering Research (FoSER 2010)*, pp. 17-22 (2010)

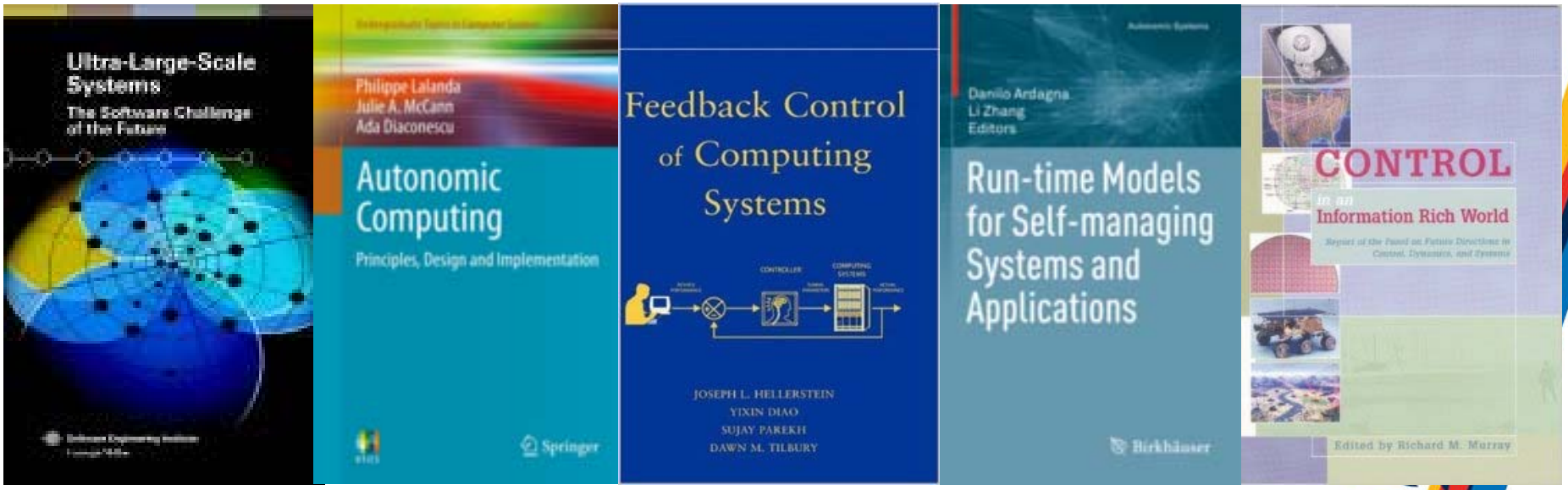
EXERCISE

Convince each other why software engineers and computer scientists should take a course in control theory?

CONTROL SCIENCE

Control science can be defined
as a systematic way to study certifiable
V&V methods and tools to allow humans to
trust decisions made by self-adaptive smart systems.

BOOKS TO PROBE FURTHER



BOOKS THAT PROFOUNDLY INFLUENCED US

- Villegas: Context Management and Self-Adaptivity for Situation-Aware Smart Software Systems, PhD Thesis, University of Victoria 327 pages, (2013) http://dspace.library.uvic.ca/bitstream/handle/1828/4476/Villegas_Norha_PhD_2013.pdf?sequence=6&isAllowed=y
- de Lemos, Giese, Müller, Shaw (Eds.): Software Engineering for Self-Adaptive Systems II, LNCS 7475, Springer (2013) http://link.springer.com/book/10.1007/978-3-642-35813-5/page/1#
- Cheng, de Lemos, Inverardi, Magee (Eds.): Software Engineering for Self-Adaptive Systems, LNCS 5525, Springer (2009) http://link.springer.com/computer/swe/book/978-3-642-02160-2
- Bencomo, France, Cheng, Assmann (Eds.): Models@run.time, LNCS 8378, Springer, pp. 101-136 (2014) http://www.springer.com/us/book/9783319089140

- Villegas: Context Management and Self-Adaptivity for Situation-Aware Smart Software Systems, PhD Thesis, University of Victoria 327 pages, (2013) http://dspace.library.uvic.ca/bitstream/handle/1828/4476/Villegas_Norha_PhD_2013.pdf?sequence=6&isAllowed=y

- Chignell, Cordy, Kealey, Ng, Yesha (Eds.): The Personal Web: A Research Agenda, LNCS 7855, Springer, pp. 151-184 (2013) http://www.springer.com/us/book/9783642165986
- Northrop, et al.: Ultra-Large-Scale Systems. The Software Challenge of the Future. Technical Report, Carnegie Mellon Software Engineering Institute, 134 pages ISBN 0-9786956-0-7 (2006) http://www.sei.cmu.edu/uls
- Hellerstein, Diao, Parekh, Tilbury: Feedback Control of Computing Systems. John Wiley & Sons (2004) http://books.google.ca/books
- Ardagna et al. (Eds.): Run-time Models for Self-managing Systems and Applications, Springer (2010) http://www.springer.com/us/book/9783034604321
- LaLanda et al.: Autonomic Computing: Principles, Design & Implementation, Springer (2013) http://www.springer.com/us/book/9781447150060
- Janert: Feedback Control for Computer Systems, O' Reilly (2014) http://shop.oreilly.com/product/0636920028970.do
- Murray: Control in an Information Rich World: Report Panel on Future Directions in Control, Dynamics, and Systems. SIAM 2003. http://www.cds.caltech.edu/~murray/cdspanel/report/cdspanel-15aug02.pdf

CPS PAPERS

- NIST Cyber-Physical Systems Program: http://www.nist.gov/cps/
- New Reports Define Strategic Vision, Propose R&D Priorities for Future Cyber-Physical Systems, NIST Tech Beat, (2013) http://www.nist.gov/el/isd/cps-020613.cfm
- Sztipanovits, Ying, et al.: Foundations for Innovation: Strategic R&D Opportunities for the 21th Century Cyber-Physical Systems, National Institute of Standards and Technology (NIST), 32 pages (2013) http://www.nist.gov/el/upload/12-Cyber-Physical-Systems020113_final.pdf
- Sztipanovits, Ying, et al.: Foundations for Innovation in Cyber-Physical Systems (2013) http://www.nist.gov/el/upload/CPS-WorkshopReport-1-30-13-Final.pdf
- Stojmenovic: Machine-to-Machine Communications With In-Network Data Aggregation, Processing, and Actuation for Large-Scale Cyber-Physical Systems, IEEE Internet of Things Journal, Vol. 1, No. 2 (2014) http://ieeexplore.ieee.org/xpl/articleDetails.jsp?arnumber=6766661

IOT PAPERS

- Schmidt, Cohen: The New Digital Age: Transforming Nations, Businesses, and Our Lives, Vintage Books (2014) https://play.google.com/store/books/details/Eric_Schmidt_The_New_Digital_Age?id=FI_LPoLdGKsC&hl=en
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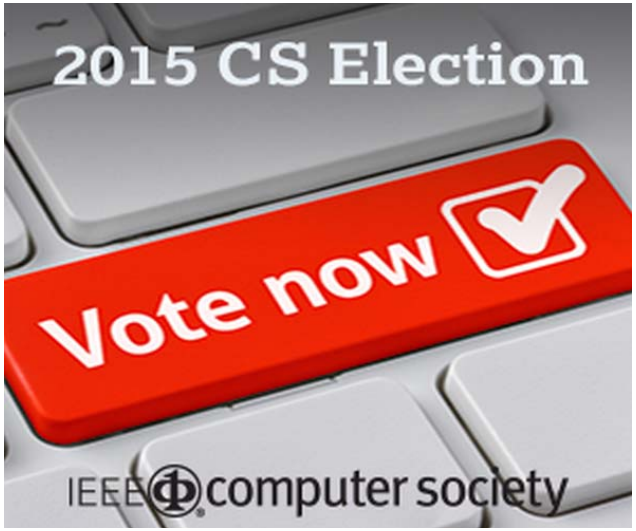
IEEE COMPUTER SOCIETY ELECTIONS

IEEE Computer Society Board of Governors Election

- http://www.computer.org/web/volunteers/bog/
- Hausi Müller is running for 1st Vice President of IEEE Computer Society



IEEE CS TCSE Election

- Marin Litoiu is running for TCSE Chair

ありがとうございます
Thank you

TAKE HOME MESSAGES

- Take on a leadership role in CPS research

- Software engineering at runtime
- Control and systems science for CPS
- Hierarchical and networked control
- Assurance at runtime

- Vote for Marin and Hausi in IEEE CS Elections

ありがとうございます
Thank you