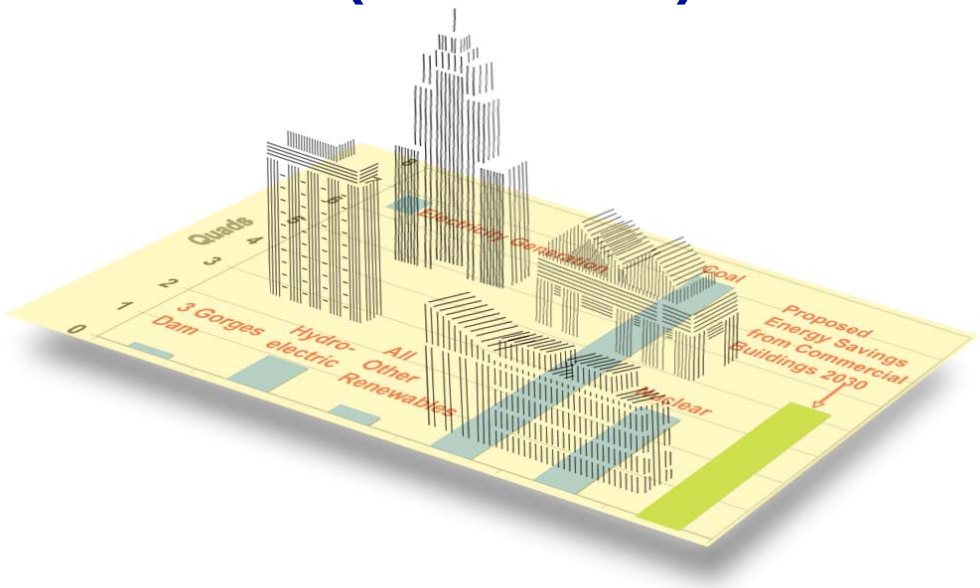
High Performance Buildings Research & Implementation Center (HiPer BRIC)



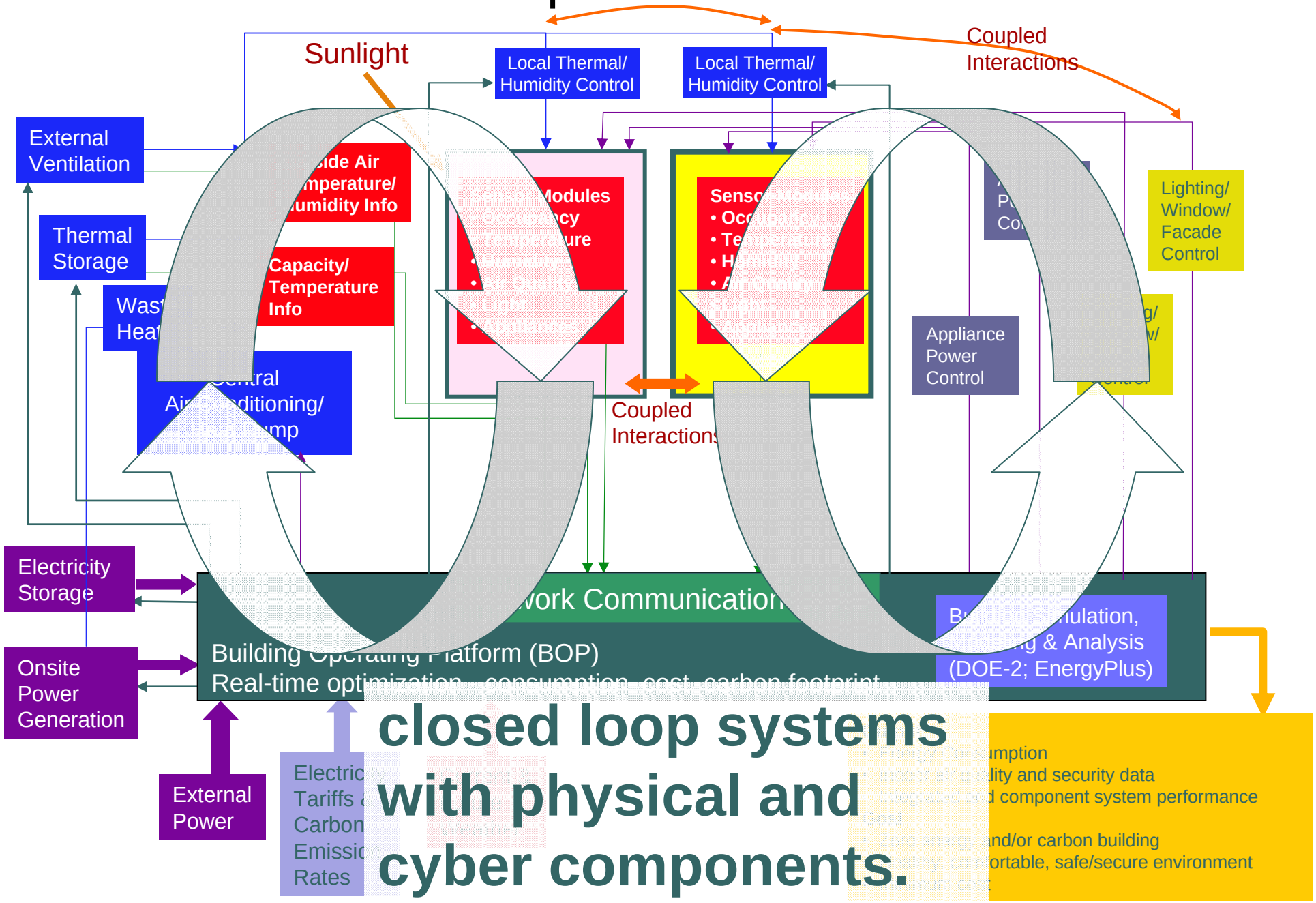
Cyber-Physical Infrastructure Systems for Buildings

Edward A. Lee
Professor, Chair of EECS
Robert S. Pepper Distinguished Professor

UC Berkeley

December 21, 2007

Recall Technical Scope



closed loop systems with physical and cyber components.

Background: The ANI Initiative

In 2005, UC Berkeley worked with a team from United Technologies (Clas Jacobson, Scott Bortoff, Susan Brandes, Christoph Haugstetter, Mihai Huzmezan, and Michael Sahm) on a proposal for the ANI ERC (Adaptive Networked Infrastructure) to NSF. The proposal reached the final stages, and was finally not funded by NSF. Some spinoff projects were funded by the California Energy Commission and others, but *the core ANI mission is still very much on the agenda. It has morphed broadly into Cyber Physical Systems (CPS).*

ANI was proposal for a long-term research project on the application of networked embedded software systems in societal-scale infrastructure systems. In a partnership with UT we would focus on energy resource management and human-centric building management. The focus is on the *science and engineering of integration*, integrating software and network behavior with system dynamics, and integrating physical properties of systems into the semantics of software.

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- Raz Bodik
- Karl Hedrick
- Tom Henzinger
- Kurt Keutzer
- George Necula
- Masayoshi Tomizuka
- Pravin Varaiya

Original ANI Participants in 2005

UC Berkeley
- Ed Arens (Architecture)
- Alexander Bayen (CE)
- Eric Brewer (EECS)
- David Culler (EECS)
- **Edward A. Lee** (EECS)
- Kris Pister (EECS)
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- Pravin Varaiya (EECS)
- Paul Wright (ME)

Vanderbilt
- Mark Abkowitz (CEE)
- Larry Howard (ISIS)
- **Gabor Karsai** (EECS)
- John Koo (EECS)
- Xenofon Koutsoukos (EECS)
- Akos Ledeczi (ISIS)

Cornell
- Ken Birman (CS)
- Todd Cowan (CEE)
- Jon Kleinberg (CS)
- Rajit Manohar (ECE)
- **Christine Shoemaker** (CEE)
- Gun Sirer (CS)

UC Merced
- Thomas C. Harmon (Engineering)
- Roland Winston (Engineering)
- **Jeff Wright** (Engineering)

United Technologies (no cost)
- Scott A. Bortoff
- Susan Brandes
- Christoph E. Haugstetter
- Mihai Huzmezan
- Michael K. Sahm

NICTA and University of Melbourne (no cost)
- Rob Evans
- Stan Skfidas
- Iven Mareels
- Rodney Tucker

San Jose State University
- Ping Hsu (ECE, Engineering)

University of Memphis
- Bela Bollobas (Math)

Scientific Advisory Board
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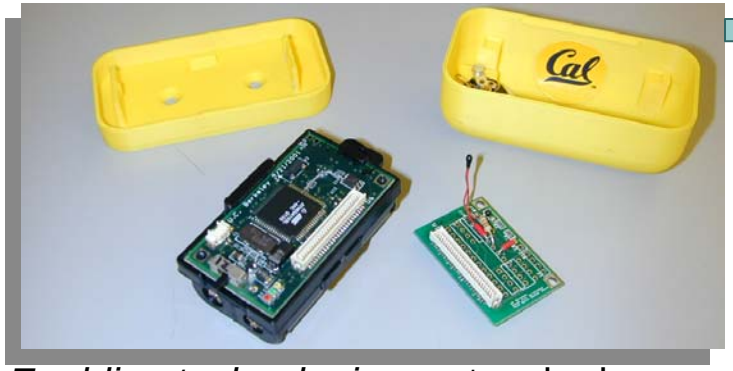
- Prof. Thomas Harris, VaNTH director, Vanderbilt University
- Ron Hofmann, California Energy Commission
- Prof. Teresa Meng, Stanford University
- Mary Ann Piette, DRRC Center Director, Lawrence Berkeley National Laboratories (LBNL)
- Joseph Sifakis, Scientific Coordinator, ARTIST-2 European Network of Excellence on Embedded Systems Design
- Janos Sztipanovits, Chair, ISIS, Vanderbilt Univeristy

Research Partners Allied with the Original ANI Proposal

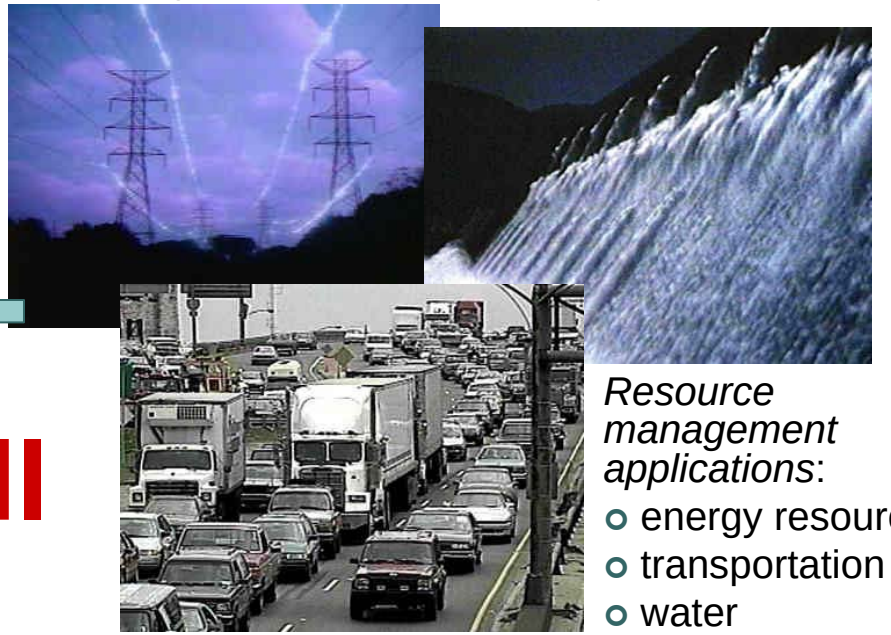
- **BWRC**: Berkeley Wireless Research Center (UC Berkeley)
- **CENTS**: Center for Emerging Network Trustable Systems (UC Berkeley)
- **CHESS**: Center for Hybrid and Embedded Software Systems (UC Berkeley)
- **CITRIS**: Center for Information Technology in the Interests of Society (UC Berkeley, Davis, Merced, Santa Cruz)
- **DRRC**: Demand-Response Research Center (Lawrence Berkeley Labs)
- **SensorNet** Program (ORNL: Oak Ridge National Lab)
- **PATH**: Partners for Advanced Transit and Highways (UC Berkeley, Caltrans)
- **PIER**: Public Interest Energy Research Program (California Energy Commission)
- **PSerc**: Power Systems ERC (Arizona State, Berkeley, Carnegie Mellon, Colorado School of Mines, Cornell, Georgia Tech, Howard, Illinois, Iowa State, Texas A&M, Washington State, Wisconsin, Wichita State)
- **TIER**: Technology and Infrastructure for the Developing World (UC Berkeley)
- **TRUST**: Proposed STC on Ubiquitous Secure Technology (Berkeley, Cornell, Vanderbilt)
- Center for the Management, Utilization and Protection of Water Resources (Tenn. Tech. Univ.)
- **VaNTH** ERC for Bioengineering Educational Technologies (Vanderbilt, Northwestern, Texas, Harvard, and MIT)
- **VECTOR**: Vanderbilt Center for Transportation Research (Vanderbilt)

Adaptive Networked Infrastructure



Enabling technologies: networked embedded systems with sensors and actuators

Approach: Engineering methods for integrating computer-controlled, networked sensors and actuators in large-scale infrastructure systems.



Resource management applications:

- energy resources
- transportation
- water

ANI

Deliverables: Engineering Methods, Models, and Toolkits for:

- design and analysis of systems with embedded computing
- computation integrated with the physical world
- analysis of control dynamics with software and network behavior
- programming the ensemble, not the computer
- computer-integrated systems oriented engineering curricula

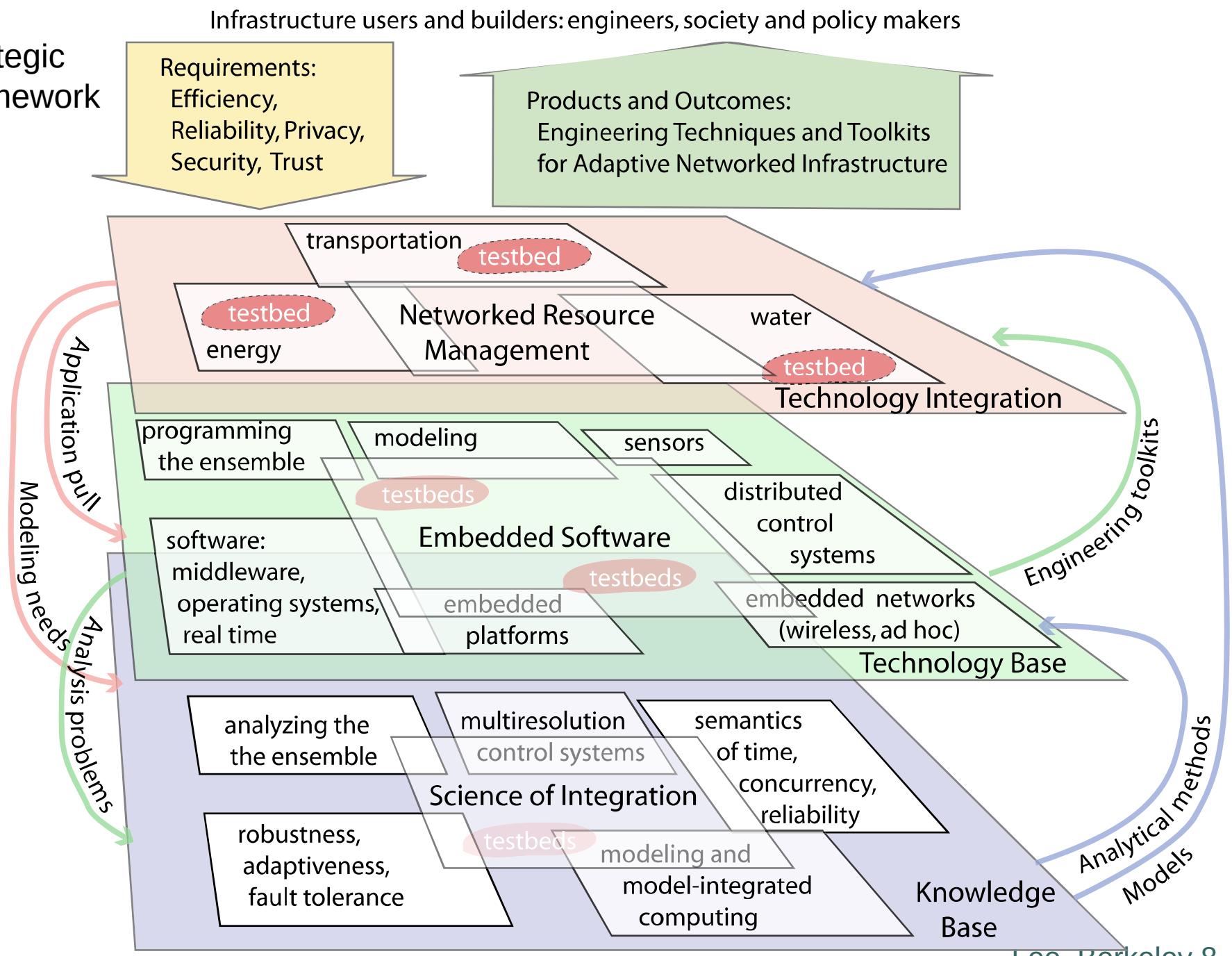
Energy Resource Management Testbed
UC Merced Building Systems

ANI team from Berkeley, Merced, and UTRC on site at the phase 1 Merced campus. Science/Engineering Bldg. 1 is in the background.

ANI proposed to:

- Build models of Merced buildings & campus.
- Populate buildings with wireless sensors.
- Develop feedback control for commissioning and optimization.
- Expose models and data in the educational process.

Strategic Framework



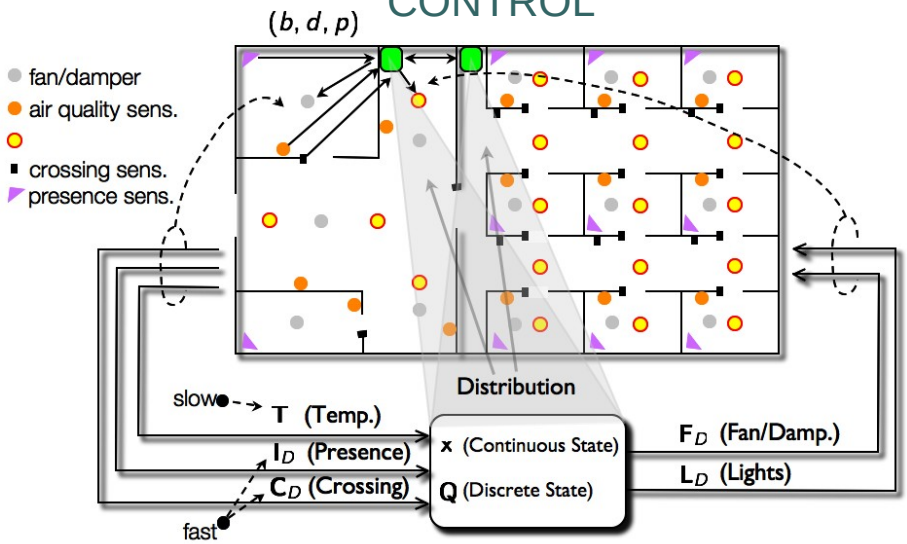
From ANI Towards CPS

ANI was, we believe, ahead of its time. NSF is building broad momentum on a new initiative that they are calling Cyber Physical Systems (CPS). The following NSF sponsored workshops related to this have been held:

- "High Confidence Medical Device Software and Systems (HCMDSS)" Workshop, June 2 - 3, 2005, Philadelphia, PA.
- National Workshop on “Aviation Software Systems: Design for Certifiably Dependable Systems”, October 5-6, 2006, Alexandria, TX.
- NSF Workshop on “Cyber-Physical Systems”, October 16-17, 2006, Austin, TX.
- National Meeting on “Beyond SCADA: Networked Embedded Control for Cyber Physical Systems”, November 8 & 9, 2006, Pittsburgh, PA.
- National Workshop on “High-Confidence Software Platforms for Cyber-Physical Systems (HCSP-CPS)”, November 30 – December 1, 2006, Alexandria, VA.
- NSF Industry Round-Table on Cyber-Physical Systems, May 17, 2007, Arlington, VA.
- "Joint Workshop On High-Confidence Medical Devices, Software, and Systems (HCMDSS) and Medical Device Plug-and-Play (MD PnP) Interoperability", June 25-27, 2007, Boston, MA.
- National Workshop on "Composable and Systems Technologies for High Confidence Cyber-Physical Systems", July 9-10, 2007, Arlington, VA.

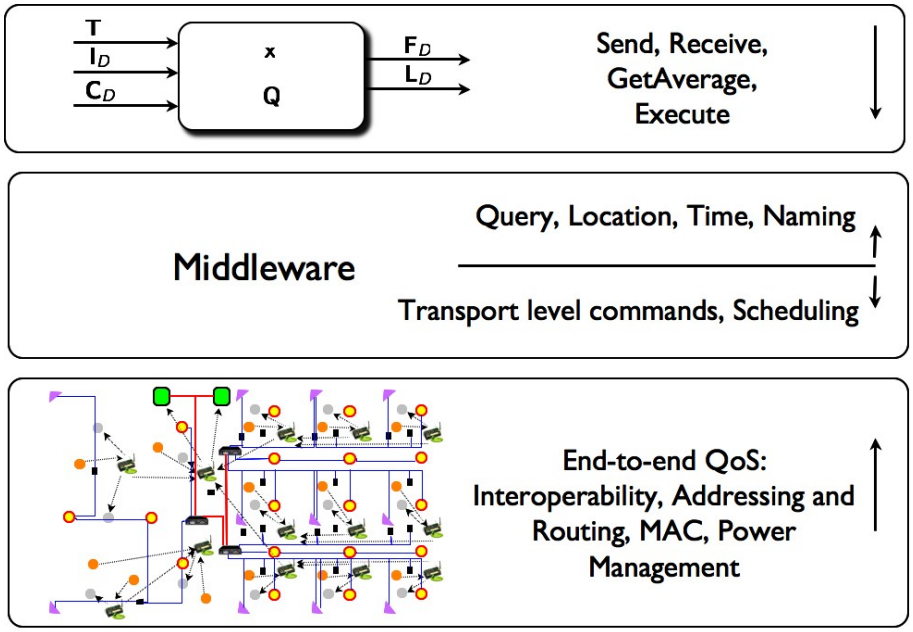
ANI-inspired efforts blend physical dynamics, hybrid control, and network and software behaviors:

CONTROL

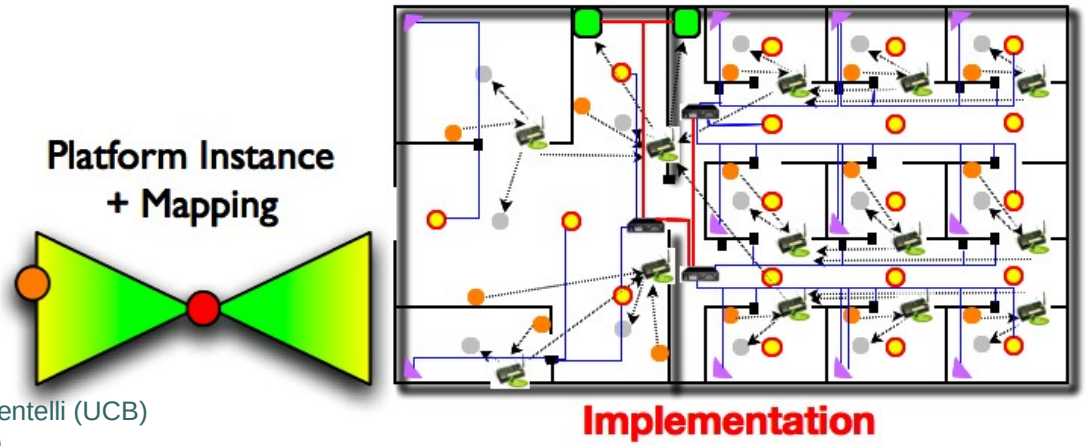


Multi-scale, Multi-Agent, Potentially Distributed Hybrid Control System

MIDDLEWARE



COMMUNICATION



1. Heterogenous
2. Fault Tolerant
3. QoS Guaranteed
4. Cost Effective

Alberto Sangiovanni-Vincentelli (UCB)
Kameshwar Poolla (UCB)
Clas Jacobson (UTC)

Summary of the Vision

Closed-loop multi-resolution feedback control systems are essential to achieving energy efficiency. The building engineer's toolkit is based on theories of physical dynamics (control theory, fluid dynamics, etc.). The software and network designer's toolkit is based on the theories of computation (complexity, computability, semantics, etc.). For cyber physical systems, a new toolkit is required that is at once physical and computational. It must be about the dynamics of couplings of physical processes with computational ones. It must provide a science of integration of heterogeneous components, and engineering methods for designing ensembles rather than individual components.