EE249
Embedded System Design: Models, Validation and Synthesis
Alberto Sangiovanni Vincentelli
eMerging Societal-Scale Systems

New System Architectures
New Enabled Applications
Diverse, Connected, Physical, Virtual, Fluid

Embedded Systems
MEMS BioMonitoring

Information Appliances

“Server”

“Client”

Scalable, Reliable, Secure Services

Gigabit Ethernet Clusters

Clusters
Embedded Systems

- Computational
  - but not first-and-foremost a computer
- Integral with physical processes
  - sensors, actuators
- Reactive
  - at the speed of the environment
- Heterogeneous
  - hardware/software, mixed architectures
- Networked
  - shared, adaptive

Source: Edward A. Lee
Observations

• We are on the middle of a revolution in the way electronics products are designed
• System design is the key (also for IC design!)
  – Start with the highest possible level of abstraction (e.g. control algorithms)
  – Establish properties at the right level
  – Use formal models
  – Leverage multiple “scientific” disciplines
Course overview

Managing Complexity

Orthogonalizing Concerns

Behavior vs. Architecture

Computation vs. Communication
Behavior Vs. Architecture

Models of Computation

Quantity estimation

Synthesis: HW and SW

Mapping

Refinement

Comm. and comp. resources

Assign functionality to arch elements
HW/SW partitioning, Scheduling

Flow To Implementation

- Polis (1990-1996)
- Metropolis (2003-present)
Behavior Vs. Communication

• Clear separation between functionality and interaction model
• Maximize reuse in different environments, change only interaction model
### Course Topics

<table>
<thead>
<tr>
<th>1. Introduction</th>
<th>Design complexity, examples of embedded and cyber-physical systems, traditional design flows, Platform-Based Design, design capture and entry</th>
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<tr>
<td>3. Architecture and performance abstraction</td>
<td>Definition of architecture, examples. Distributed architecture, coordination, communication. Real time operating systems, scheduling of computation and communication.</td>
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**Grading** will be based on a final project, lab/HW assignments and literature discussions.

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**EE 249  Embedded System Design: Models, Validation, and Synthesis**

Lectures: TuTh 11-12:30PM, 521 Cory  
Discussion and Lab: Tu 5-6PM, Th 4-6PM, 540A/B Cory

Instructor:  
Alberto Sangiovanni-Vincentelli (alberto@eecs.berkeley.edu)

GSI:  
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CCN: 25709, 26035  
Units: 4
Administration

• Course web page: [http://chess.eecs.berkeley.edu/design/](http://chess.eecs.berkeley.edu/design/)

• All announcements made through Piazza
  – Students can post questions on the class material, HW, Labs and tools (also anonymously)
  – Instructors or other students can answer questions
Administration (cont.)

Credit: EE 249 is a 4 unit course.

- **Alberto L. Sangiovanni-Vincentelli** - 515 Cory Hall - **Email**: alberto at eecs dot berkeley dot edu. **Office hours**: Tues/Thurs, 12:30-1:30 pm, 515 Cory, or by appointment.

- **Pierluigi Nuzzo** - GSI - 545H Cory Hall - **Email**: nuzzo at eecs dot berkeley dot edu. **Office hours**: Tues, 4-5 pm, 540A/B Cory, or by appointment.

- **Lectures**: Tuesday and Thursday, 11-12:30 pm, 521 Cory Hall.
  **Discussion**: Tuesday, 5-6 pm, 540A/B Cory Hall.
  **Lab Sessions**: Thursday, 4-6 pm, 540A/B or 204 Cory Hall.

- EE 249 Fall 2012 Piazza website: [https://piazza.com/berkeley/fall2012/ee249](https://piazza.com/berkeley/fall2012/ee249)

- **Grading Policy**:
  - Course project: 50%
  - Lab: 20%
  - Homework: 20%
  - Discussion: 10%
Schedule

• Labs (Th. 4-6):
  – Presentation of tools followed by hands-on tutorial and assignments

• Discussion Session (Tu. 5-6)
  – Each student (possibly in groups of 2 people) will have to make one or more oral presentations during the class

• Last week of class dedicated only to projects (usually due the last week of November or the 1st week of Dec.)

• Auditors are OK but please register as P-NP (resources are assigned according to students…)
Introduction Outline

• Evolution of IT Systems
• Cyber-physical Systems
  – Societal Scale Systems
  – Automobile of the future
  – Smart grid and buildings
• The Far Future
  – Bio-Cyber Systems
• Design Challenges
The Emerging IT Scene!

The Cloud!

Infrastructural core

Sensory swarm

Mobile access

Courtesy: J. Rabaey
Computers and mobiles to disappear!

Predictions: 7 trillions devices servicing 7 billion people!
1,000 devices per person by 2025

The Immersed Human

Real-life interaction between humans and cyberspace, enabled by enriched input and output devices on and in the body and in the surrounding environment

Courtesy: J. Rabaey
IBM Smarter Planet Initiative: Something profound is happening… CYBER PHYSICAL SYSTEMS!

**INSTRUMENTED**
We now have the ability to measure, sense and see the exact condition of practically everything.

**INTERCONNECTED**
People, systems and objects can communicate and interact with each other in entirely new ways.

**INTELLIGENT**
We can respond to changes quickly and accurately, and get better results by predicting and optimizing for future events.
Intelligent systems that gather, synthesize and apply information will change the way entire industries operate.

**Smart water**
Apply monitoring and management technologies to help optimize the availability, delivery, use, and quality of water as well as related systems including energy and chemical treatment.

**Smart traffic**
Use real-time traffic prediction and dynamic tolling to reduce congestion and its byproducts while positively influencing related systems.

**Smart energy**
Analyze customer usage and provide customized products and services that help to boost efficiency from the source through the grid to the end user.
Vision 2025

- Integrated components will be approaching molecular limits and/or may cover complete walls
- Every object will be smart
- The Ensemble is the Function!
  - Function determined by availability of **sensing, actuation, connectivity, computation, storage and energy**
- Collaborating to present unifying experiences or to fulfill common goals

A humongous networked, distributed, adaptive, hierarchical control problem
Outline

• Evolution of IT Systems
• What is possible? Cyber-physical Systems
  – Societal Scale Systems
  – Automobile of the future
  – Smart grid and buildings
• The Far Future
  – Bio-Cyber Systems
• Design Challenges
The Birth of Cyber-Physical Systems

Complex collections of sensors, controllers, compute and storage nodes, and actuators that work together to improve our daily lives.
An example of Cyber-Physical System (provided by UTC)

Aircraft Vehicle Management System

Electrical Power System

Propulsion and Power

Landing Gear

Environmental Control System

Power Transmission

Servo System
VMS Functions (replace flight engineer)

- Operate and monitor engine/aircraft systems controls and indicators;
- Perform engine starts, monitor run-up, flight operation and engine shutdown;
- Operate engine controls to provide desired efficiency and economy;
- Monitor engine instruments throughout period of operation;
- Control, monitor and regulate some or all aircraft systems: hydraulic, pneumatic, fuel, electronic, air conditioning, pressurization; ventilation; lubrication; communication, navigation, radar, etc

VMS architecture (design exploration)

- Implement fully distributed system, with all subsystems integrated across a networked communications interface

System Demonstrations

- **System startup**: From a cold start, turn all subsystems on and go into a normal operating mode
- **Transport mission**: pick up ground cargo using winch from hovering configuration, transport cargo as swung load to drop-off location, deposit on ground, and depart from area
- **Landing operations**: support aircraft landing in easy (daylight, clear conditions), moderate (nighttime and/or rainy conditions) and difficult (dusty with icy weather) conditions
- **Safing mode**: perform operations that put vehicle in safe operating mode, depending on condition of vehicle
- **System diagnostics**: during normal operations, log diagnostic data from all subsystems, w/ variable resolution
Where CPS Differs

• **The traditional embedded systems problem**
  – Embedded system is the union of computing hardware and software immersed in a physical system it monitors and/or controls. The physical system is a given. The design problem is about the embedded system only.

• **Hybrid Systems**
  – Mixed discrete and continuous time systems

• **The CPS problem**
  – Cyber-Physical Systems (CPS): **Orchestrating** networked computational resources with physical systems
  – Co-design of physical system and controller
  – Computation and networking integrated with physical processes. The technical problem is managing dynamics, time, and concurrency in networked, distributed computational + physical systems.
Modeling Cyber-Physical Systems

Model
- Equation-based model
- Abstraction "physical modeling"

System
- Physical system (the plant)
- Embedded systems (computation)

Sensors
- Actuators
- Networking

Courtesy: D. Broman

\[ M_1 = -I^{-1} M_2 \]
Modeling Cyber-Physical Systems

Physical system (the plant)
Embedded systems (computation)
Networking
Sensors
Actuators
System
Model
Equation-based model
Abstraction "physical modeling"

Different models of computation

Concept of Time

C-code

Networks

Physical system (the plant)
Embedded systems (computation)

Courtesy: D. Broman
A richer, systems view of computer science is needed. Ingredients include:

Enriching CS models with relevant physical/resource properties
- Physical, model-based computing
- Resource aware (time/energy) computing

Formal composition of multiple physics, models of computation, languages
- Composition of heterogeneous components

Impact of cyber components on physical components and vice versa
- Physically-aware computing
Automotive Industry
Three Levels of Players

Automakers
- 2005 Revenue: $1.1T
- CAGR 2.8% (2004-2010)

Tier 1 Suppliers
- 2004 Revenue ~$200B
- CAGR 5.4% (2004-2010)

IC Vendors
- 2005 revenue $17.4B
- CAGR 10% (2004-2010)

Source: Public financials, Gartner 2005
### The Evolution of the Automotive DNA

#### CURRENT DNA

- **Energized by** Petroleum
- **Powered Mechanically by** Internal Combustion Engine
- **Controlled** Mechanically
- **Stand-alone**
- **Totally Dependence** on the Driver
- **Vehicle Sized for Maximum Use – People and Cargo**

#### NEW DNA

- **Energized by** Electricity and Hydrogen
- **Powered Electrically by Electric Motors**
- **Controlled** Electronically
- **“Connected”**
- **Semi/Full Autonomous Driving**
- **Vehicle Tailored to Specific Use**
Software content in automobiles could increase by 100 X over the next 5-6 years. Challenges will include:

- Software system architecture
- Partitioning for modularity & system reliability
- Reuse
- Standardization of interfaces
360° SENSING CAPABILITY

TODAY
- Forward Vision System
  - Lane tracking
  - Object detection
  - Far IR capability
- Short-Range Sensors
- Rear Vision System
  - Object detection
  - Far IR capability
- Enhanced Digital Map System
- Long-Range Scanning Sensor

FUTURE
- Side Blind-Zone Alert
- Long-Range Side/Rear Lane-Change Assist
- Forward Vision System
- Short-Range Radars
- Dedicated Short-Range Communication + GPS (V2V)
- Ultrasonic Sensors
V2V/V2X COMMUNICATIONS
CMOS mmWave Circuits and SoC: 60GHz Today

- Multiple 60GHz standards complete
- WirelessHD products available
  - SiBeam (BWRC startup)
  - Wall-powered
  - Dissipate <2W
- A $10 Radar is a possibility!
VEHICLE IS PART OF A “CONNECTED” ECO-SYSTEM
ELECTRIC, CONNECTED, AUTONOMOUS

- Satellite Communications
- Terrestrial Broadcast
- Mobile Communications
- Navigation
- Intermodal Communications
- Vehicle-to-Vehicle
- Safety Systems
- Traffic Signs
- Passenger Information
- Passenger Assistance
- Adaptive Cruise Control
- Fleet Management
- Toll Collection
- Trip Planning
- ©ETSI 2008
The Tire of the Future

New materials: enhanced performances, reduced rolling resistance, lower noise, reduced puncture risk, nanotechnologies, new compounds, new tread design, “self sealing” technologies.

New design technologies: virtual engineering for reducing time to market & engineering costs.

New electronics technologies inside the tire: pressure monitoring, friction, slip, tire consumption, contact force, “health” check-up information extraction & transmission....

The Tire as an Intelligent Sensor!
Cyber™ Tire System

Vehicle dynamics control system

User Applications

Processing unit

Receivers

Marco Tronchetti Provera
Chairman of Pirelli & C. S.p.A.

Major broadcast channel in Italy
Experimental Tests

Wide database
- Different tires
- Different sensor positioning
- Different speeds
- Different tracks
  - Steering pad
  - Straight line
  - Braking
  - Acceleration
  - ...
- Different conditions
  - Dry
  - Wet
  - Ice
Tread Length Estimation

- **Minimum** of the tangential component signal: tread area **entry**
- **Maximum** of the tangential component signal: tread area **exit**

\[
PL = \frac{N_p}{f_c} \cdot \omega \cdot R_{rot}
\]

- **PL**: tread length
- **R_{rot}**: rolling radius
- **\( \omega \)**: angular speed
- **\( f_c \)**: sampling rate
Cyber™Tyre Development Partners

Politecnico di Milano
- Feature Extraction, Kinematics pre-conditioner

UMC
- IP and chip manufacturing

University of California, Berkeley
- Ultra low power radio
- Advanced new communication protocols

Politecnico di Torino
- Prototype Vehicle Integration, Engineering Support

Valtronic Technologies SA
- MEMS Accelerometers
- Assembly and packaging technologies

ST Micro.
- MEMS Accelerometers

Accent S.p.A.
- Acquisition, processing and advanced architectural technologies

- RX/TX antenna
- Pico-radio communication block
- Data processing and computing
- Physical properties sensing system (e.g. pressure, temperature, acceleration)
- Power Management
- Energy Scavenging

- Advanced new communication protocols
The Future Immersed Devices?

Courtesy: Corning Glass
“A World Made of Glass”
(http://www.youtube.com/watch?v=iY1Q0bNwXuI)
Building Energy Demand Challenge

Buildings consume
- 39% of total U.S. energy
- 71% of U.S. electricity
- 54% of U.S. natural gas

Building produce 48% of U.S. Carbon emissions

Commercial building annual energy bill: $120 billion

The only energy end-use sector showing growth in energy intensity
- 17% growth 1985 - 2000
- 1.7% growth projected through 2025

Figure 10. Energy Consumption and Intensity by Year Constructed, 1995

Sources: Ryan and Nicholls 2004, USGBC, USDOE 2004
Greenhouse Gas Emissions by Sector

European Union thinking

- **Buildings**
  - From 2019 all new buildings produce as much energy as they consume
  - Member States set minimum targets for zero-energy buildings in 2020
  - Member States to set energy targets for existing buildings

- **Residential**
  - After 2018 must generate as much as consume via solar, heat pumps and conservation
  - Member States set energy targets for existing buildings by 2015
Energy Efficient Buildings: Current State

“One size fits all”

Increasing integration of subsystems & control
Different types of equipment
Different skills
Different deliver

“Climate Adaptive Design”

Debitel Stuttgart, Germany
120K ft², 165kWhr/m²/yr

KIW Frankfurt, Germany
55K ft², 100kWhr/m²

Market Penetration/Size and Readiness

Energy Efficiency
energy efficient buildings: reality

large variability in performance predictions

• performance simulations conducted (only) for peak conditions

• as-built specifications differ from design intent, resulting in compromise of energy performance due to detrimental sub-system interactions

• uncertainty in operating environment and loads
Energy Efficient Buildings: Reality

Cambria Office Building
Design Intent: 66% (ASHRAE 90.1); Measured 44%

KfW Building, Frankfurt, GERMANY
Design Intent: 100kWH/m²/yr

Actual energy performance substantially lower than design predictions due to detrimental sub-system interactions and control system issues

“As designed” energy performance accomplished after substantial system tuning

What is Hard (Missing): Products, Services and Delivery?

Barrier: Scalability
- Climate specific
  - Multiple subsystems
  - Dynamic energy flows
- Implication on Cost
  - Hardware/process for calibration
- Implication on Risk
  - No Design ProCert/quality process

Barrier: Robustness
- Unknown sensitivities
- No supervisory control
- Implication on Cost
  - No ProCert process/quality process
  - Commissioning costs/process
- Implication on Risk
  - Control of design in handoffs

Barrier: Productivity
- No diagnostics/guaranteed performance without consulting
- Implication on Cost
  - Measurement costs
  - Recommissioning costs
- Implication on Risk
  - Facility operations skillsets
  - Unbounded costs to ensure performance

Low Energy
- Savings Potential
- Unaware
- Miss
- Loss

Current State
- As-built variances from spec
- Poor operation or maintenance

Unapproachable analysis tools

Concept & Design
- A & E Firms

Build
- Contractors

Operations & Maintenance
- Property Managers & Operations Staff
They Don’t Even Create Comfortable Environments

I can’t hear myself think.

It’s really hard to type with your mittens on.

Another day at the sweat shop.

Another day working in the dark, literally.

Think I can see my breath.

Turn down the #@$! heat.

Turn up the #@$! heat.

It’s too quiet in here.

Our new task force on cubicle comfort has been very effective. They’ve eliminated any trace of it.

You could fly a kite in this breeze.

I can still smell Wally’s chill.

I don’t think this air moved since 1957.
Really … Not Just In Dilbert

UC Berkeley Center for the Built Environment
Occupant Satisfaction Survey Results, ~35,000 responses
1.0 Executive Summary

1.1 This report summarizes observations of the system based on a review of the trend data in early September, primarily on the operation of the chilled water plant.

1.2 Central Air Handlers

A. Each air handler shows significant issues that may contribute to poor zone temperature control and significant excess energy use. These issues may be partly related to the intentional false-loading of the chilled water plant to ensure stable operation. AHU-1 and AHU-2 are consistently unable to meet the supply air temperature setpoints even though the chilled water valves are usually wide open. The hot water valve at AHU-2 appears to be intentionally controlled to operate simultaneously with the chilled water valve. This may also be the case at AHU-1, or there may be an issue with hot water valve leakage. AHU-3 appears to have inappropriate dehumidification sequence programmed which is resulting in unnecessary simultaneous heating and cooling and poor temperature control.

B. The three air handlers are each operating with 100% outside air, although it is not clear that this was the design intent for AHU-1 and AHU-2.

1.3 Chilled Water Plant

A. The chilled water plant is largely operated in manual control, reportedly due to stability problems with the chillers operating at low loads. So much of the system is
Building Performance Problems

- Poor Controls Design
- No Modeling or Optimization
- Poor Controls Implementation
- Lack of Commissioning
- No Automated Fault Diagnostics
- Lack of information transfer from design to construction to operation
Building Information Flow

Building Life-Cycle – 3 distinct phases

Design

Consortiun

Operation

Engineers
Consultants

Contractors
Commissioning Agents

Owners
Operators
Facility Managers

with distinct players

roles / products

sequences
schematics
spec's
plans
schedules

architecture
installation
programming
testing
re-work

monitoring
billing
maintenance
repair
changes / updates

work flow & information flow is “manual”

paper &
PDF

paper &
PDF
Components do not have mathematically similar structures and involve different scales in time or space;

The number of components are large/enormous

Components are connected in several ways, most often nonlinearly and/or via a network. Local and system wide phenomena depend on each other in complicated ways

Overall system behavior can be difficult to predict from behavior of individual components. Overall system behavior may evolve qualitatively differently, displaying great sensitivity to small perturbations at any stage

* APPLIED MATHEMATICS AT THE U.S. DEPARTMENT OF ENERGY: Past, Present and a View to the Future

Going from 30% efficiency to 70-80% efficiency
Every Building is Unique

A380
- $10 billion to develop
- $300 million each to build
- Design = 30 x construction

Typical Building
- Design = 10% of construction cost

Building design about 1/300 of airplane design costs.
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