EE249

Embedded System Design: Models, Validation and Synthesis

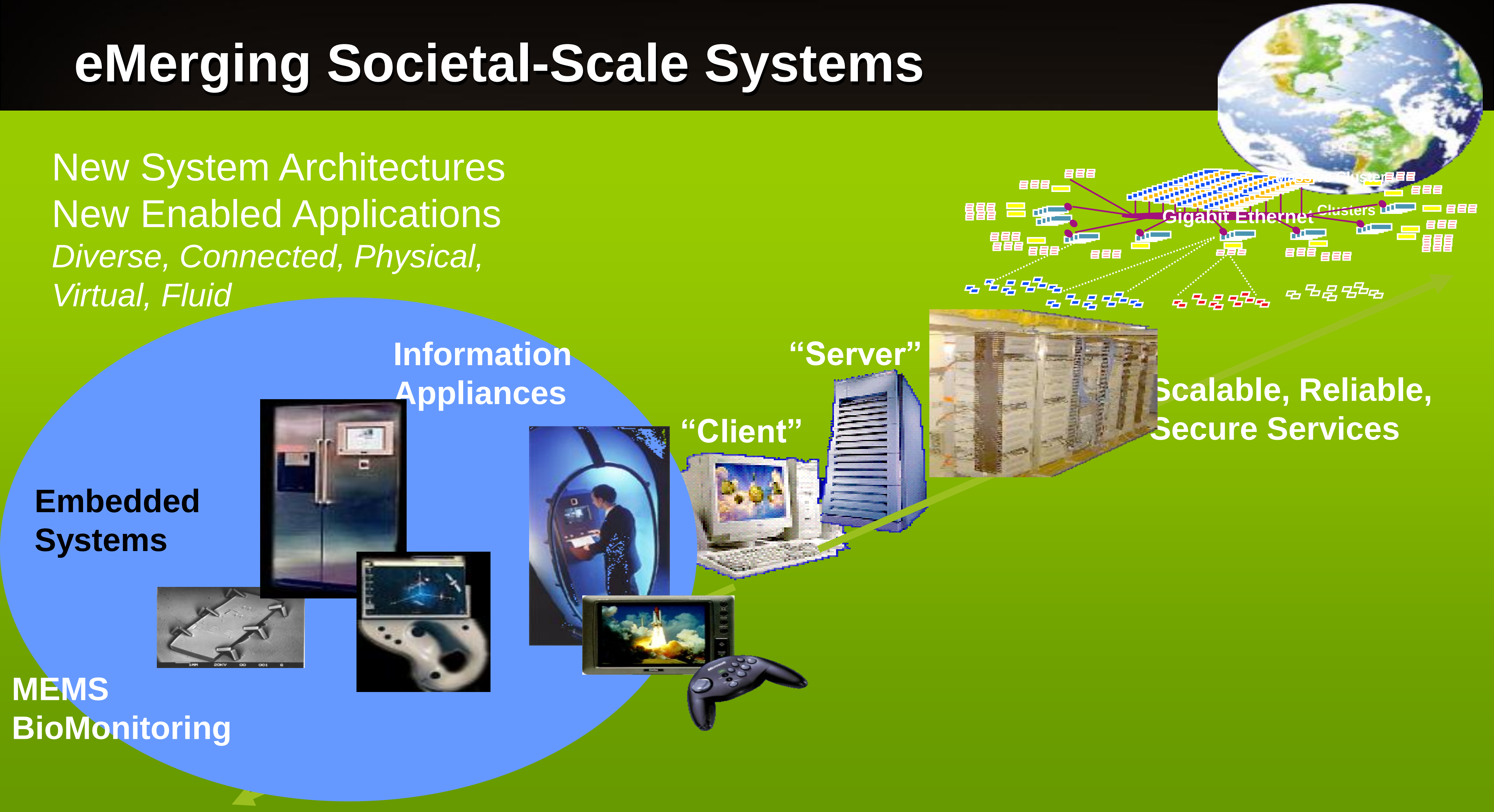
Alberto Sangiovanni Vincentelli

eMerging Societal-Scale Systems

New System Architectures

New Enabled Applications

Diverse, Connected, Physical,
Virtual, Fluid



Information Appliances

"Server"

"Client"

Scalable, Reliable, Secure Services

Embedded Systems

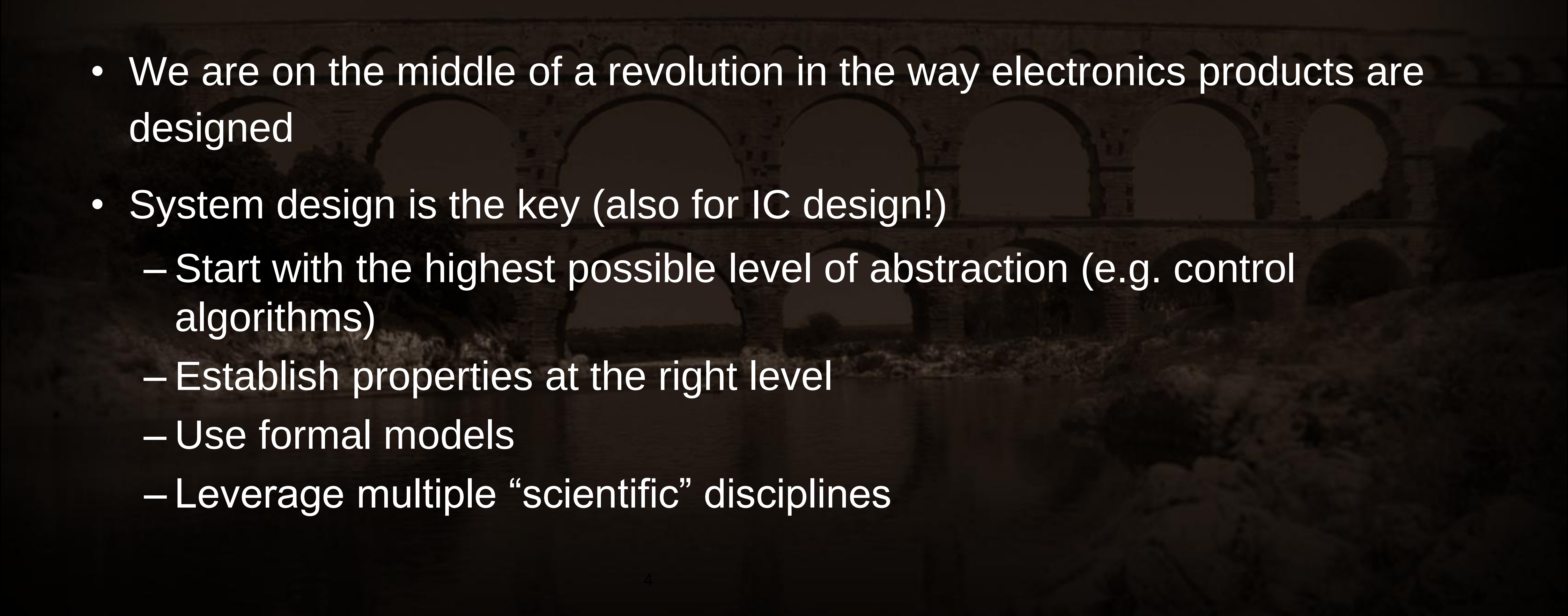
MEMS
BioMonitoring

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

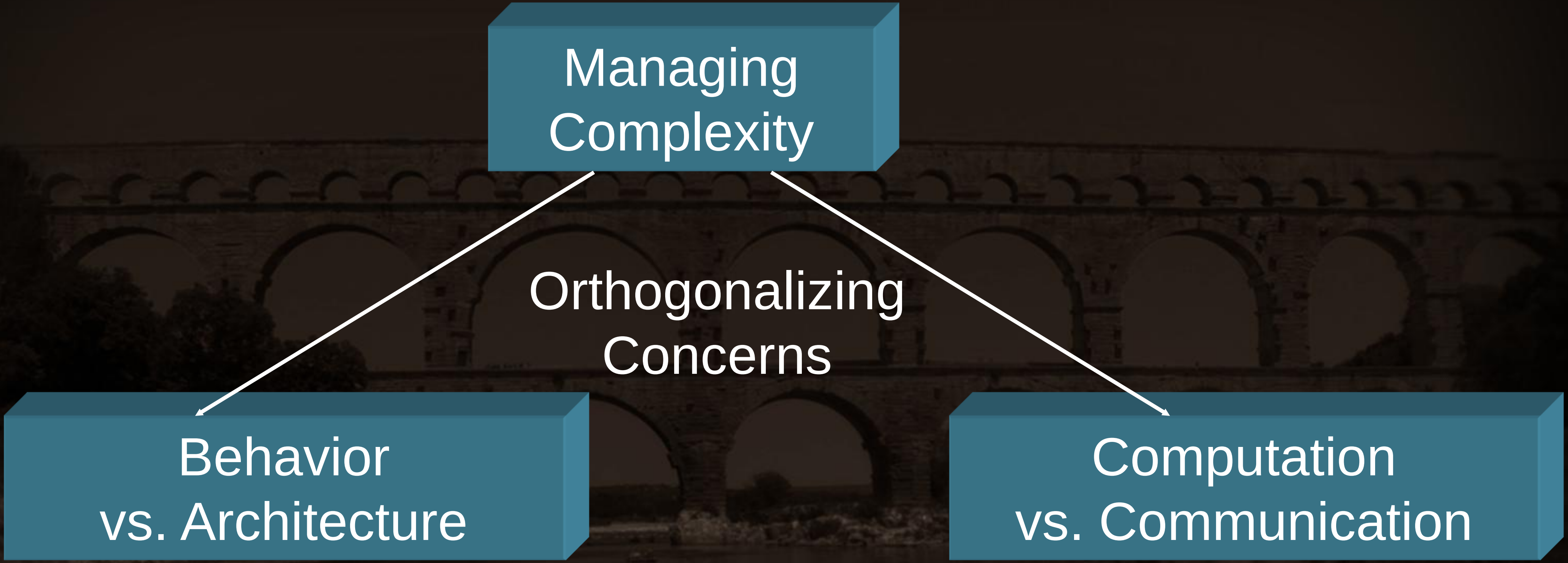
Source: Edward A. Lee

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



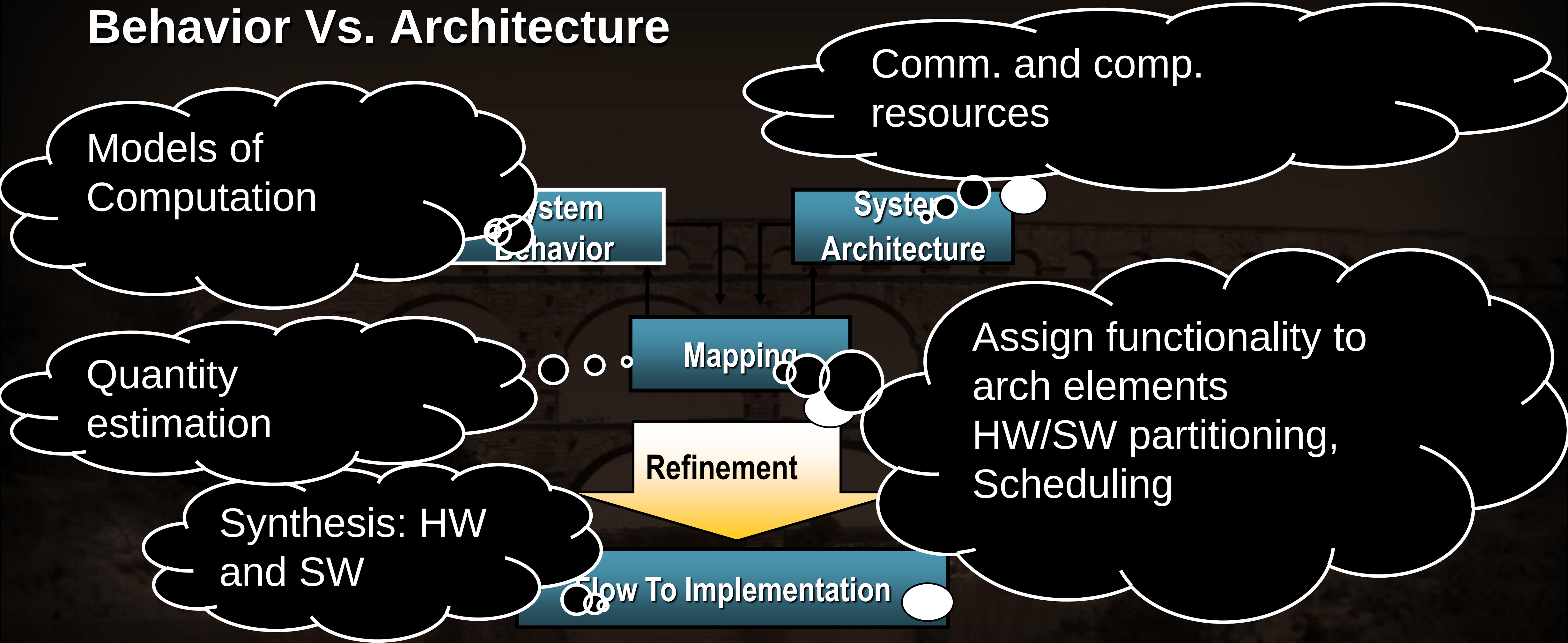
Managing Complexity

Orthogonalizing Concerns

Behavior vs. Architecture

Computation vs. Communication

Behavior Vs. Architecture



Models of Computation

Comm. and comp. resources

System Behavior

System Architecture

Mapping

Quantity estimation

Assign functionality to arch elements HW/SW partitioning, Scheduling

Refinement

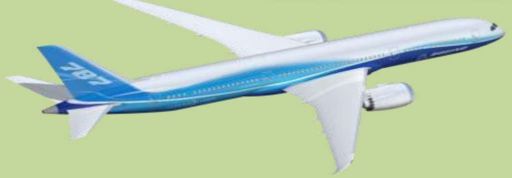
Synthesis: HW and SW

Flow To Implementation

- Polis (1990-1996)
- VCC (1996-2003)
- Metropolis (2003-present)

Behavior Vs. Communication

- Clear separation between functionality and interaction model
- Maximize reuse in different environments, change only interaction model



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

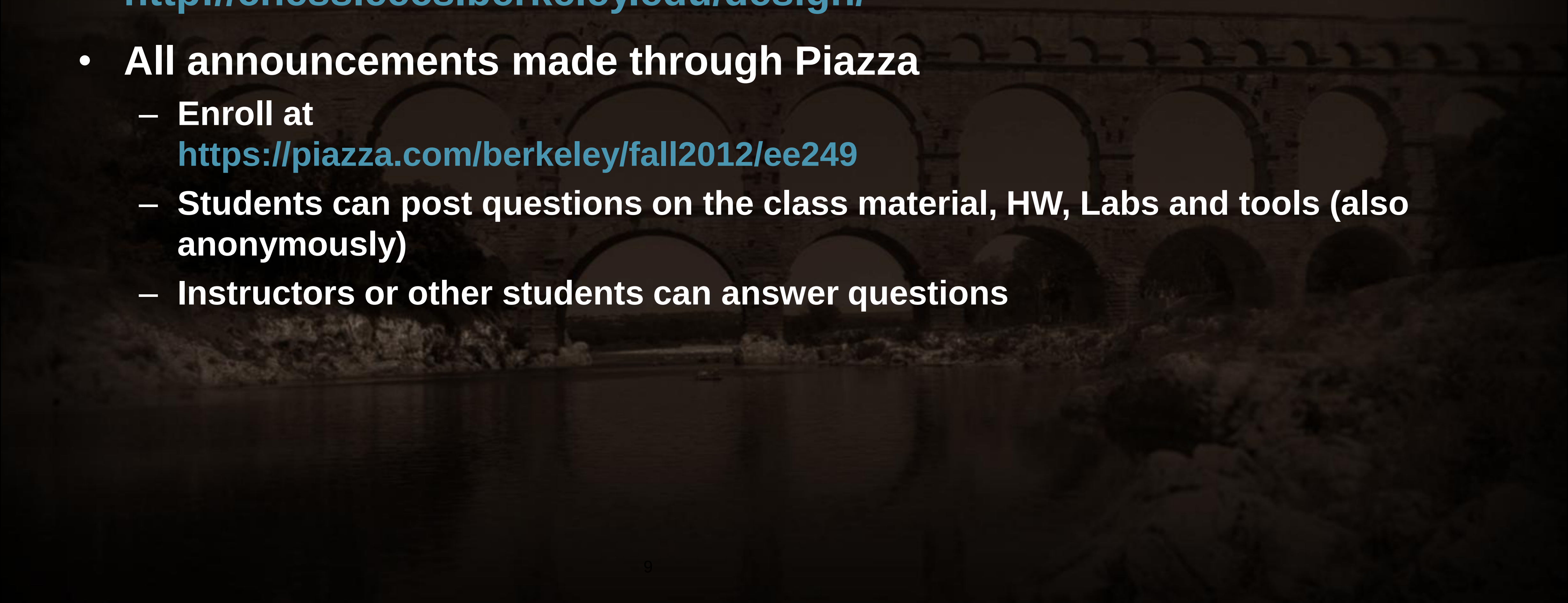
Lectures: TuTh 11-12:30PM, 521 Cory Discussion and Lab: Tu 5-6PM, Th 4-6PM, 540A/B Cory
Instructor: Alberto Sangiovanni-Vincentelli (alberto@eecs.berkeley.edu)
GSI: Pierluigi Nuzzo (nuzzo@eecs.berkeley.edu)
CCN: 25709, 26035 Units: 4

Course Topics

1. Introduction	Design complexity, examples of embedded and cyber-physical systems, traditional design flows, Platform-Based Design, design capture and entry
2. Functional modeling, analysis and simulation	Overview of models of computation. Finite State Machines, Process Networks, Data Flow, Petri Nets, Synchronous Reactive, Hybrid Systems. Unified frameworks: Tagged Signal Model, Agent Algebra. Compositional methods and Contract-based Design.
3. Architecture and performance abstraction	Definition of architecture, examples. Distributed architecture, coordination, communication. Real time operating systems, scheduling of computation and communication.
4. Mapping	Definition of mapping and synthesis. Software synthesis, quasi static scheduling. Communication Synthesis and Communication-Based Design. Design Space Exploration.
5. Verification	Validation vs. Simulation. Simulation of heterogeneous systems. Formal methods. Verification of hybrid system. Horizontal and Vertical Contracts. Interface automata and assume-guarantee reasoning.
6. Applications	Automotive: car architecture, communication standards (CAN, FlexRay, AUTOSAR), scheduling and timing analysis. Building automation: Communication (BanNet, LonWorks, ZigBee).

Grading will be based on a final project, lab/HW assignments and literature discussions.

Administration



- Course web page: http://chess.eecs.berkeley.edu/design/
- All announcements made through Piazza
  - Enroll at https://piazza.com/berkeley/fall2012/ee249
  - 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
- **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!

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.

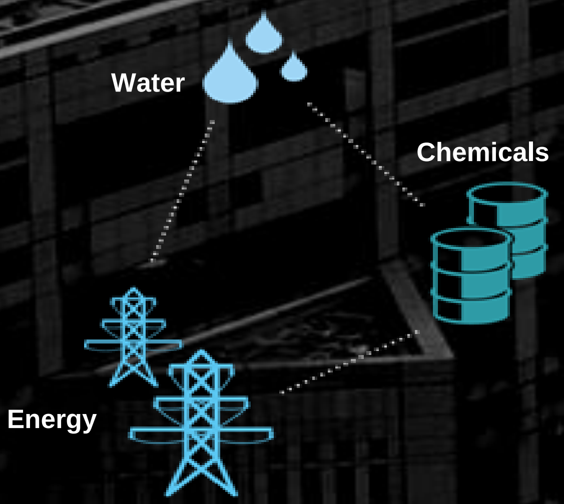
INTELLIGENT

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.

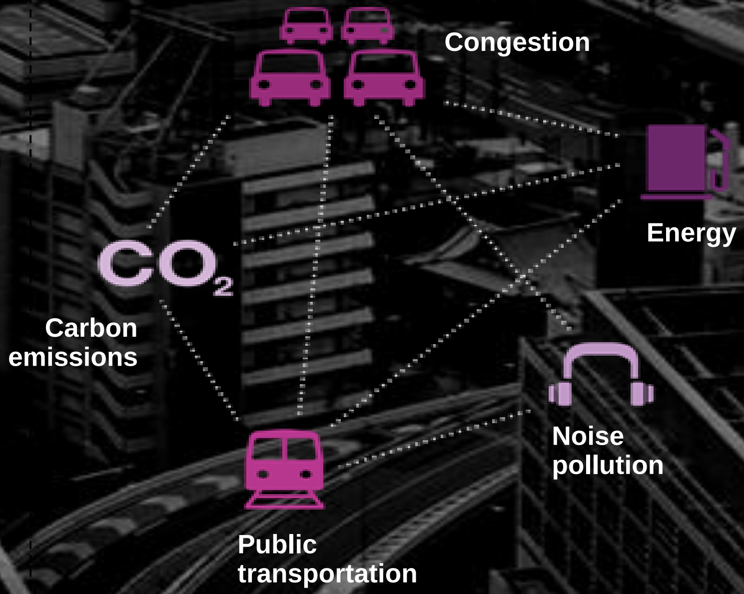
Smart water

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.



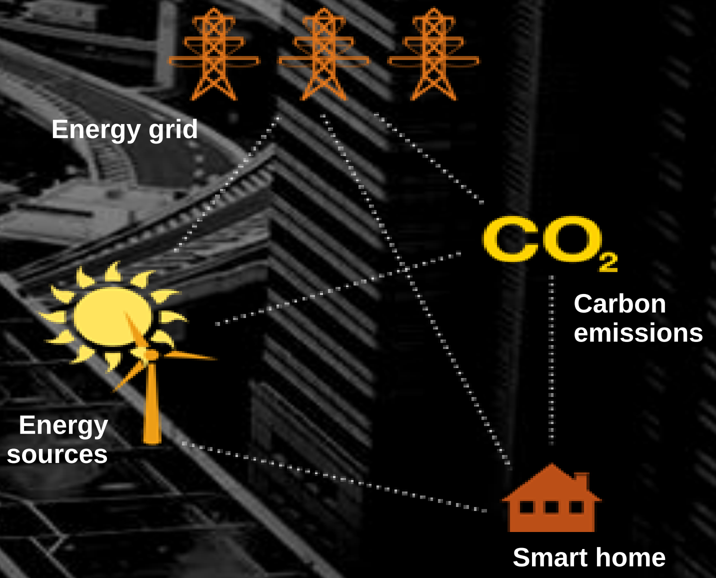
Smart traffic

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

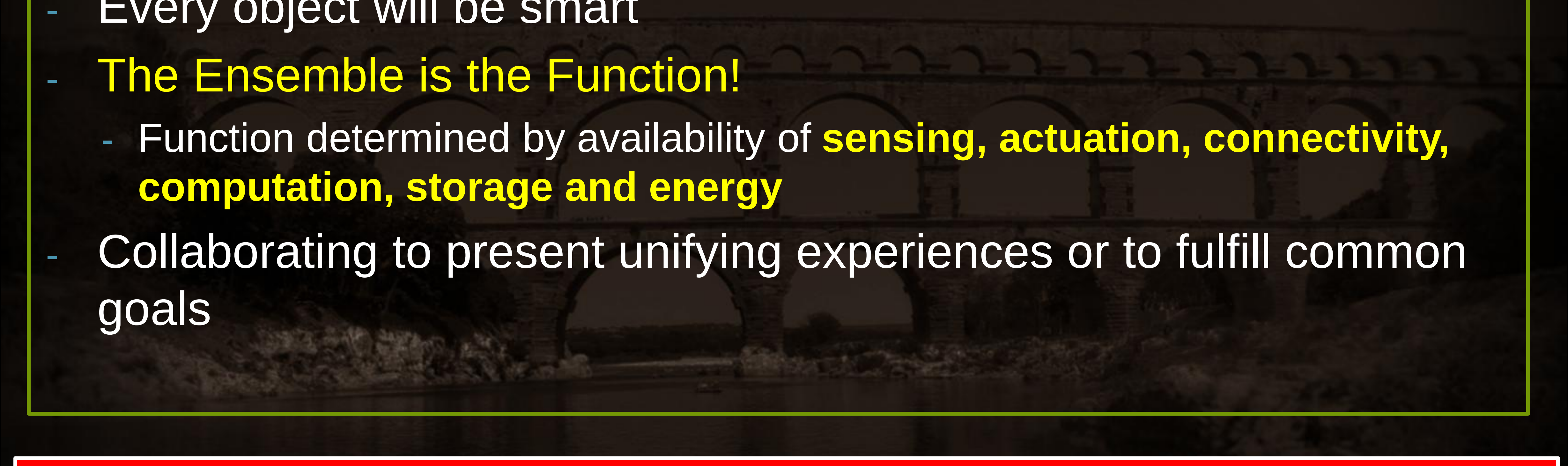


Smart energy

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

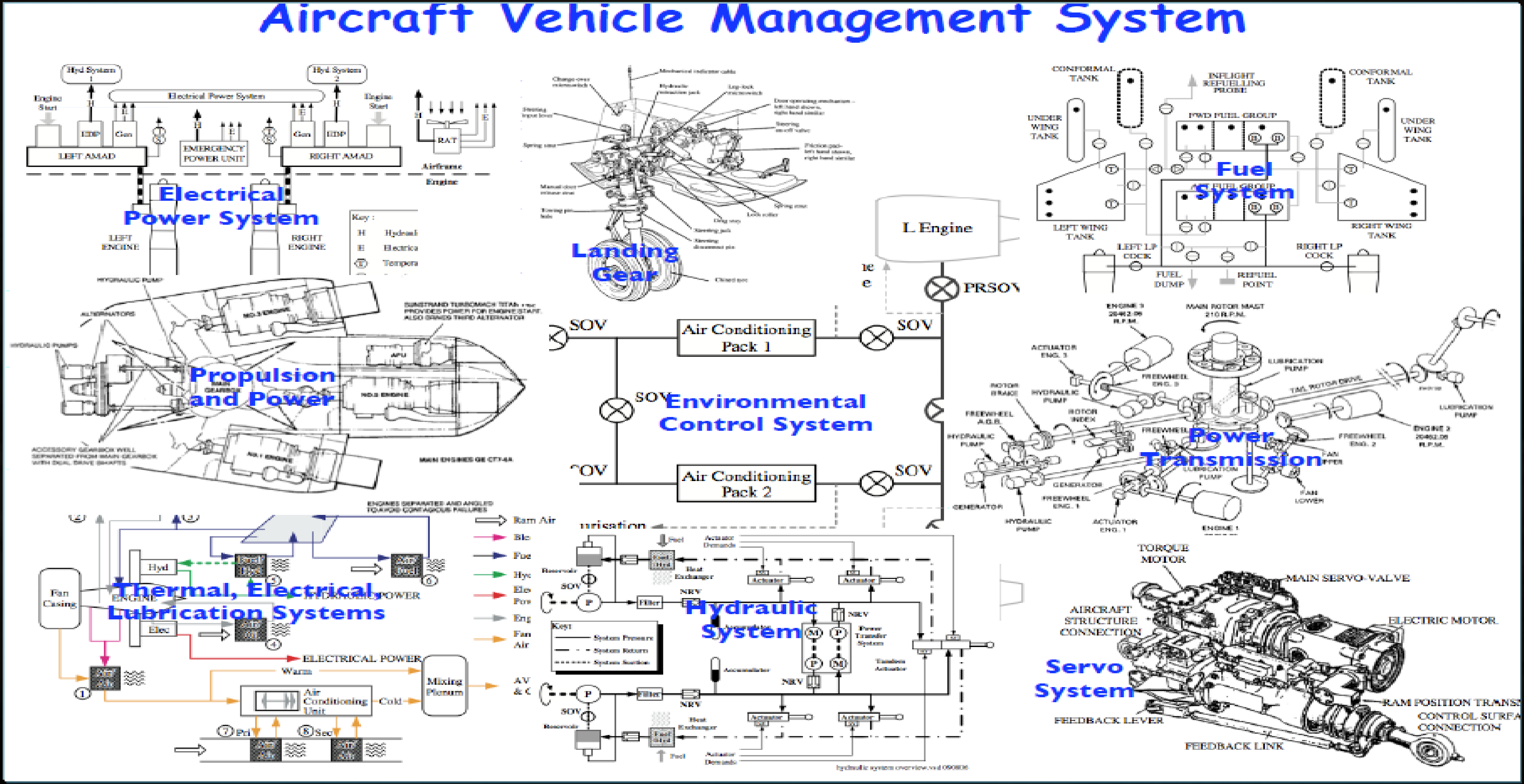
Outline

- 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

VMS Challenge Problem v1.0 (1Nov2010)

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

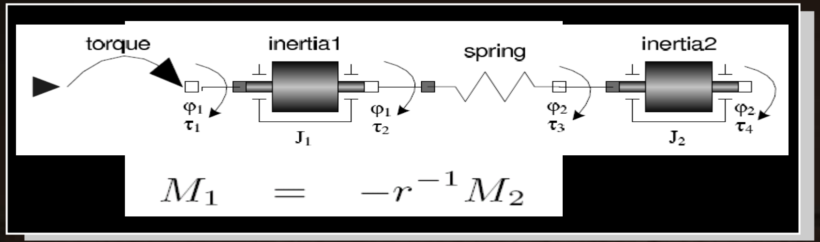
- **System startup**: From a cold start, turn all subsystems on and go into a normal operating mode
- **Transport mission**: pick up ground cargo using winch from hovering configuration, transport cargo as swung load to drop-off location, deposit on ground, and depart from area
- **Landing operations**: 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

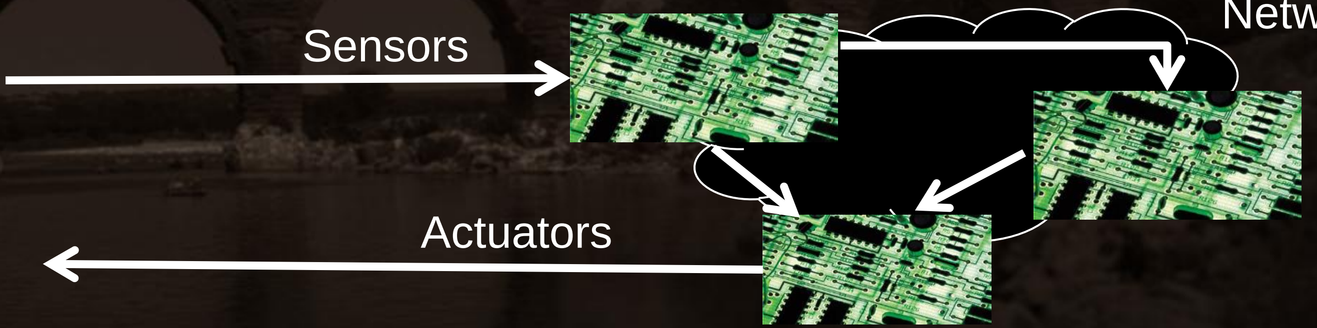


Equation-based model

Abstraction
“physical modeling”

System

Physical system (the plant)



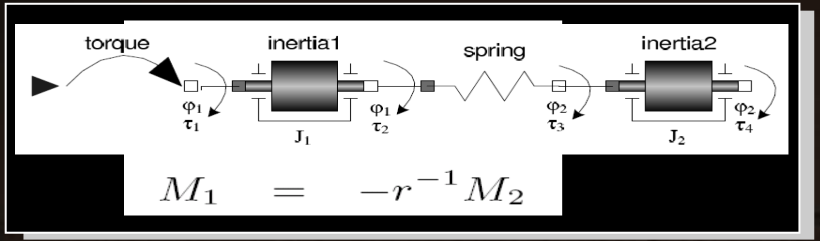
Embedded systems (computation)

Courtesy: D. Broman

Modeling Cyber-Physical Systems

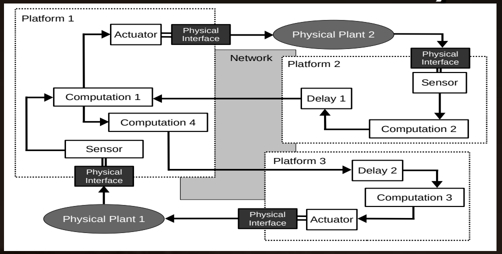
(Lee, ASV: A framework for comparing models of computation, IEEE Trans. CAD, 1998)

Model



$$M_1 = -r^{-1} M_2$$

Equation-based model



Different models of computation

Abstraction
“physical modeling”

Concept of Time

C-code

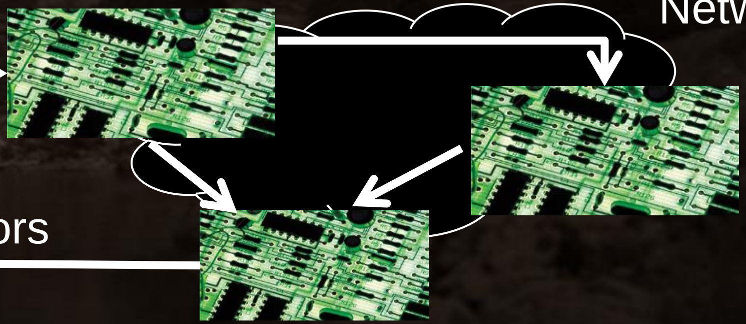
System

Physical system (the plant)

Sensors

Actuators

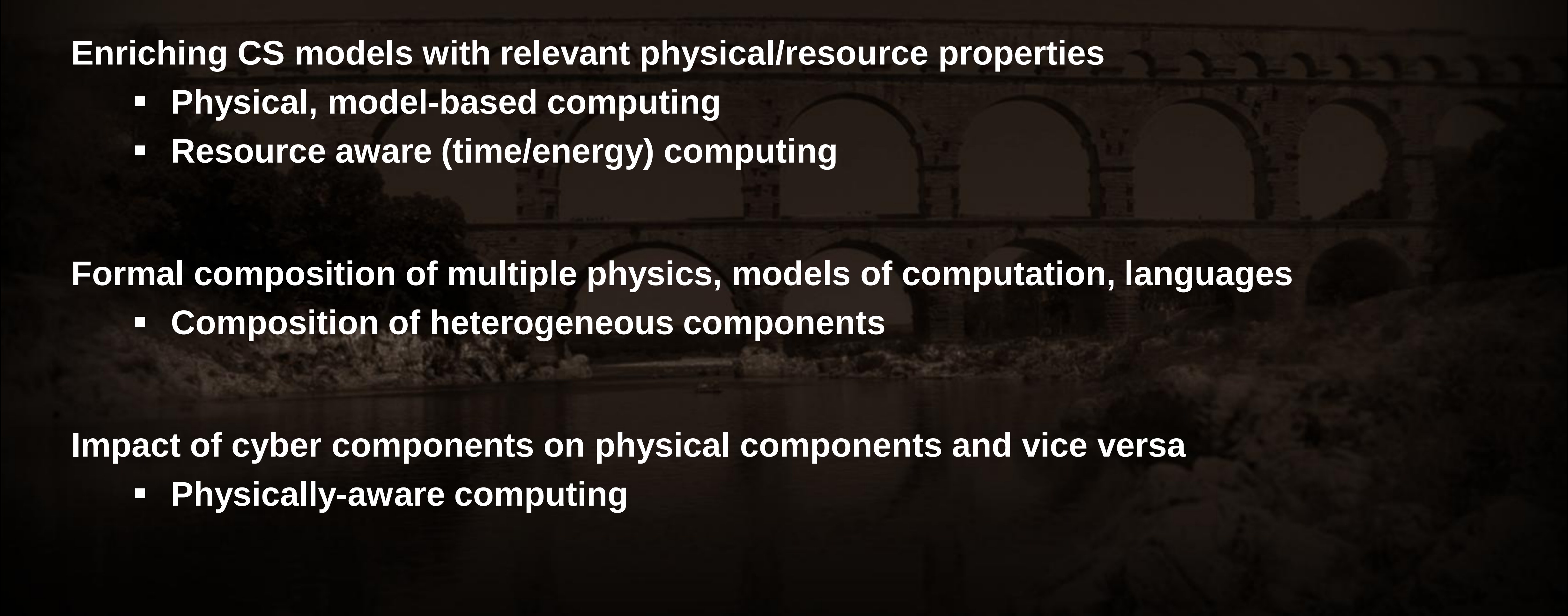
Networking



Embedded systems (computation)

Courtesy: D. Broman

CS modeling challenges for CPS



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

GM Ford TOYOTA VW HONDA DAIMLERCHRYSLER

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

Tier 1 Suppliers

Visteon DENSO JOHNSON CONTROLS BOSCH DELPHI

90%+ of revenue from automotive

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

IC Vendors

freescale semiconductor RENESAS ST infineon NEC

~15% of revenue from automotive

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

Source: Public financials, Gartner 2005

The Evolution of the Automotive DNA

CURRENT DNA	NEW DNA
Energized by Petroleum	Energized by Electricity and Hydrogen
Powered Mechanically by Internal Combustion Engine	Powered Electrically by Electric Motors
Controlled Mechanically	Controlled Electronically
Stand-alone	“Connected”
Totally Dependence on the Driver	Semi/Full Autonomous Driving
Vehicle Sized for Maximum Use – People and Cargo	Vehicle Tailored to Specific Use

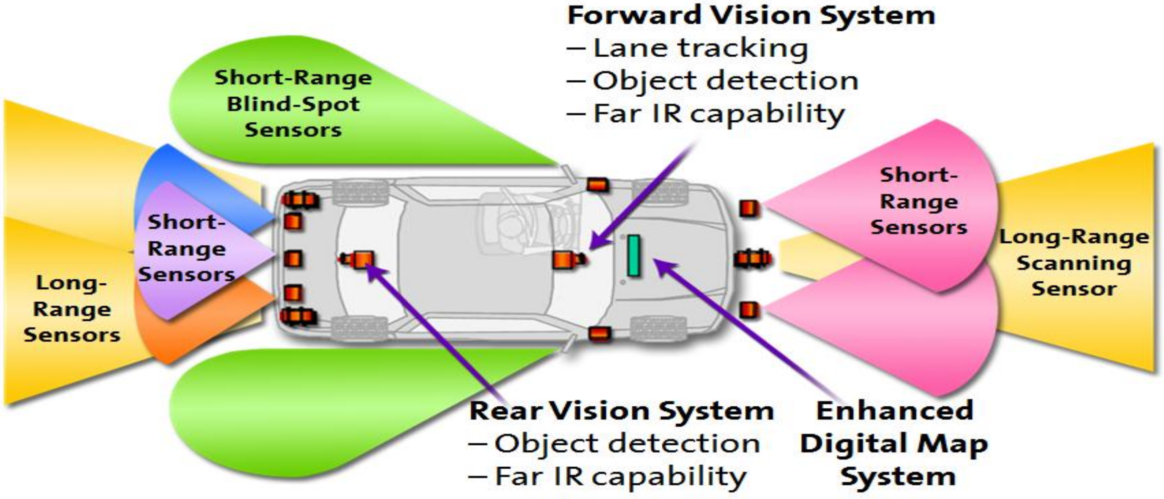
GM SAC Vehicular Electronics, Controls and Software Study

Software content in automobiles could increase by 100 X over the next 5-6 years. Challenges will include:

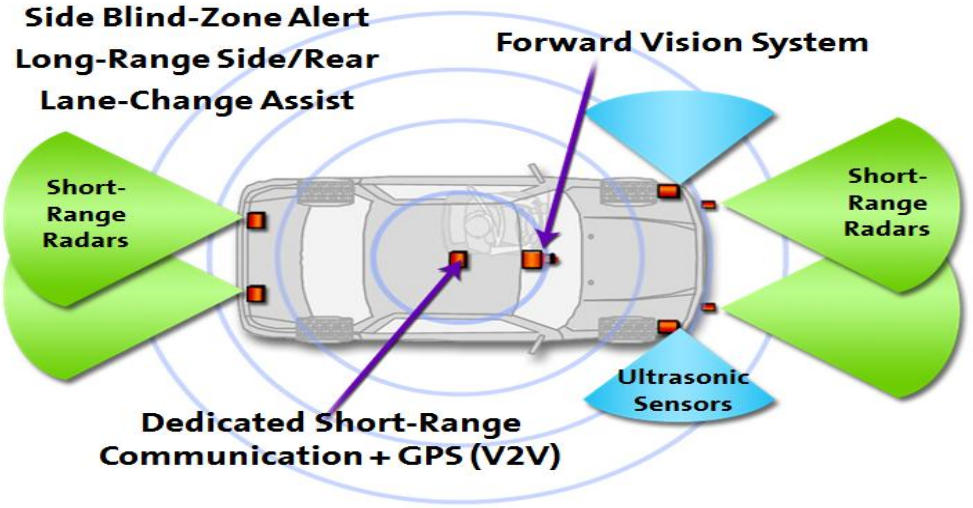
- Software system architecture
- Partitioning for modularity & system reliability
- Reuse
- Standardization of interfaces

360° SENSING CAPABILITY

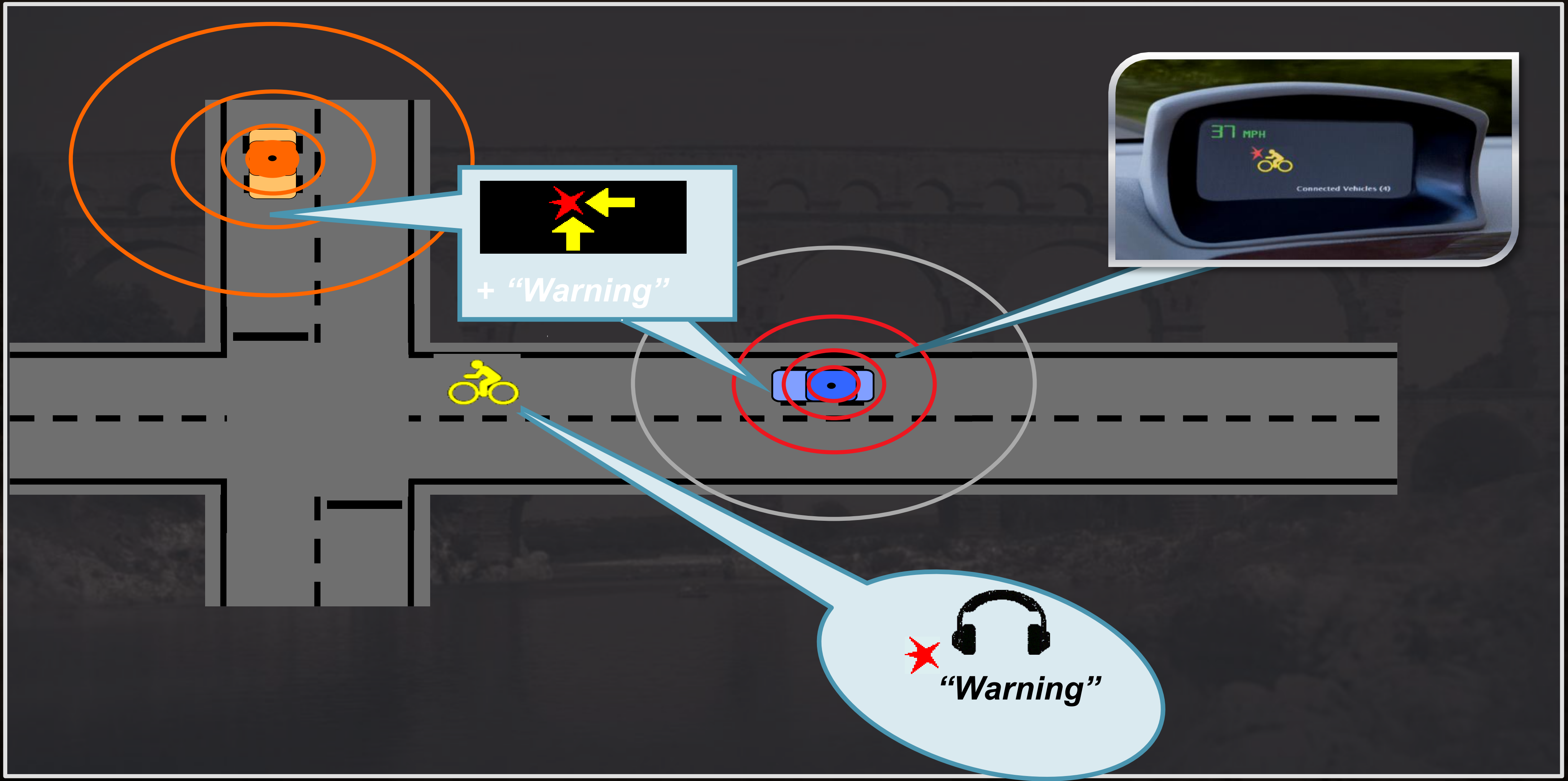
TODAY



FUTURE



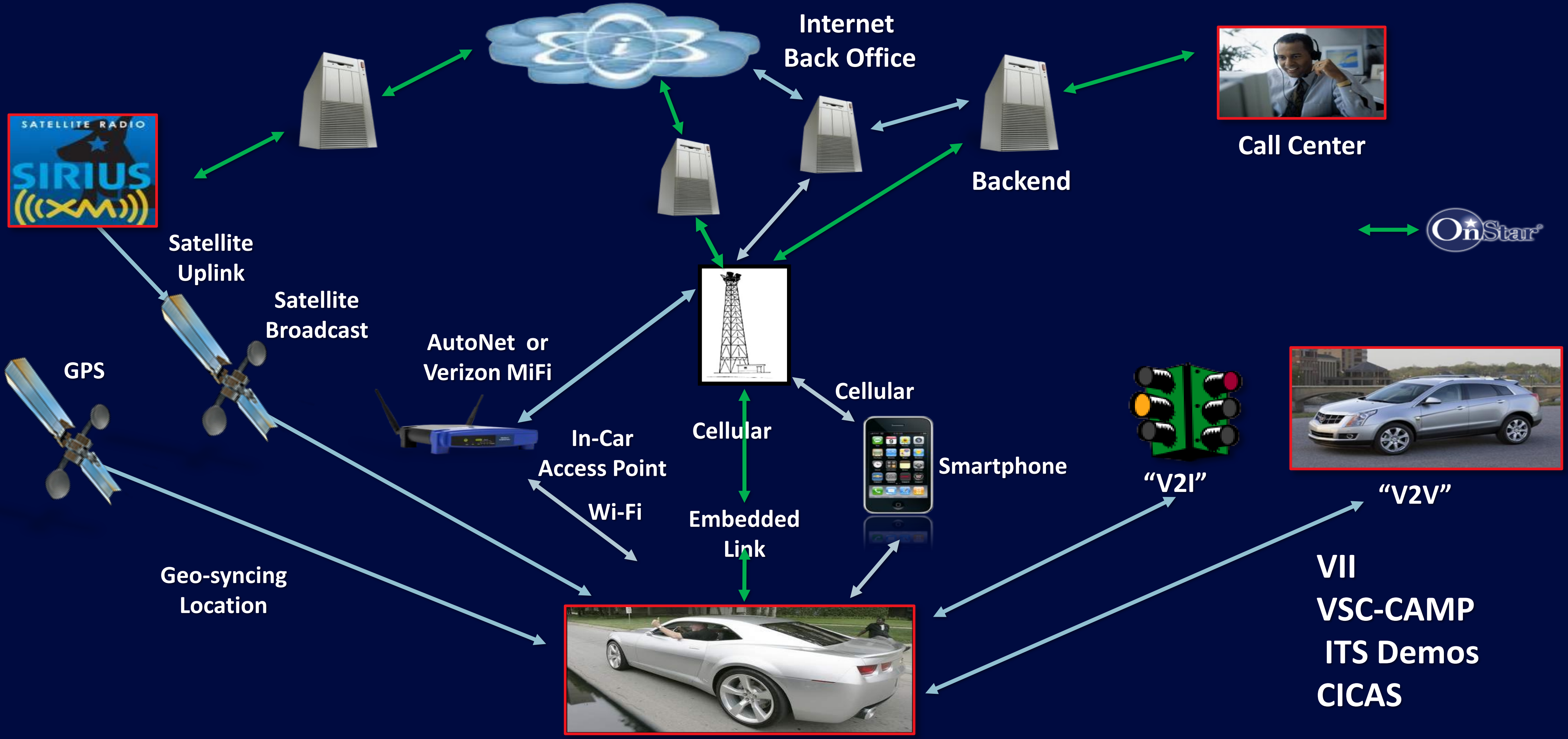
V2V/V2X COMMUNICATIONS



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



Internet
Back Office

Call Center

Backend

OnStar

Satellite
Uplink

Satellite
Broadcast

GPS

AutoNet or
Verizon MiFi

Cellular

In-Car
Access Point

Cellular

Smartphone

“V2I”

“V2V”

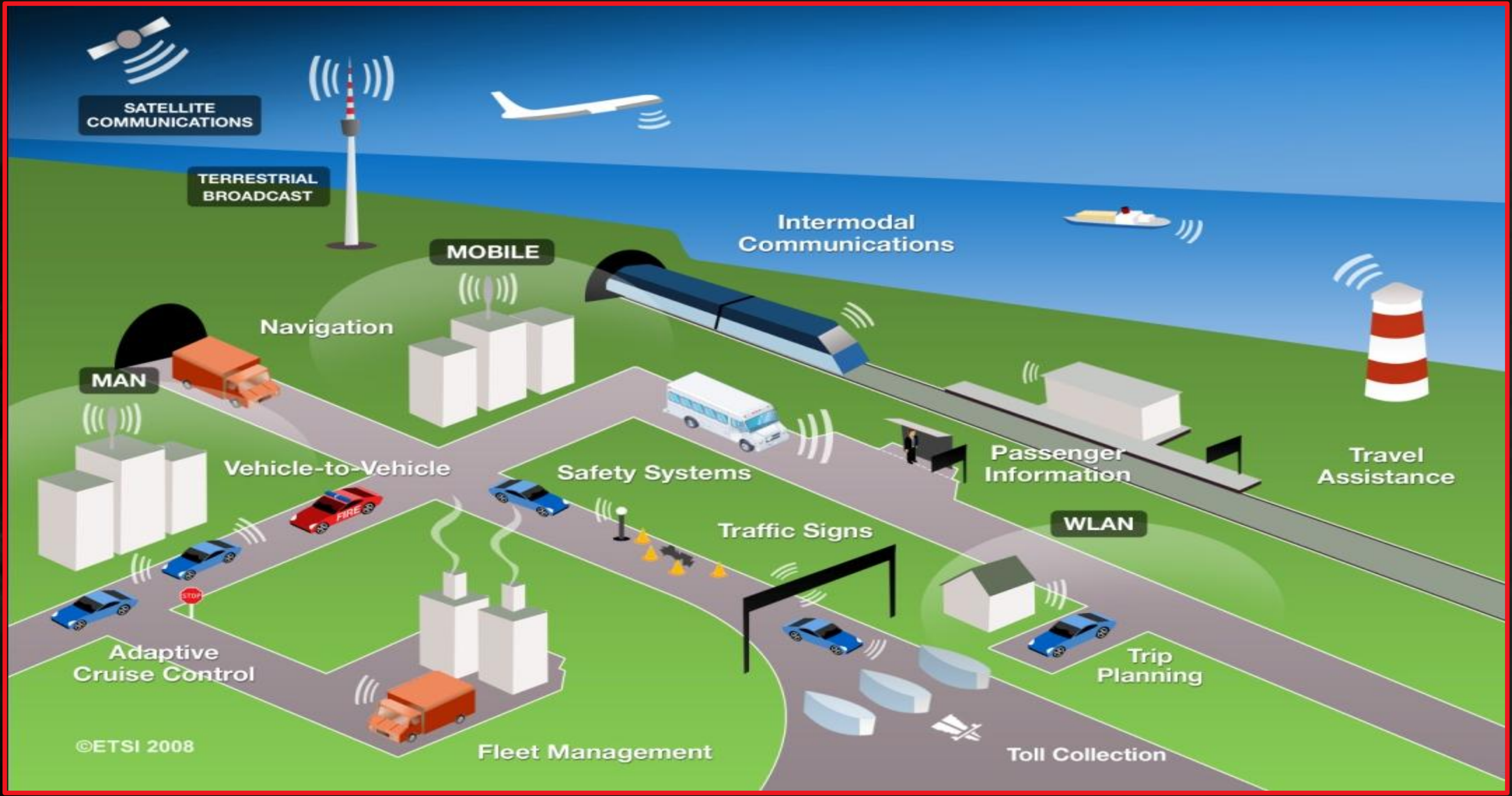
Wi-Fi

Embedded
Link

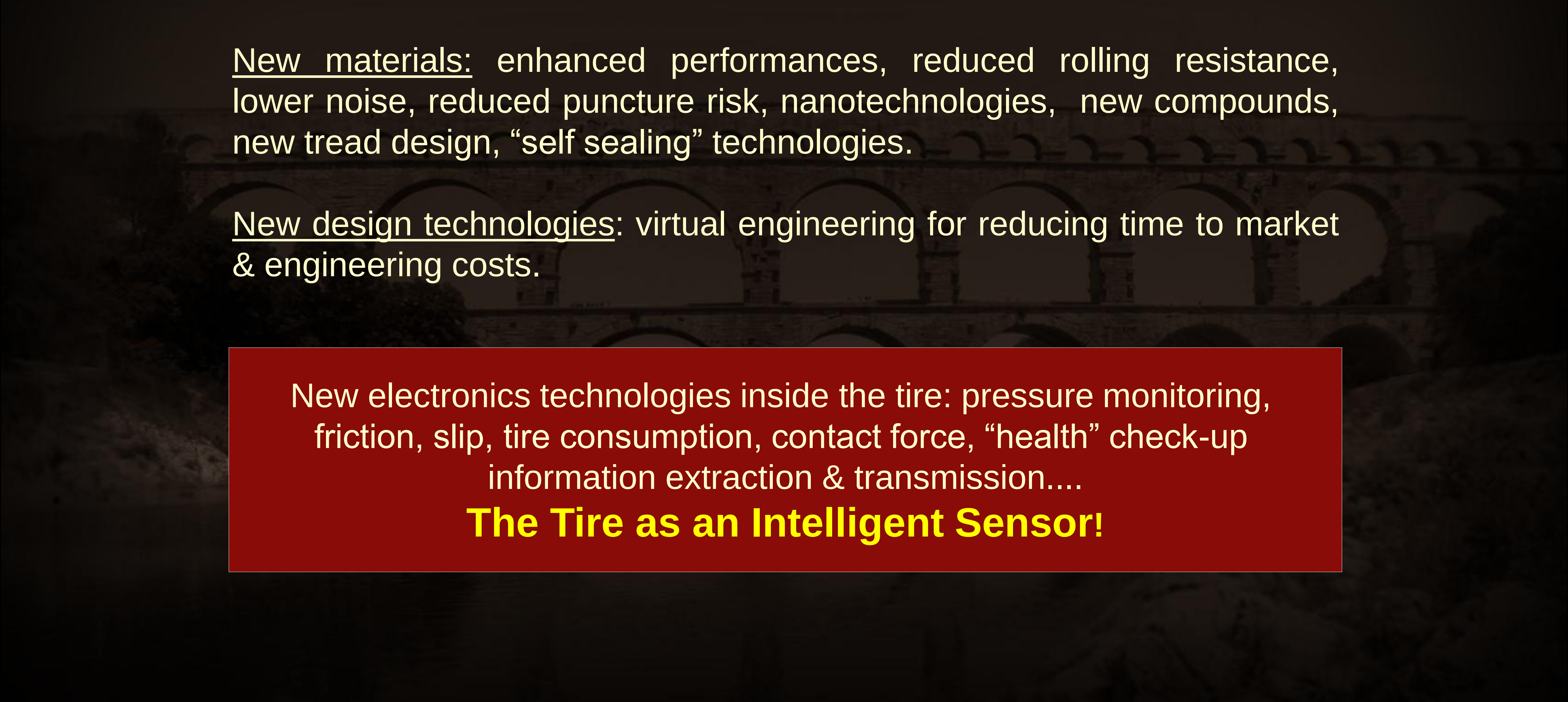
Geo-syncing
Location

VII
VSC-CAMP
ITS Demos
CICAS

ELECTRIC, CONNECTED, AUTONOMOUS



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.

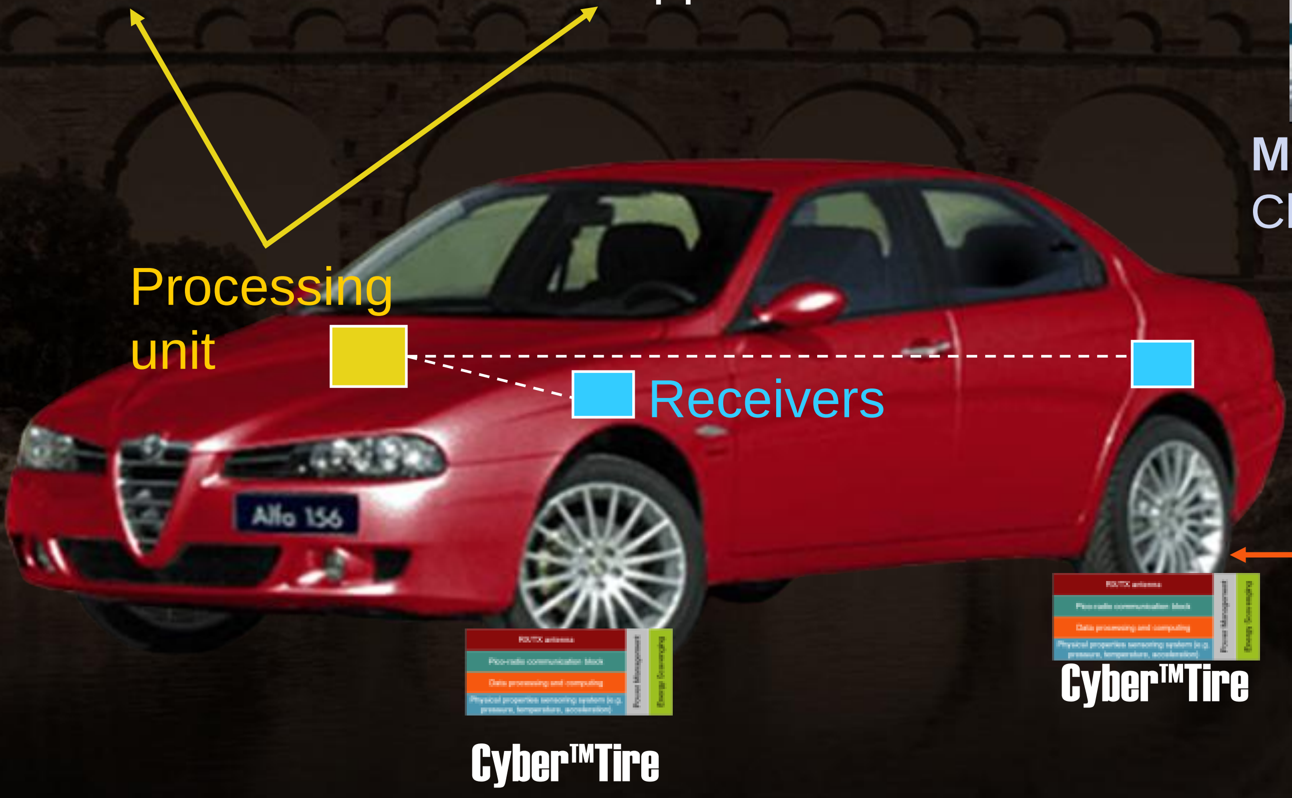
New electronics technologies inside the tire: pressure monitoring, friction, slip, tire consumption, contact force, “health” check-up information extraction & transmission....

The Tire as an Intelligent Sensor!

Cyber™ Tire System

Major broadcast channel in Italy

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



Vehicle dynamics control system

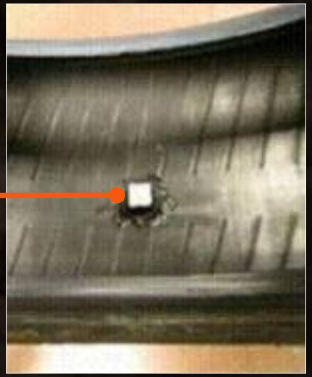
User Applications

Processing unit

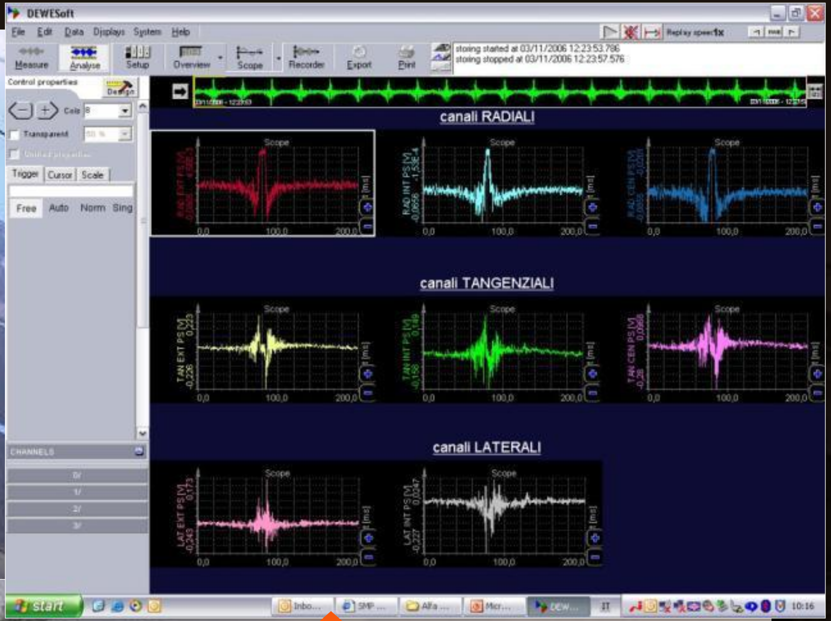
Receivers

Cyber™Tire

Cyber™Tire



Experimental Tests



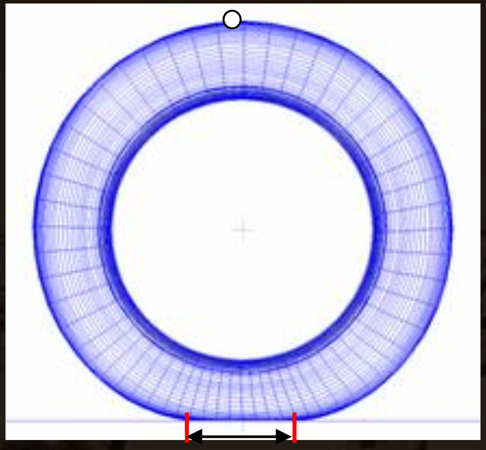
storing started at 03/11/2006 12:23:53.786
storing stopped at 03/11/2006 12:23:57.576

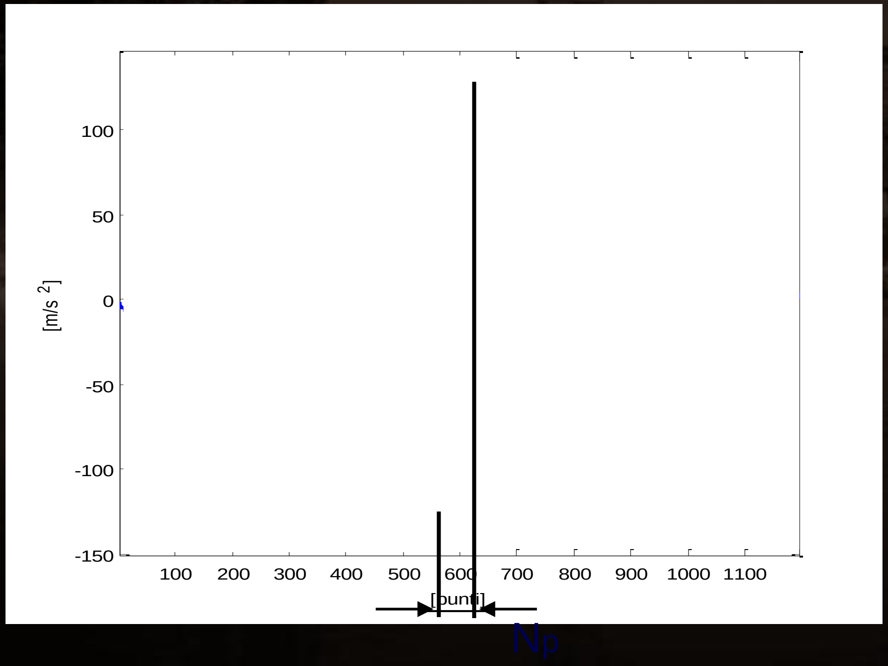
Accelerometers

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





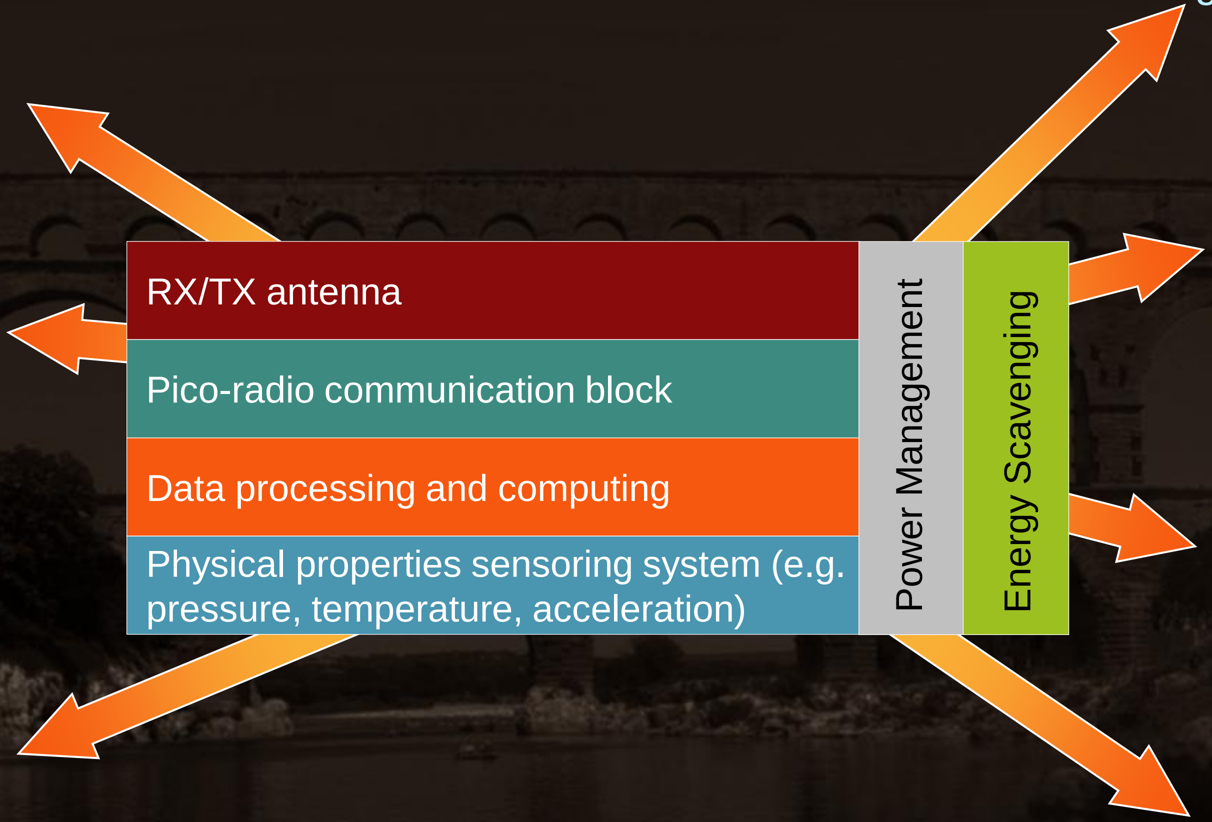
- **<u>Minimum</u> of the tangential component signal: tread area <u>entry</u>**
- **<u>Maximum</u> of the tangential component signal: tread area <u>exit</u>**

$$PL = N_p / f_c \cdot \omega \cdot R_{rot}$$

PL : tread length

R_{rot} : rolling radius
ω : angular speed
f_c : sampling rate

Cyber™ Tyre Development Partners



RX/TX antenna

Pico-radio communication block

Data processing and computing

Physical properties sensoring system (e.g. pressure, temperature, acceleration)

Power Management

Energy Scavenging

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
assembly and
packaging
technologies

ST Micro.
MEMS
Accelerometers

Accent S.p.A.
acquisition, processing and
advanced architectural
technologies

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

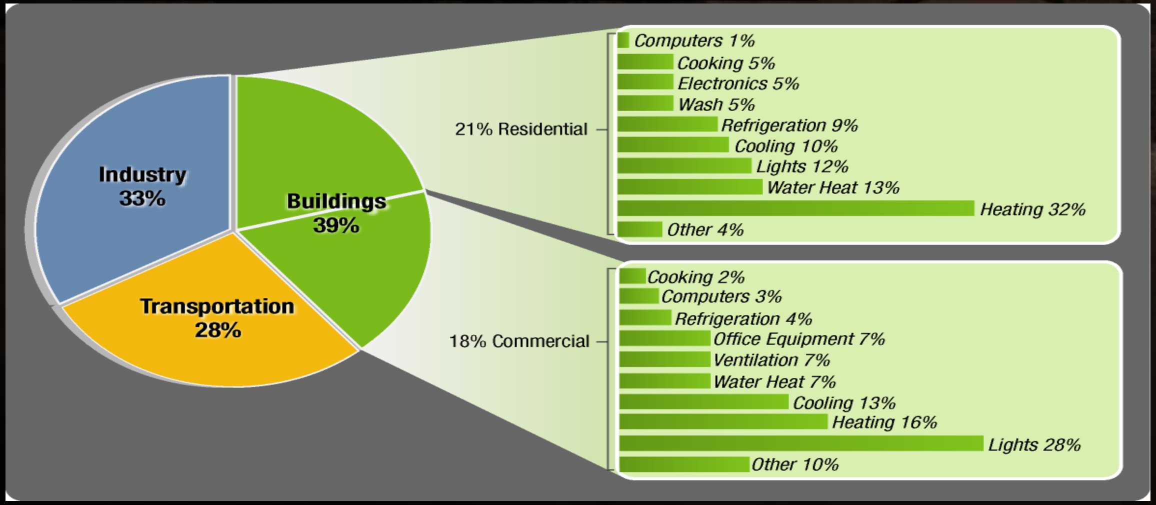
Building produce 48% of U.S. Carbon emissions

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

[redacted]

[redacted]



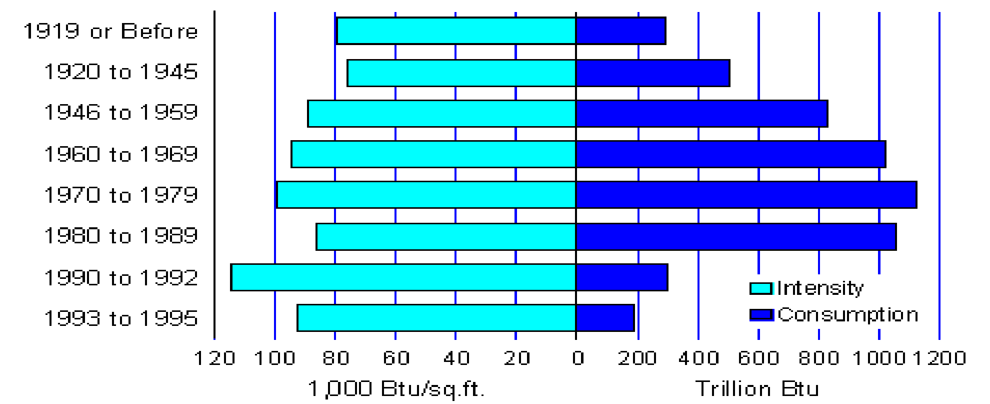
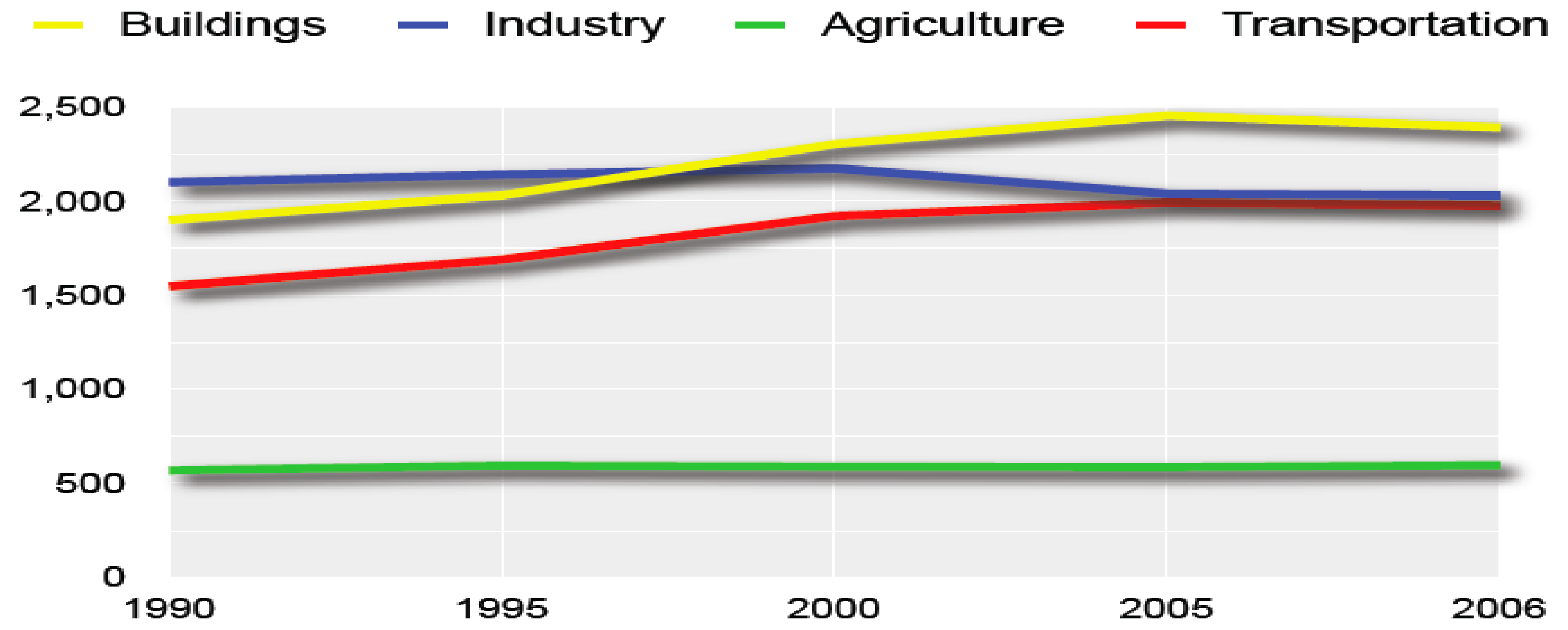


Figure 10. Energy Consumption and Intensity by Year Constructed, 1995

Energy Information Administration
1995 Commercial Buildings Energy Consumption Survey

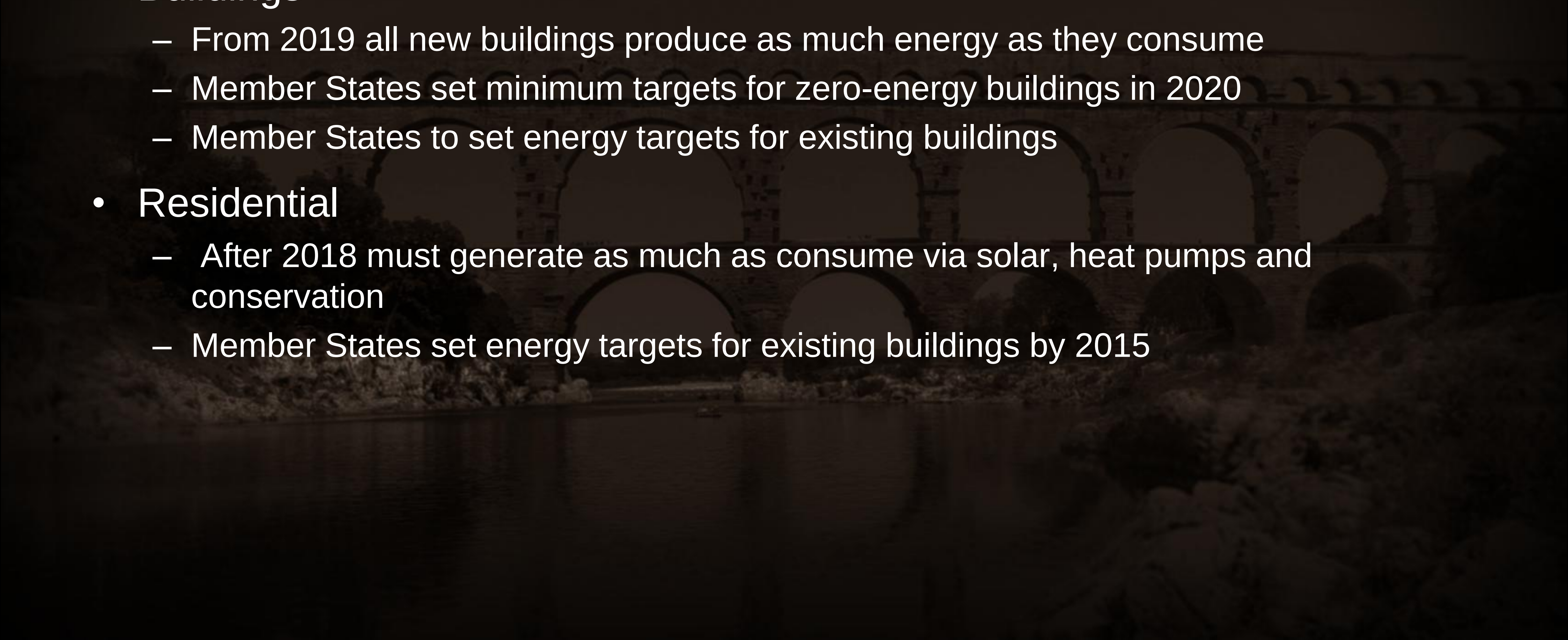
Sources: Ryan and Nicholls 2004, USGBC, USDOE 2004

Greenhouse Gas Emissions by Sector



U.S. EPA Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2006

European Union thinking



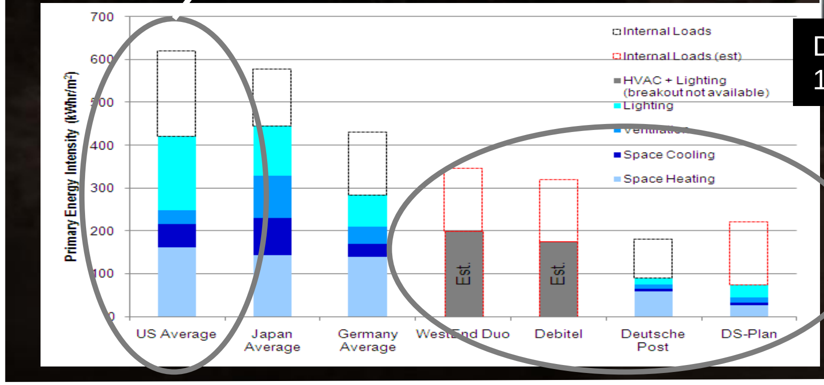
- Buildings
  - From 2019 all new buildings produce as much energy as they consume
  - Member States set minimum targets for zero-energy buildings in 2020
  - Member States to set energy targets for existing buildings
- Residential
  - After 2018 must generate as much as consume via solar, heat pumps and conservation
  - Member States set energy targets for existing buildings by 2015

Energy Efficient Buildings: Current State

Market Penetration/Size and Readiness

“One size fits all”

Chicago IL
1.2M ft², 300 kWhr/m²

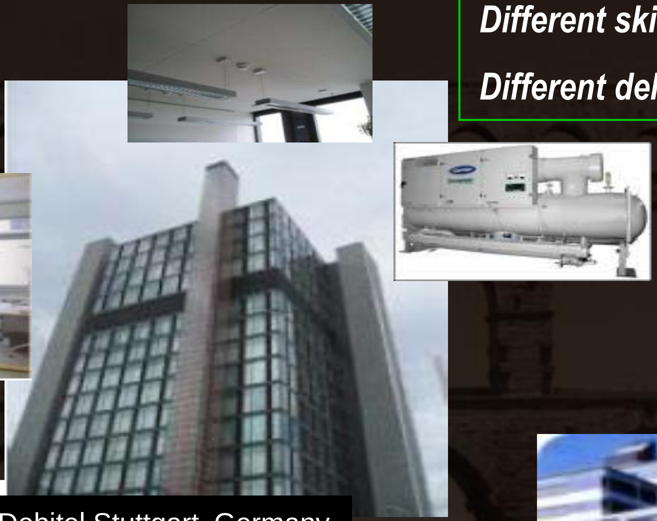


Increasing integration of subsystems & control

Different types of equipment

Different skills

Different deliver



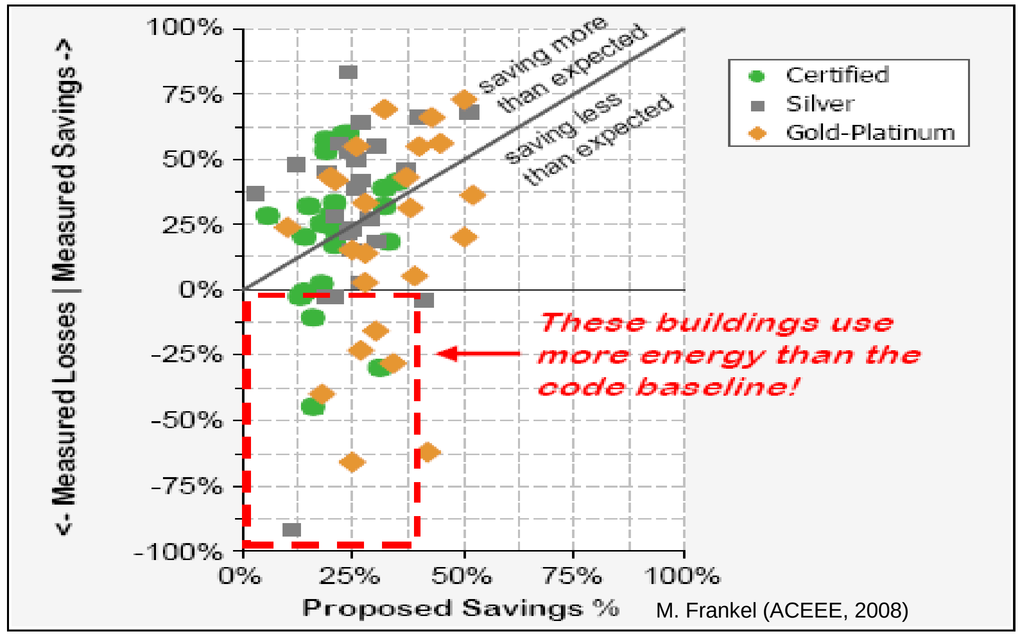
Debitel Stuttgart, Germany
120K ft², 165kWhr/m²/yr

“Climate Adaptive Design”

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

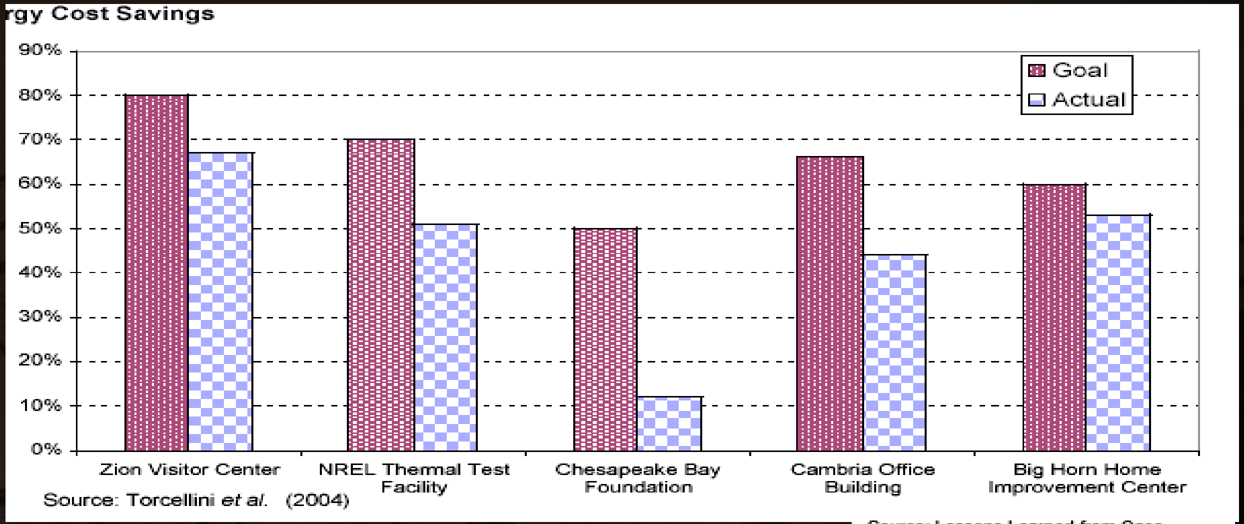
10-20% 20-40% 50%+ Energy Efficiency

Energy Efficient Buildings: Reality



M. Frankel (ACEEE, 2008)

Designs over-predict gains by ~20-30%



Source: Torcellini *et al.* (2004)

Source: Lessons Learned from Case Studies of Six High-Performance Buildings, P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, 2006, NREL Technical Report.

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

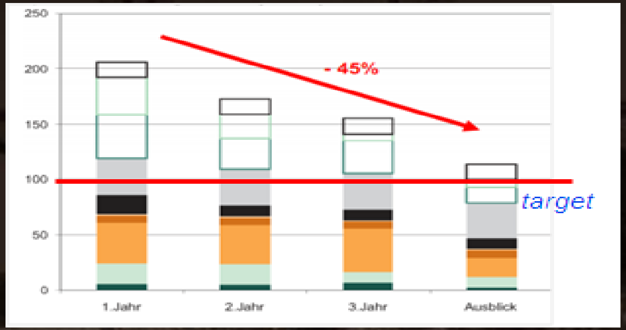
Cambria Office Building

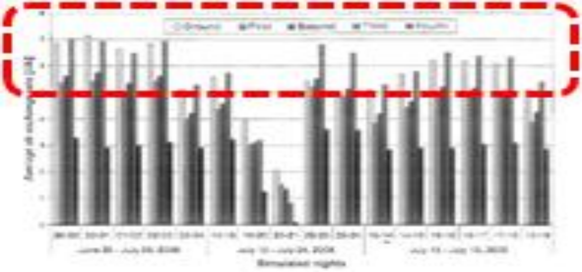
Design Intent: 66% (ASHRAE 90.1); Measured 44%

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

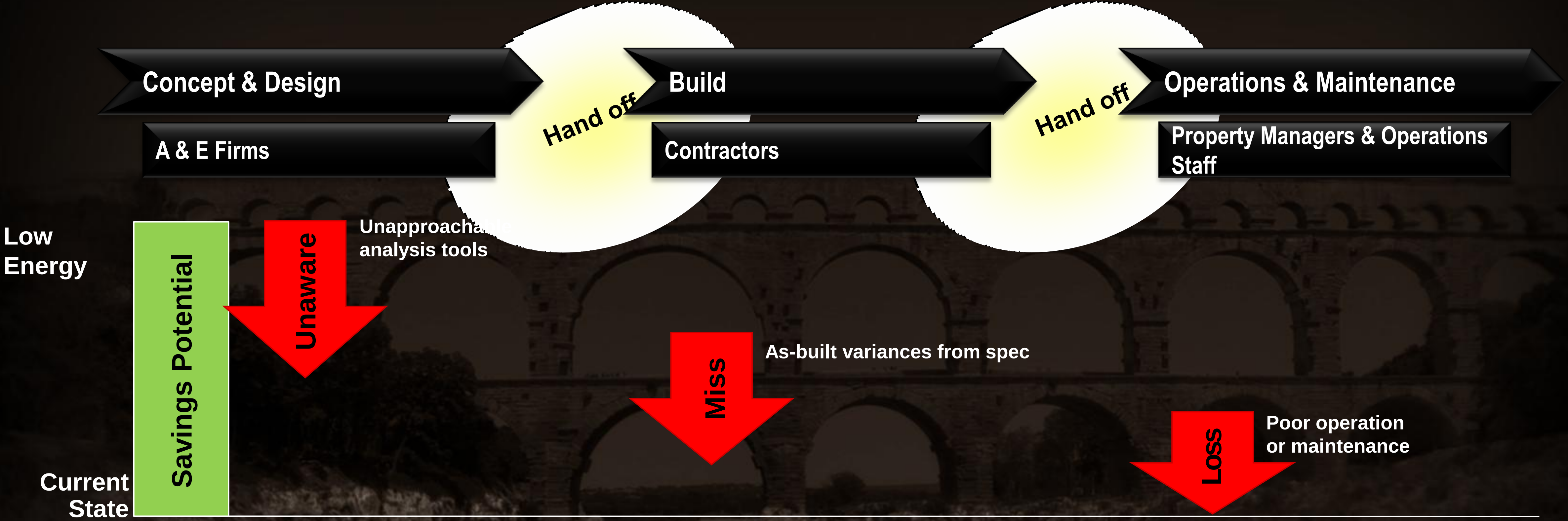




“As designed” energy performance accomplished after substantial system tuning

Source: Lessons Learned from Case Studies of Six High-Performance Buildings, P. Torcellini, S. Pless, M. Deru, B. Griffith, N. Long, R. Judkoff, 2006, NREL Technical Report.

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



Concept & Design

A & E Firms

Hand off

Build

Contractors

Hand off

Operations & Maintenance

Property Managers & Operations Staff

Low Energy

Current State

Savings Potential

Unaware

Unapproacha
analysis tools

Miss

As-built variances from spec

Loss

Poor operation
or maintenance

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

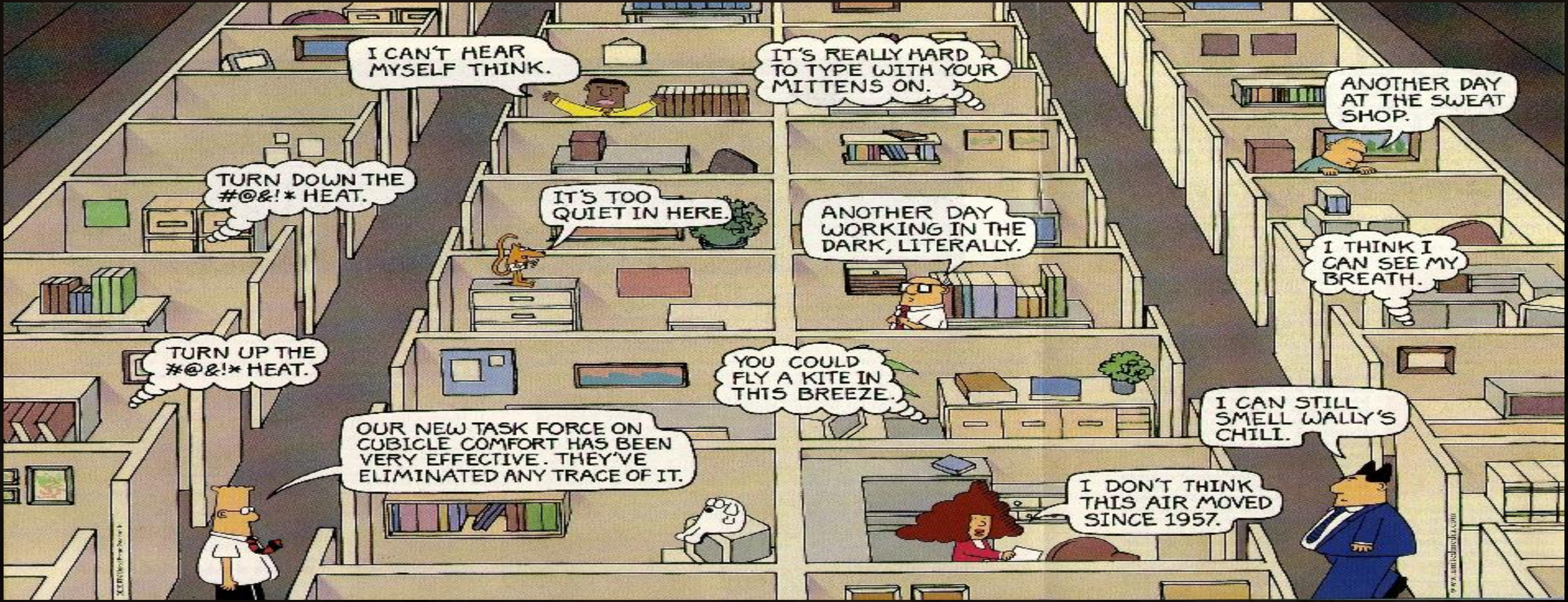
Implication on Cost

- Measurement costs
- Recommissioning costs

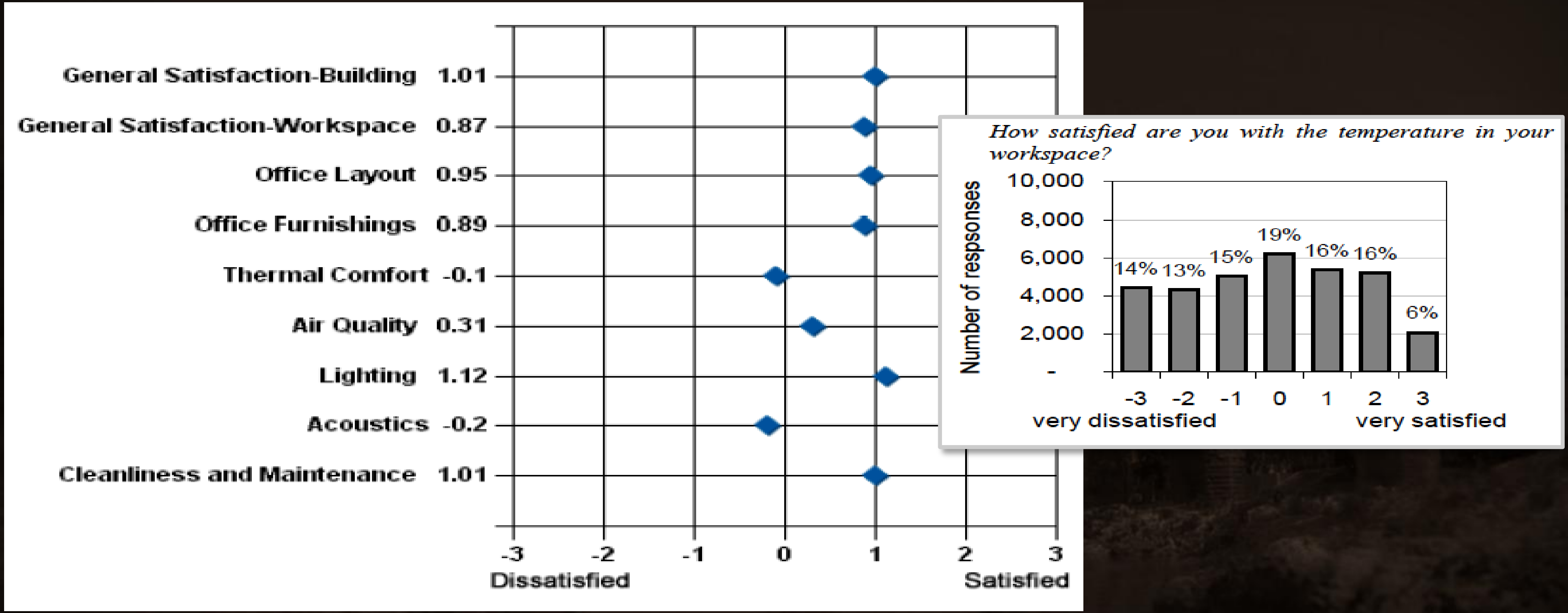
Implication on Risk

- Facility operations skillsets
- Unbounded costs to ensure performance

They Don’t Even Create Comfortable Environments

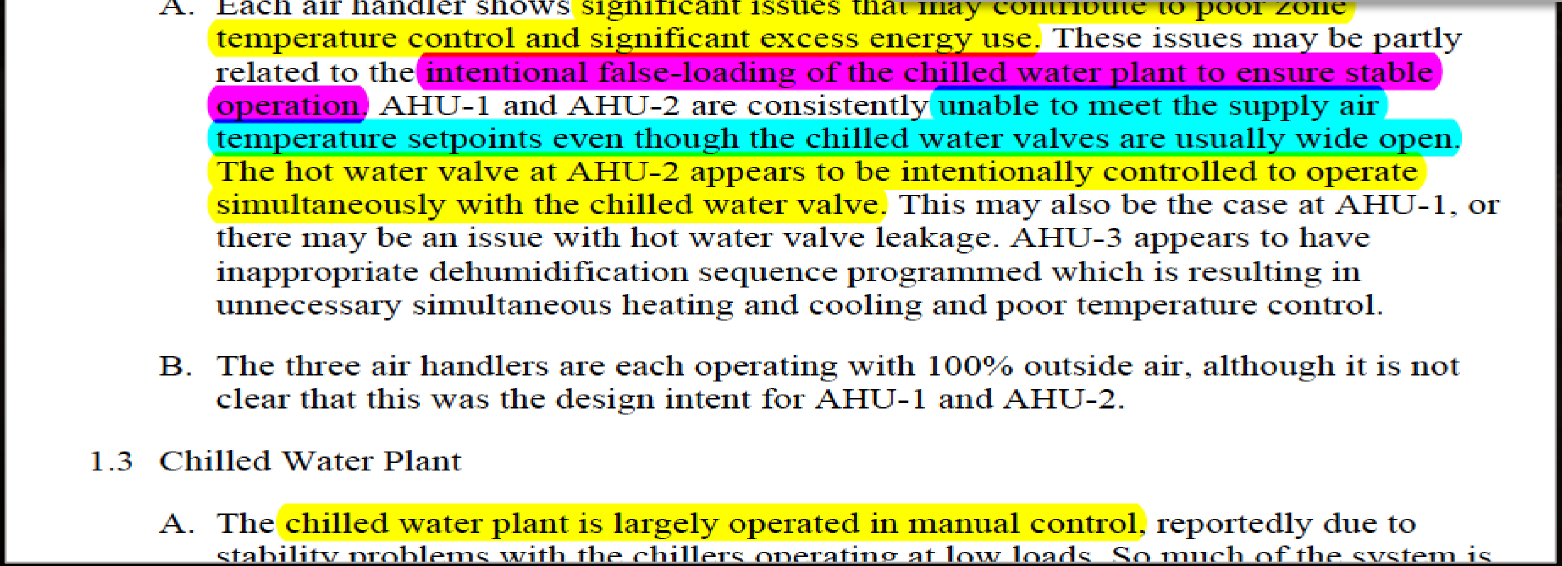


Really … Not Just In Dilbert



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

Molecular Foundry Performance Review, September 2010



1.0 Executive Summary

1.1 This report summarizes observations of the syst
based on a review of the trend data in early Sept
primarily on the operation of the chilled water p

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

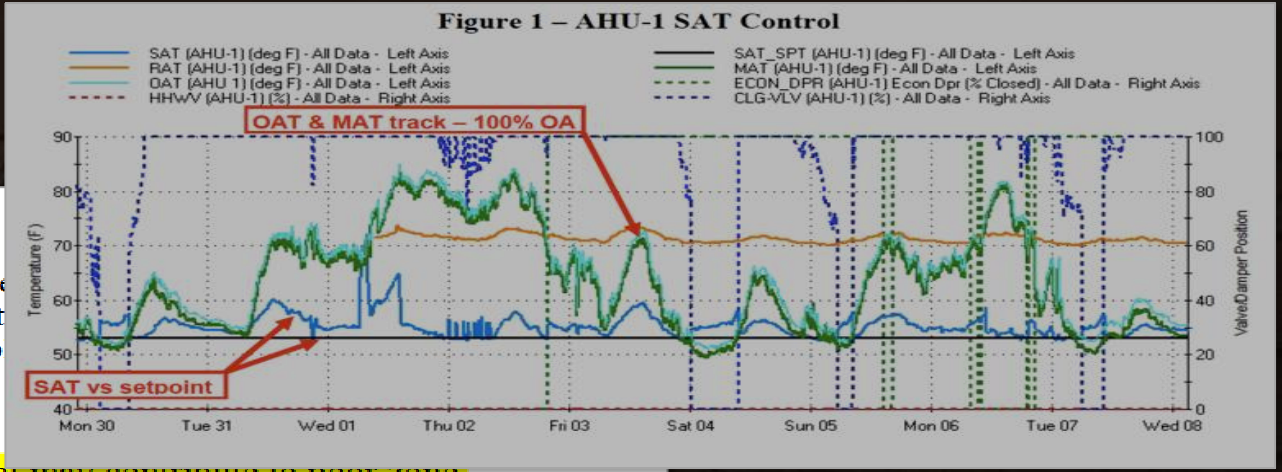
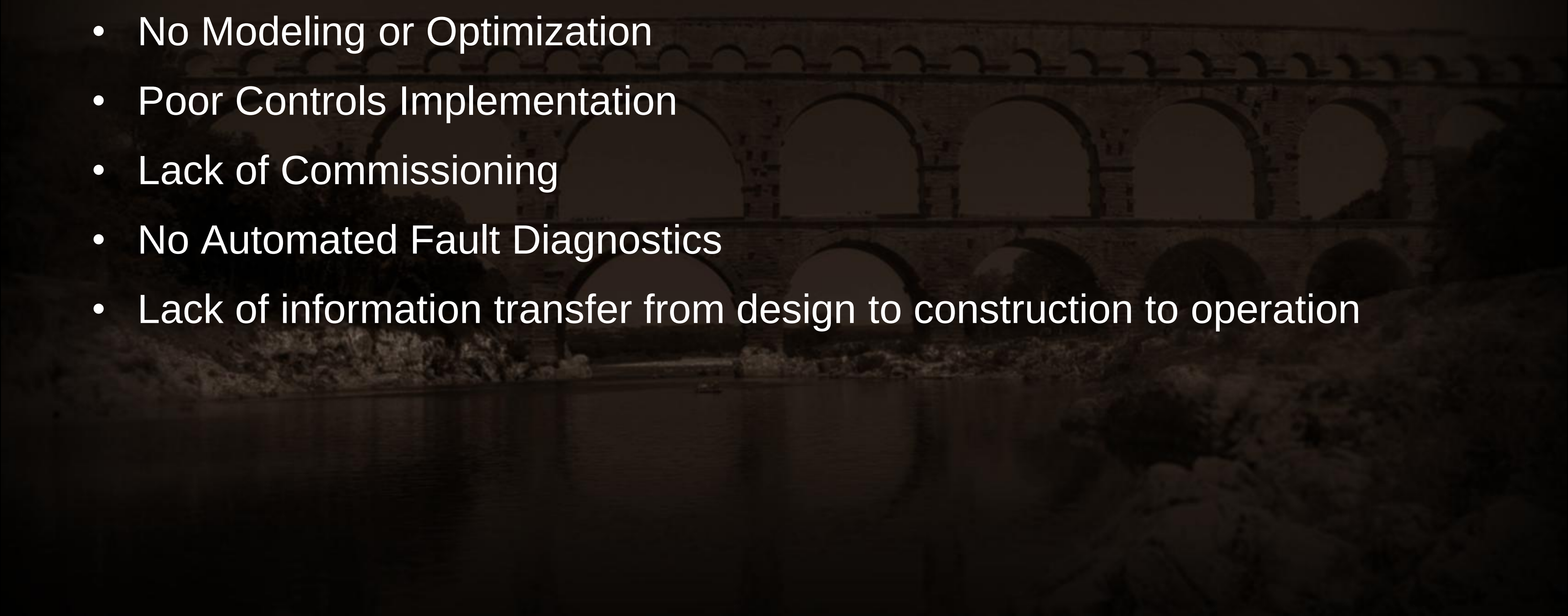


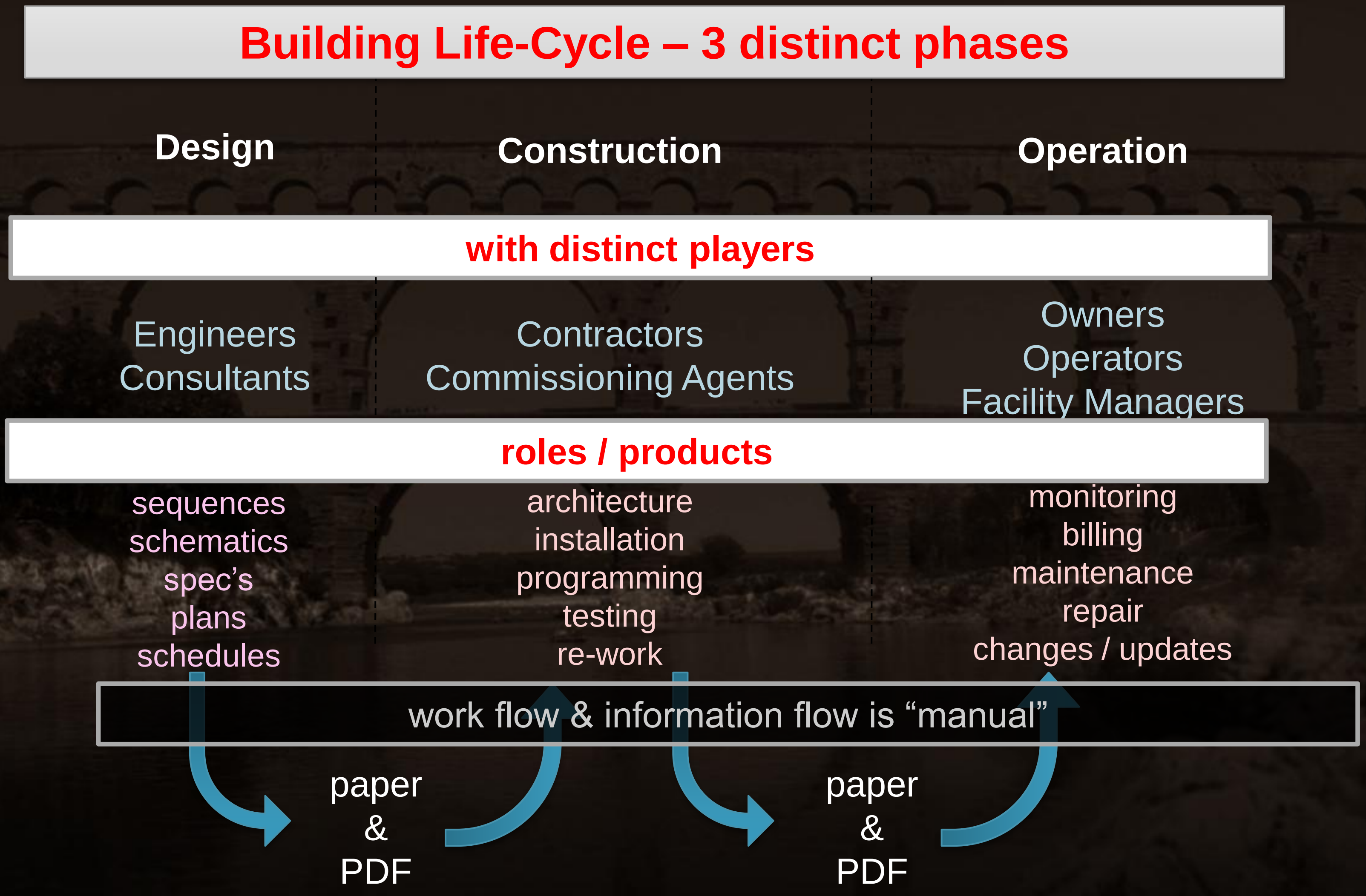
Figure 1 – AHU-1 SAT Control

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

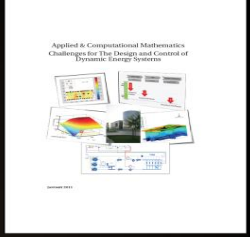
Design	**Construction**	**Operation**
with distinct players		
Engineers Consultants	Contractors Commissioning Agents	Owners Operators Facility Managers
roles / products		
sequences schematics spec's plans schedules	architecture installation programming testing re-work	monitoring billing maintenance repair changes / updates

work flow & information flow is "manual"

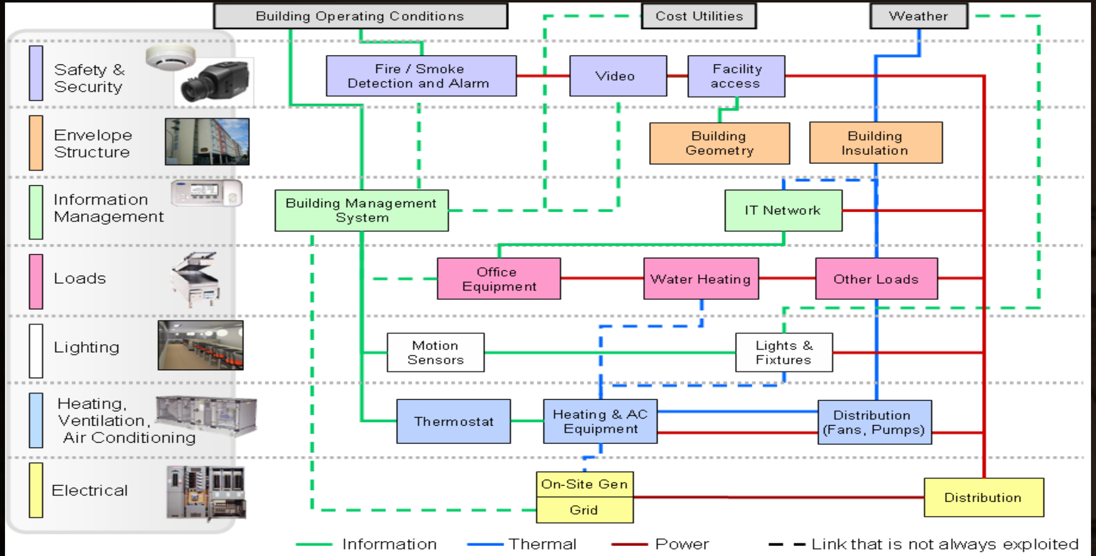
paper
&
PDF

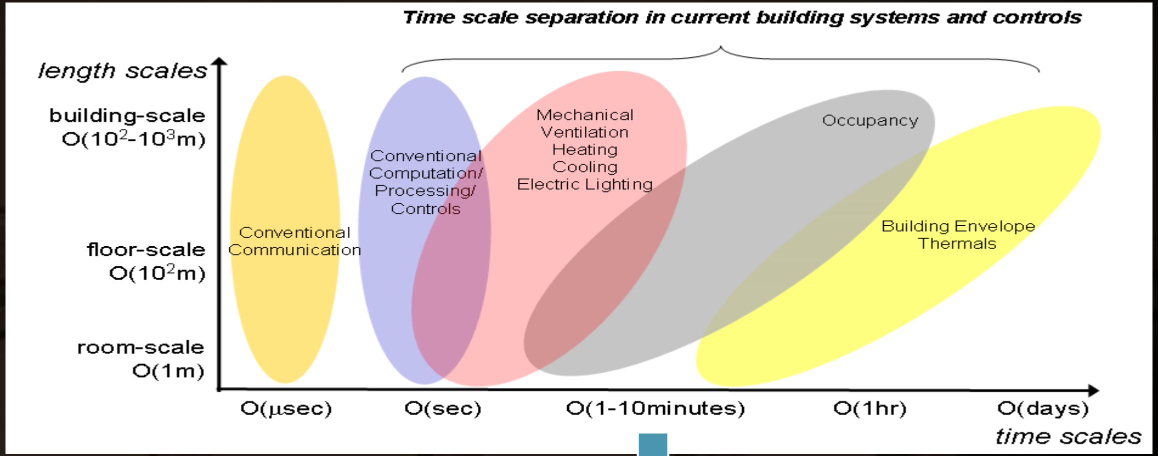
paper
&
PDF

Complexity* in Building Systems

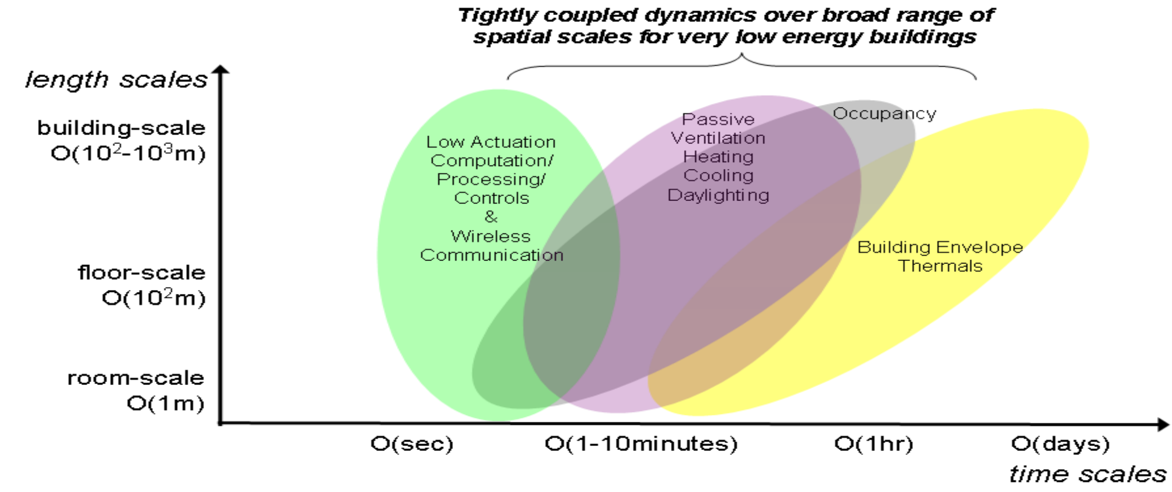


Applied & Computational Mathematics
Challenges for The Design and Control of
Dynamic Energy Systems





Going from 30% efficiency to 70-80% efficiency



- 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*
David L. Brown, John Bell, Donald Estep, William Gropp, Bruce Hendrickson, Sallie Keller-McNulty, David Keyes, J. Tinsley Oden and Linda Petzold, DOE Report, LLNL-TR-401536, May 2008.

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.

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