Communication Infrastructure Synthesis and its Application to Cyber Physical Systems: The Intelligent Building case

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Outline

- Societal IT Systems and Cyber-Physical Systems: a Perspective
- The Need for an Integrated Approach to Design: Platform-Based Design
- Communication Synthesis
- Communication Synthesis for Efficient Building Management

The Emerging IT Scene

Courtesy: J. Rabaey

The Technology Gradient: Communication

Mostly wired

Almost uniquely wireless

Exponentials Bound to Continue

EE Times: Latest News

Wireless is everywhere; ignore it at your peril

Bolaji Ojo

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EE Times

(01/07/2008 9:00 AM EST)

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REPRINTS

The search is over for the next killer app. It is wireless, it is all around you, and it will leave no sector of the global economy untouched.

EE Times,
January 07, 2008

- **5 Billion people to be connected by 2015 (Source: NSN)**
- **The emergence of Web2.0**
  - **The "always connected" community network**
- **7 trillion wireless devices serving 7 billion people in 2017 (Source: WirelessWorldResearchForum (WWRF))**
  - **1000 wireless devices per person?**

[Courtesy: Niko Kiukkonen, Nokia]

The Birth of "Societal IT Systems (SiS)" or "Cyber-Physical Systems (CPS)"

"A complex collection of sensors, controllers, compute nodes, and actuators that work together to improve our daily lives"

- **The Emerging Service Models**
  - Automotive and avionic safety and control
  - Environmental control, energy management and safety in "high-performance" homes
  - Immersion-based work and play
  - Management of metropolitan traffic flows
  - Distributed health monitoring
  - Power distribution with decentralized energy generation

Bottom Line: System Integration

- The Challenge Is NOT in the components themselves, but is Component Integration. This is true for hardware, software, and so/rdware components
  - Solution space exploration almost impossible due to large number of alternatives and lack of adoption of rigorous methods for system-level design
  - Design Validation Remains the Key Bottleneck and is CERTAINLY Getting Even Harder: unpredictable emerging collective behaviors, unexplored corner cases, unforeseen use model…..
- A synthesis approach is essential to solve some of these design problems

Overarching Design Challenge in Integration

Yesterday	Features (can you do it?)
Today	Cost (are you cheaper?)
Tomorrow	Integration (but can you also…?)

Industry will move towards robust architectures which can:

- create a system by just interconnecting modules
- mix-and-match components from different vendors
- avoid costly system-level simulations

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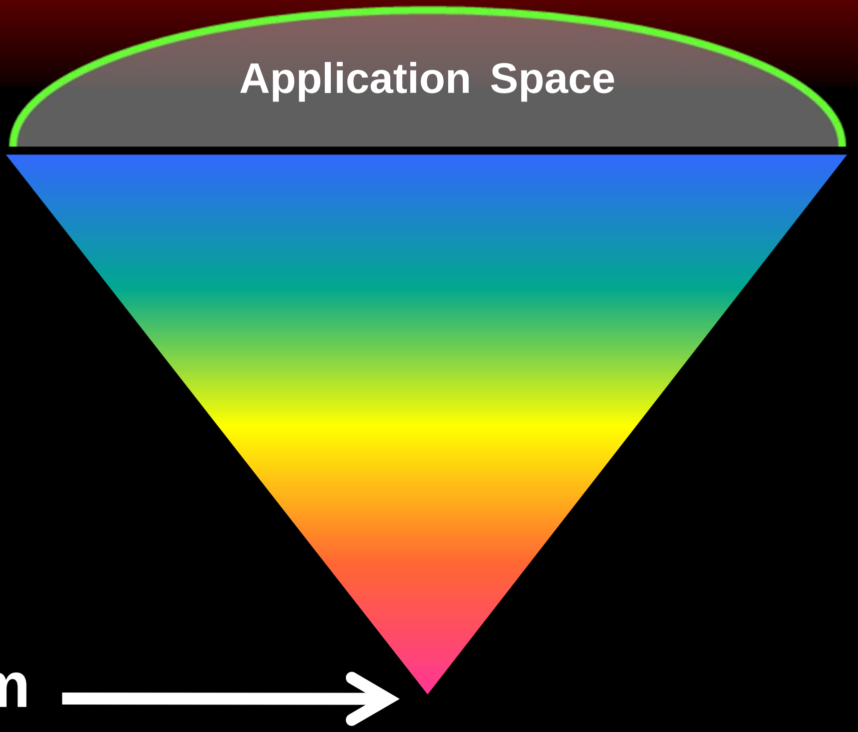
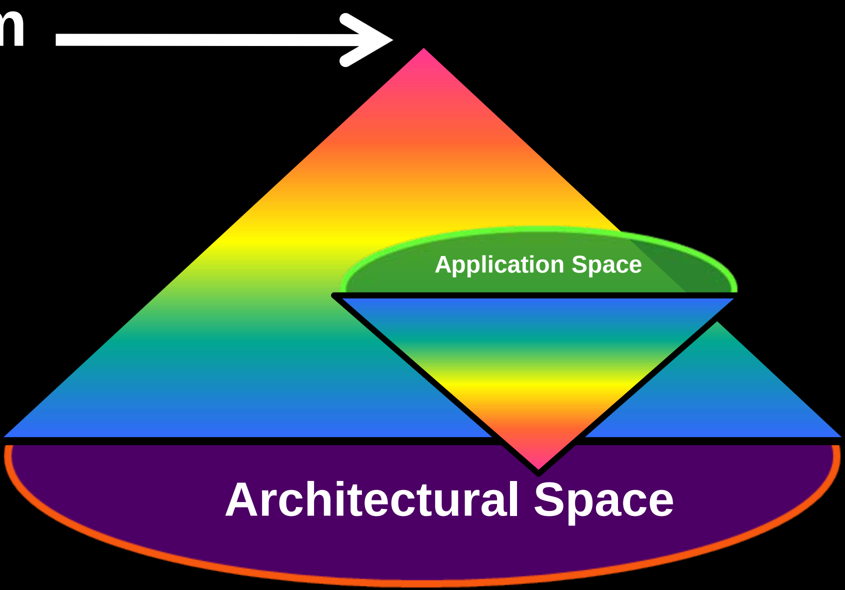
Designing Platforms: the Component Company View



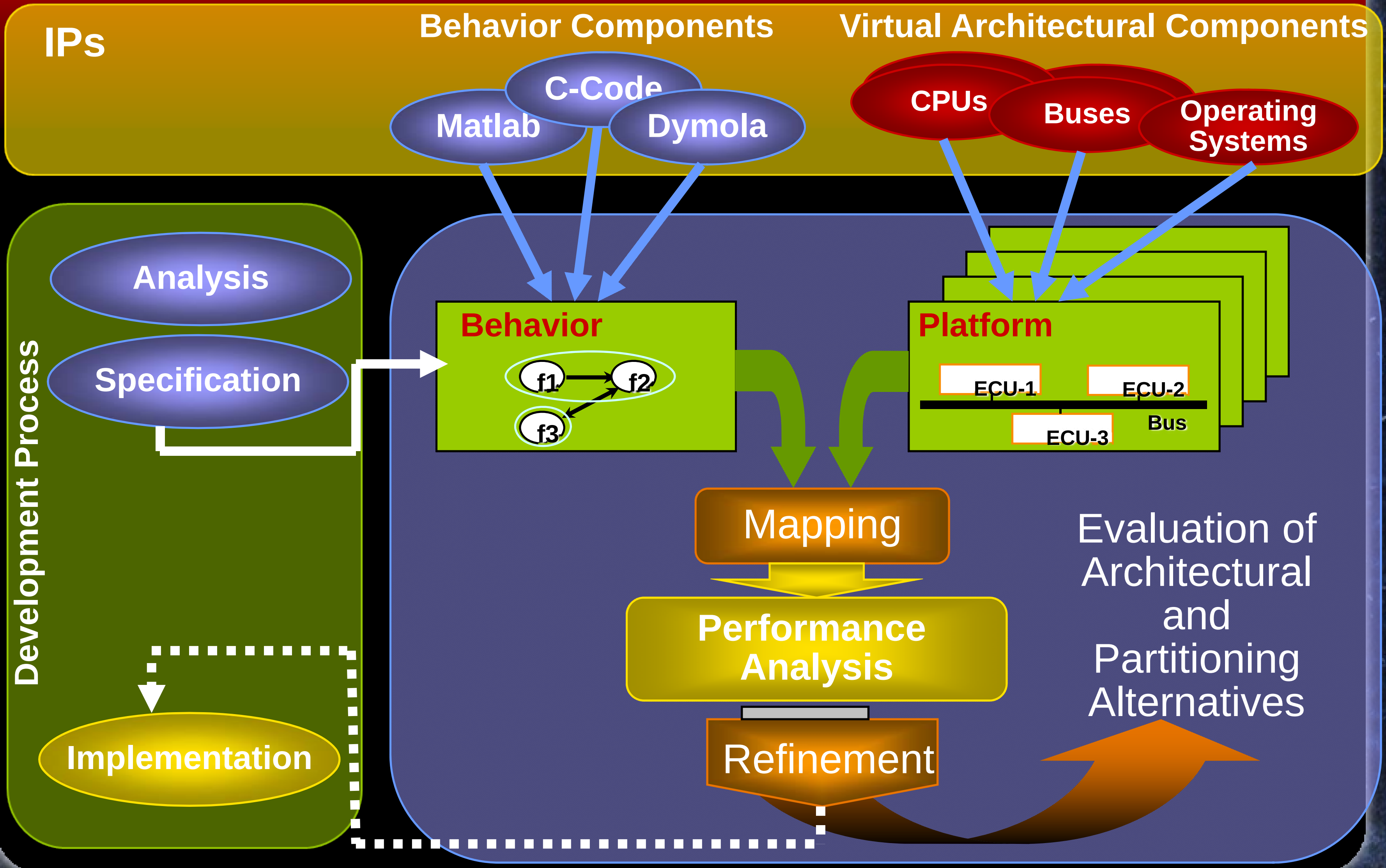
Ideal Architectural Platform

Using Platforms:
the System Company View

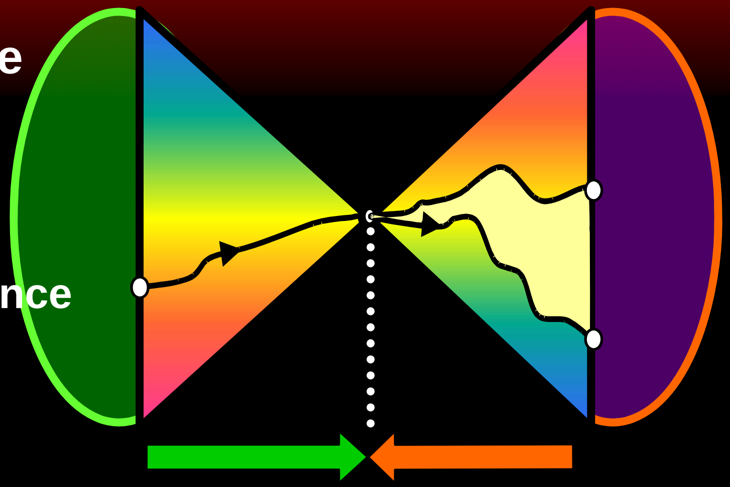
Ideal Application Platform



Separation of Concerns (ca. 1990)



Platform-Based Design



- **Platform: library of resources defining an abstraction layer**
  - Resources do contain virtual components i.e., place holders that will be customized in the implementation phase to meet constraints
  - Very important resources are interconnections and communication protocols

Platforms in Practice: Samsung

"**Platform-based design** greatly reduces time, cost and overall design risk for developing derivative products, as well as providing the framework for responding quickly to future technologies and changing market requirements. Our newest SoC device for the digital TV market stands shoulder to shoulder with industry leaders in every core technology from picture quality, performance, data processing, speed, and specialized design architecture"

- Don H. Lee, Senior Vice President ASPDAC Key Note Address

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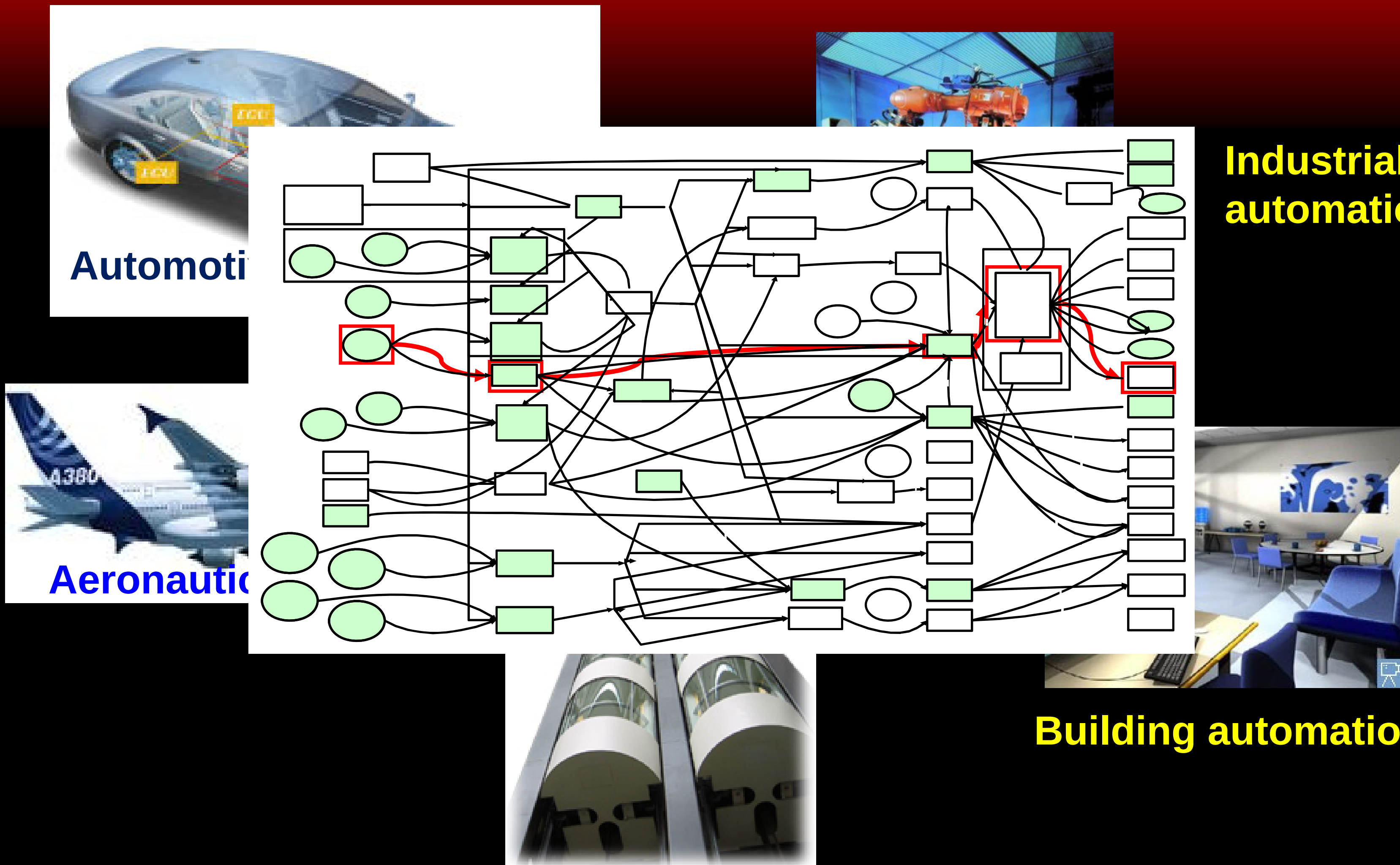
- The Need for an Integrated Approach to Design: Platform-Based Design
- Communication Synthesis (GM, Intel, UTC, Telecom Italia, Pirelli)
- Communication Synthesis for Efficient Building Management

Communication Synthesis Infrastructure (COSI) Methodology

- Capture metrics of interest with *quantities* (performance and constraints)
  - Partially ordered sets
- Define *communication structures* as components annotated with quantities
  - Function, Platform Instance, Implementation
- Define a *platform*
  - Library of components , Composition rules
- Develop *algorithms*
  - Given a function and a platform find the best mapping of the function onto a platform instance

Latency Requirements in Distributed Systems

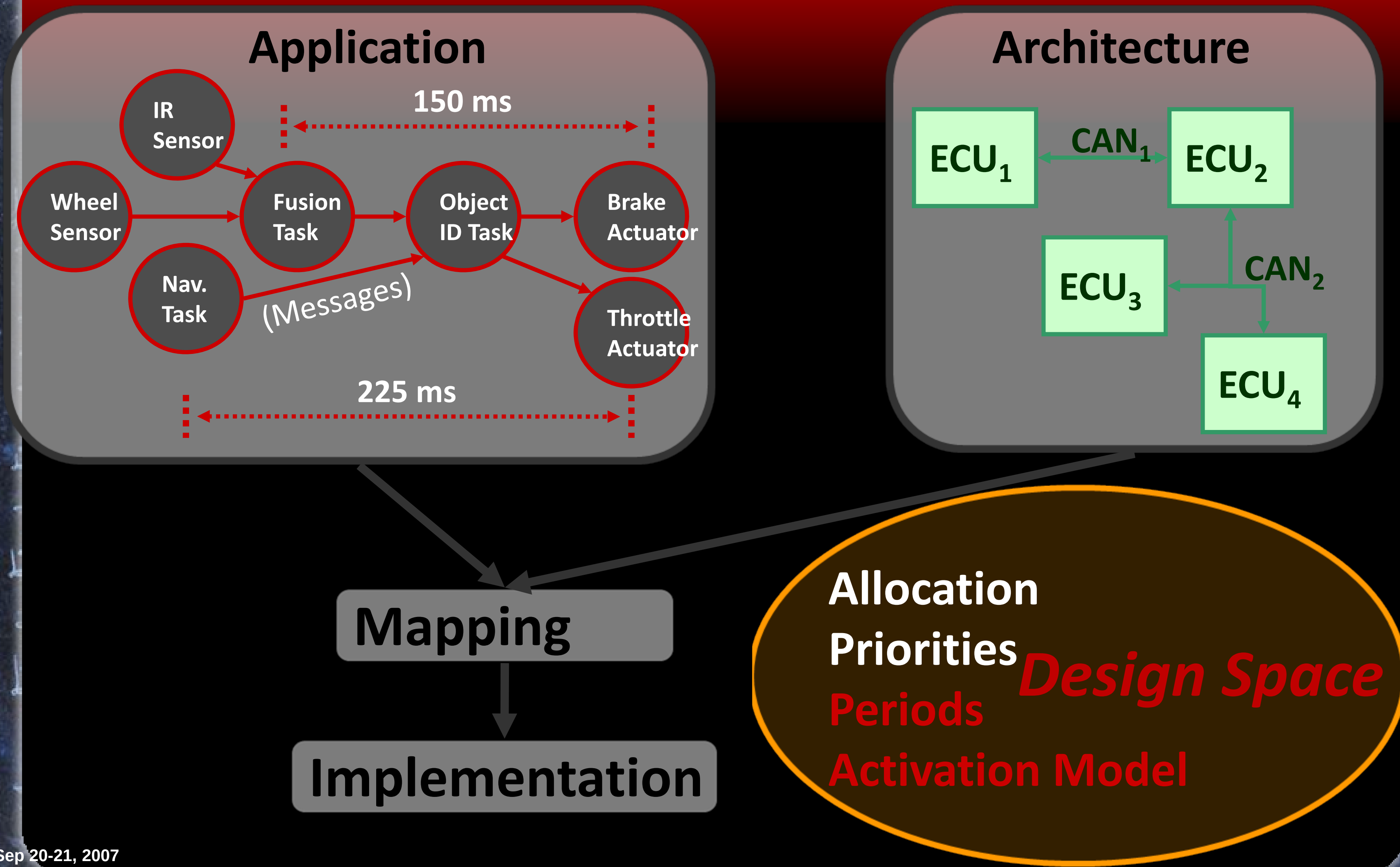


Industrial automation

Building automation

Elevators

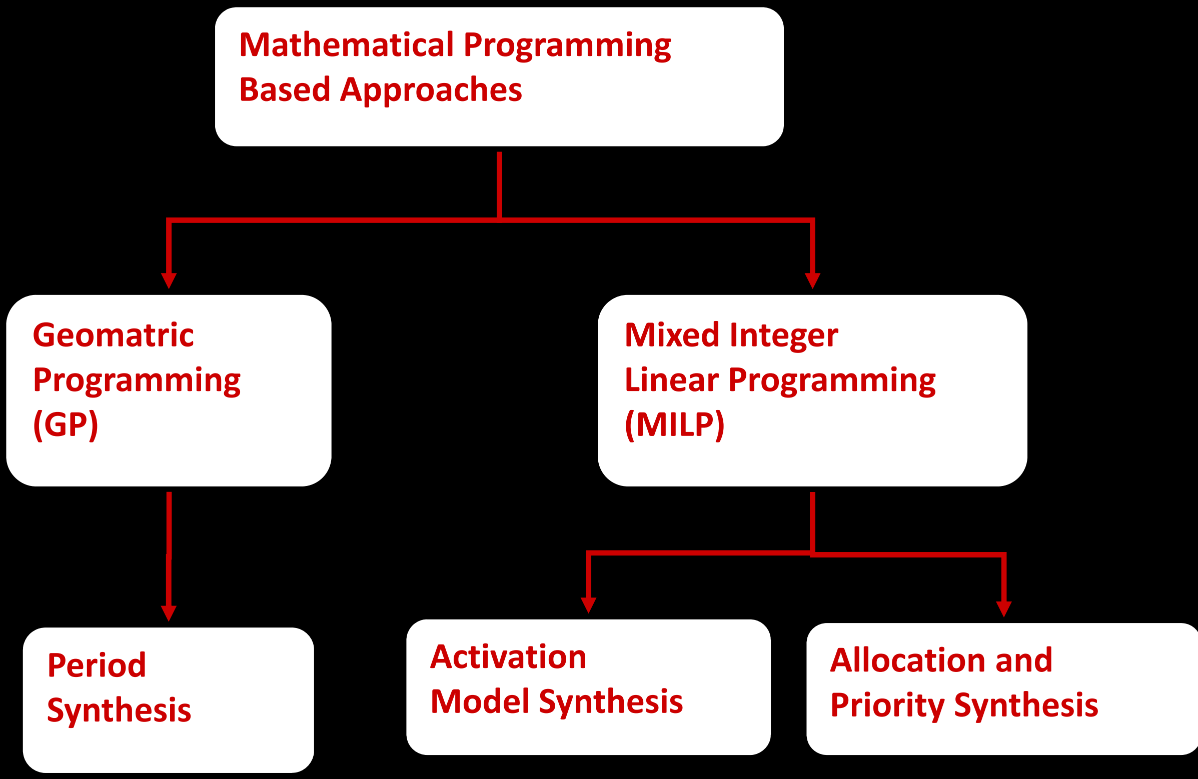
Design Flow for optimizing distributed systems with latency constraints



Extensible Mathematical Programming Approach

Extensibility to add additional constraints for system-specific situations

Design Space
- Allocation
- Priorities
- Periods
- Activation Model

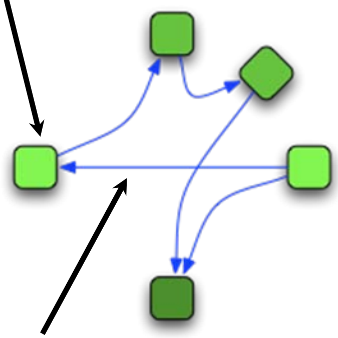


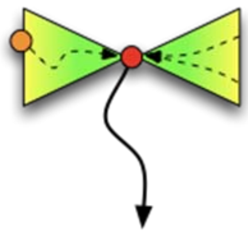
DAC 2007
BEST PAPER AWARD

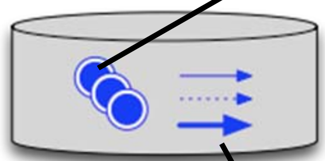
DATE 2007
Nomination BPA
RTAS 2007

RTSS 2007
BEST PAPER AWARD

Position

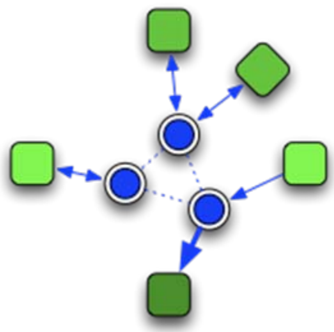






Component:
Nodes (can be sub-net with access interfaces)
Quantities:
Max number of flows, max number of ports, max bandwidth, delay, services (MAC, Network, Physical), Power consumption
Cost:
Installation and maintenance

End-to-end Latency, Bandwidth, PER Redundancy



Component:
Links
Quantities:
Maximum length, Max bandwidth, Minimum PER, Delay
Cost:
Installation and maintenance

Implementation:
A network that guarantees all end-to-end constraints at minimum installation an operation cost

Communication Design (e.g., NOCs, Wireless-Wired Automation Control)

✓ Implement end-to-end communication on a multi-hop network
✓ Characterize components (nodes, links, sub-nets)
✓ Synthesis

Courtesy: A. Pinto

	Quantities	CommStructs	Library	Models	Rules	Platforms	Environment	I/O	Algorithms
Core	Ports Bandwidth Flows...	Graphs							ShortestPath Tsp SpanningTree FacilityLocation Kmedian
On-Chip Communication	Interface IpGeometry NodeParam	Specification PltInstance Implementation	Router Link Bus	Ho-Area Ho-Power Orion	Critical length Deadlock	RouterLink BusNoc	Rectangle	Parsers SvgGen Parquet interface SyscGen	DegreeConstrained LatencyConstrained Hierarchical
Building Automation	Interface NodeParam Threads	Specification PltInstance Implementation	Sensor Actuator Controller TwistedPair	TokenRing 802.15.4	WiringRule NodePosition	DaisyChain TreeWireless	Walls CableLadder	BuildingParser SvgGen Desyre interface	DaisyChainPartition WirelessTree

The COmmunication Software Infrastructure (COSI) Design Package

Software Organization

Courtesy: A. Pinto

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Building Energy Demand Challenge

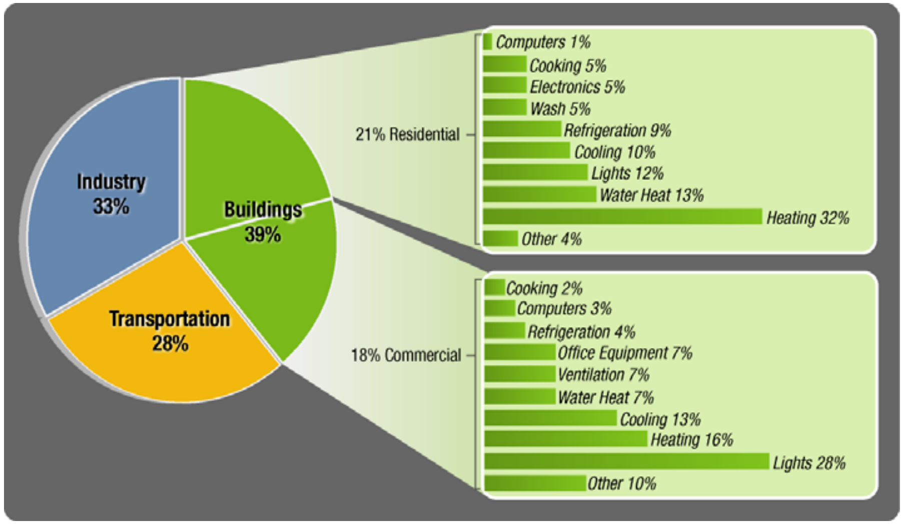
U.S. Buildings consume
- 39% of total U.S. energy
- 71% of U.S. electricity
- 54% of U.S. natural gas

U. S. Buildings produce 48% of Carbon emissions

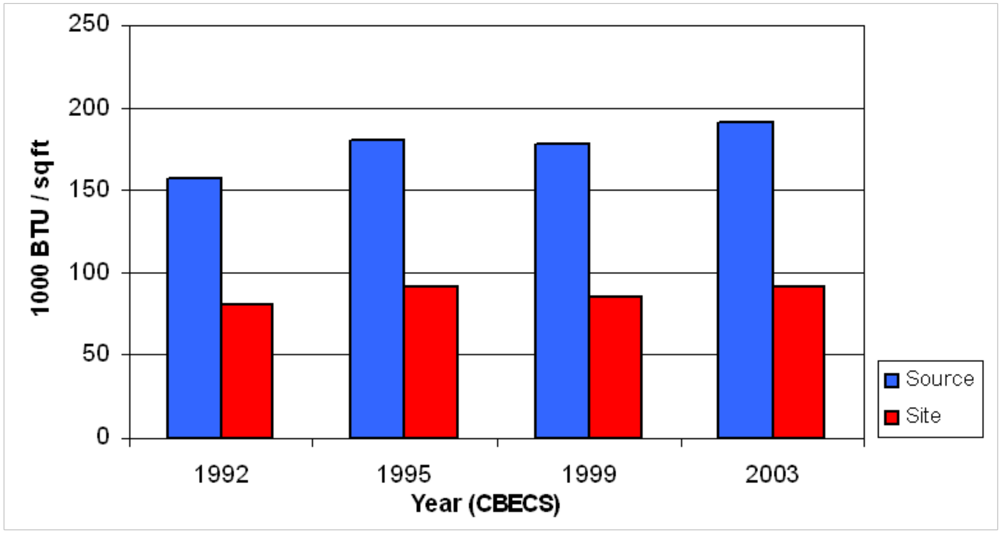
U.S. Commercial Buildings annual energy bill: $120 billion (2004)

Commercial Building Energy Intensities are increasing
- Electrical Energy consumption *doubled* in last 18 years
- 25% growth projection through 2030

Energy Breakdown by Sector



U.S. Commercial Building Energy Intensity

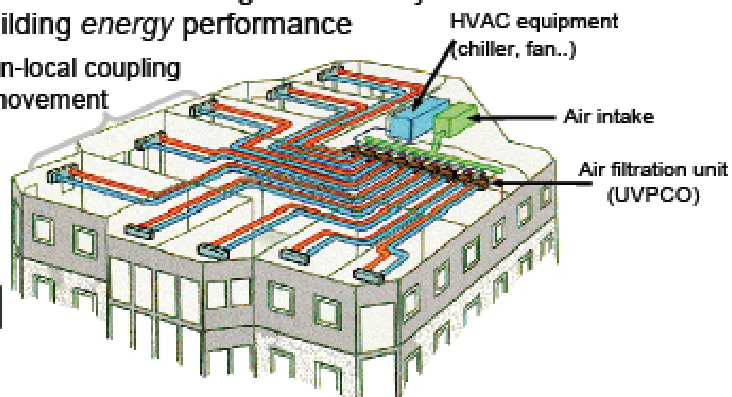


High Performance Buildings: the Problem

Objectives: Efficient energy utilization and occupant comfort for normal building operation
Robust response to health and safety threats and events

Energy & mass balances govern steady-state building *energy* performance

"Slow" non-local coupling from air movement system

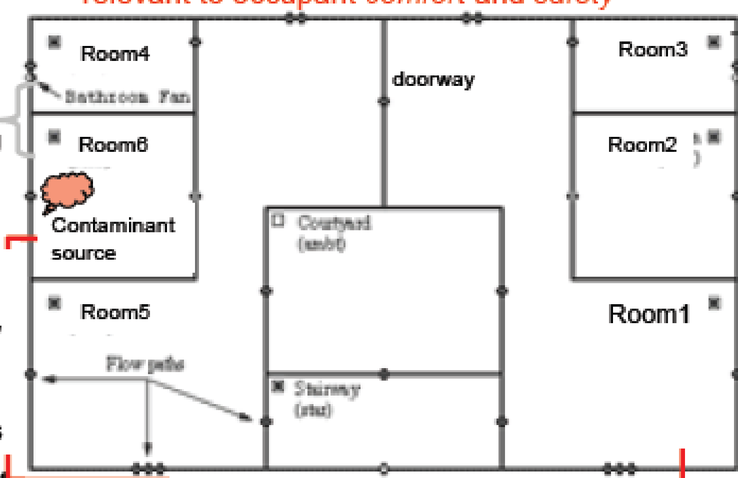


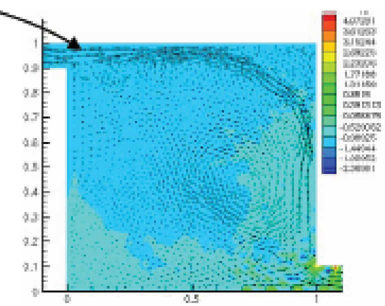
- Large, spatially distributed system
- Interconnected system
  - Room neighborhood scale
  - Building floor scale
  - Whole building scale
- Multi-scale dynamic system & its control
  - Wide time scale separation
  - "Close" coupling leading to dynamic constraints between network and physical system

Multi-zone, steady/quasi-steady behavior at intermediate scales relevant to occupant *comfort* and *safety*

Local coupling

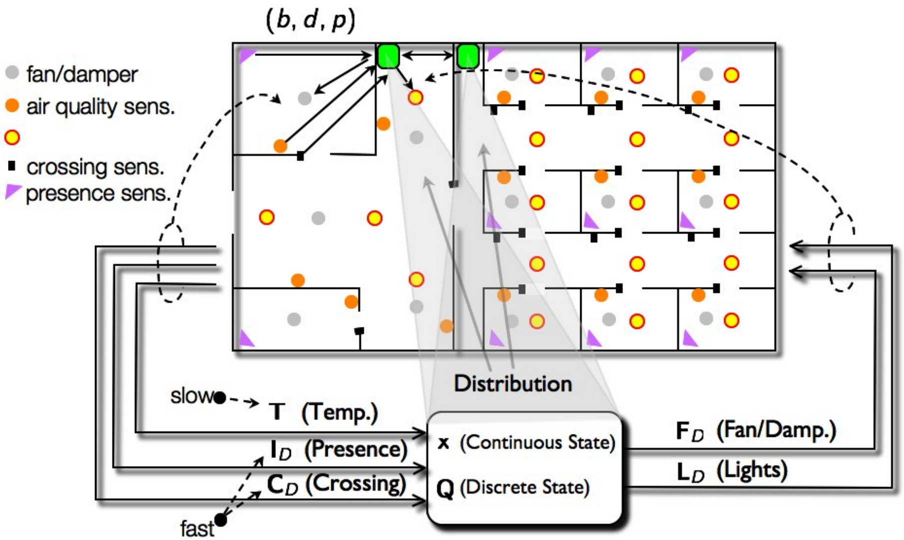
"Fast" non-local coupling over communication/ control network for response to transient events



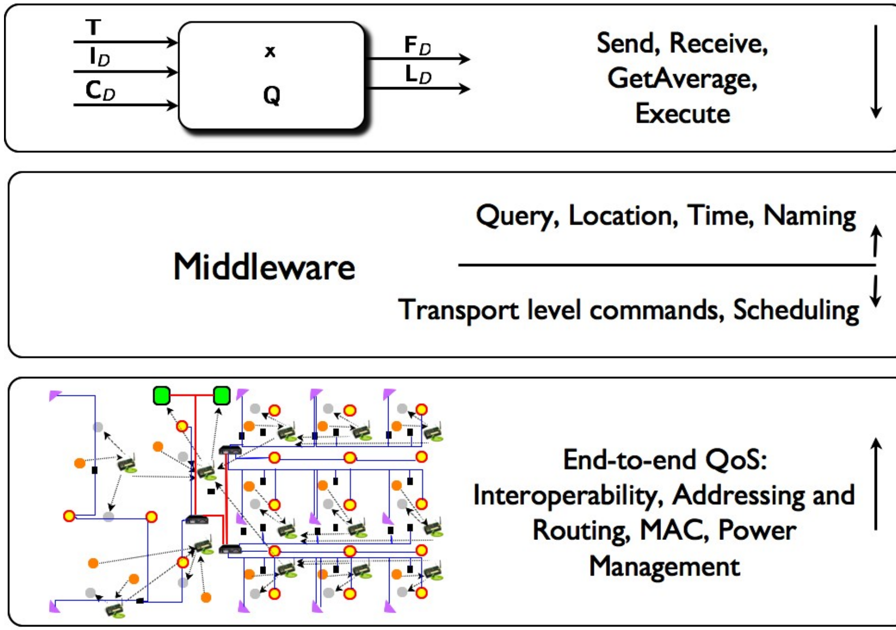


Spatiotemporal airflow dynamics at room scale relevant to *safe building environment*

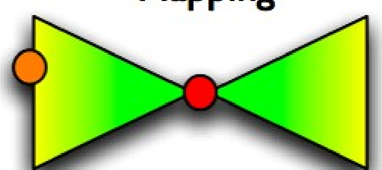
Integrated Design of Building Automation Systems

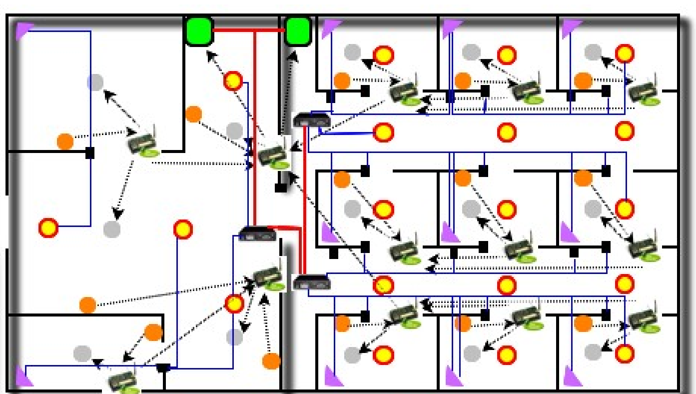


Multi-scale, Multi-Agent, Potentially Distributed Hybrid Control System



Platform Instance + Mapping

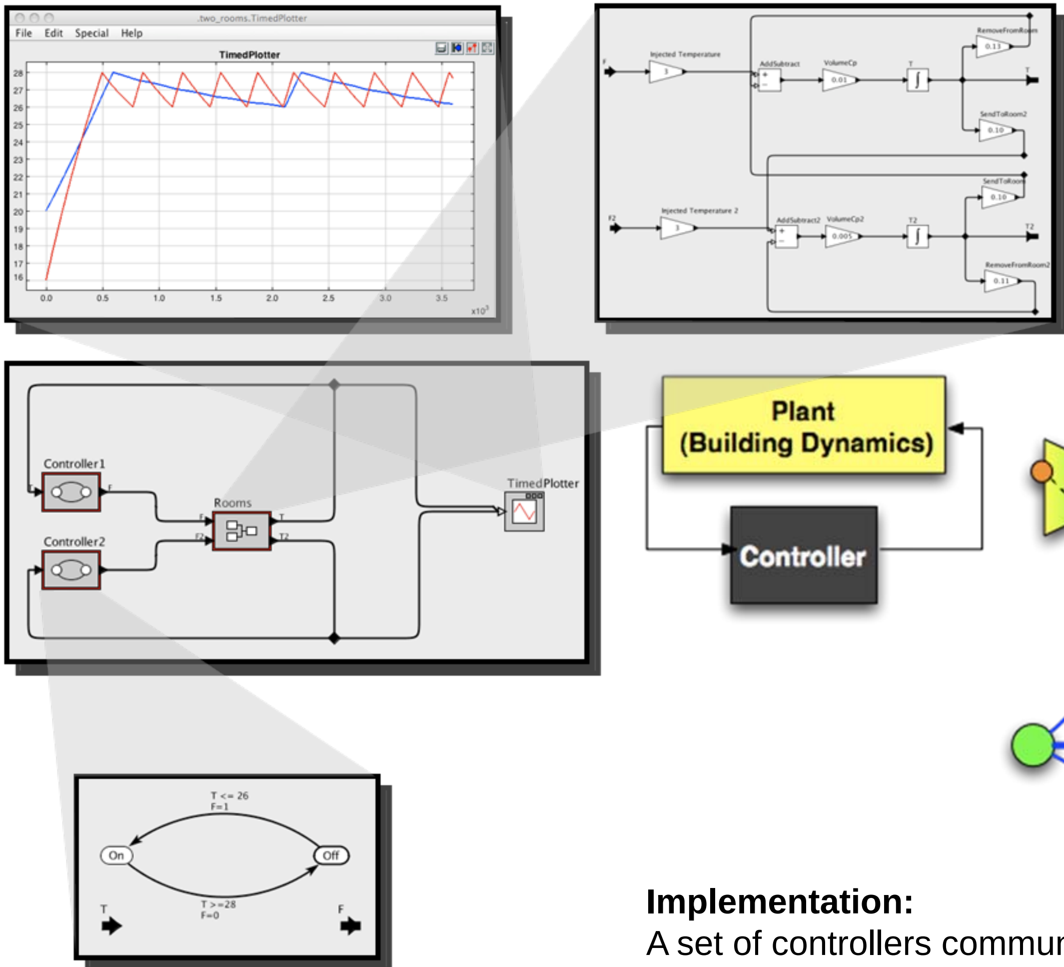




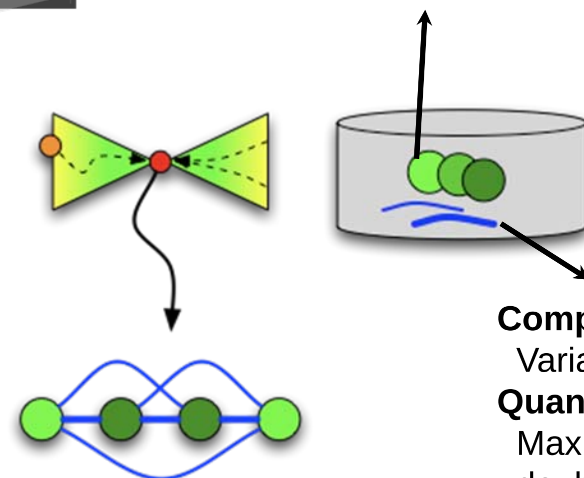
Implementation

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

Courtesy: A. Pinto



Component:
Controller
Quantities:
Maximum size of state space
Maximum number of ops



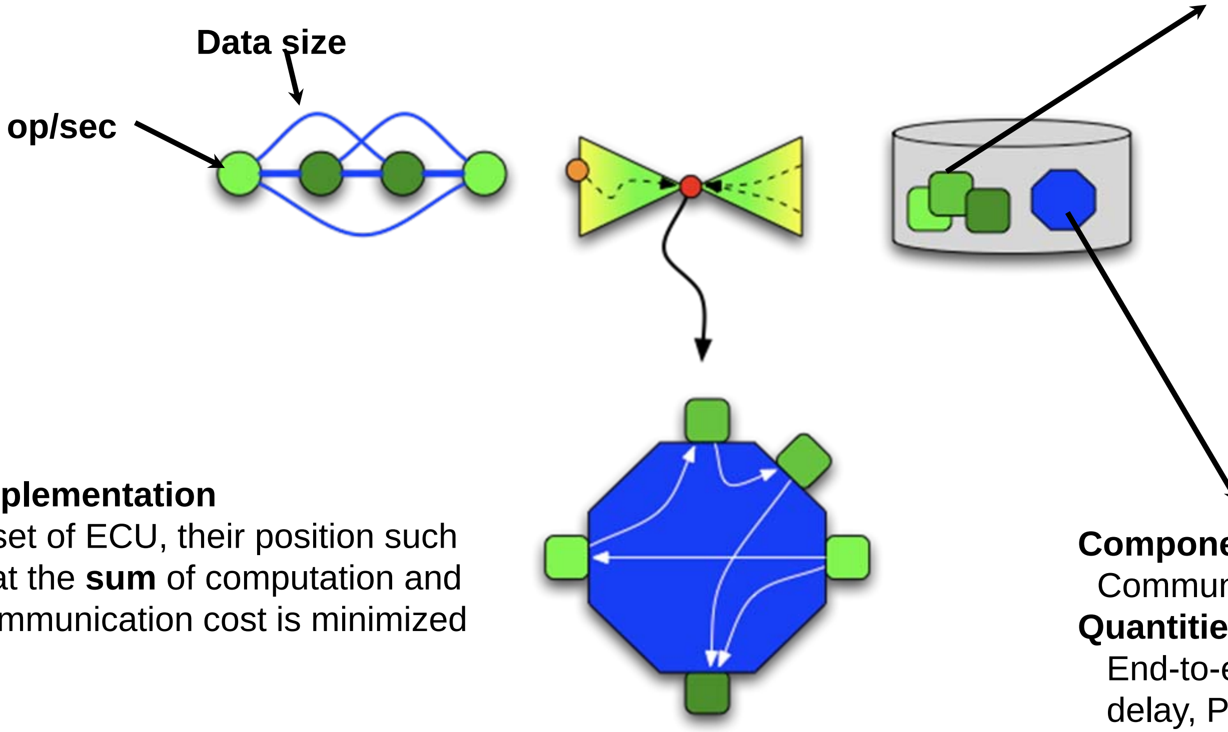
Component:
Variable
Quantities:
Maximum number of doubles/ints

Implementation:
A set of controllers communicating over shared variables such that control properties are maintained and cost is minimized

Distributed Control Design

✓ Formal Description of Specification
✓ Characterization of resources
✓ Synthesis

Courtesy: A. Pinto



Component:
Electronic Control Unit
Quantities:
Memory, computation speed, power consumption
Cost:
Installation and maintenance

Implementation
A set of ECU, their position such that the **sum** of computation and communication cost is minimized

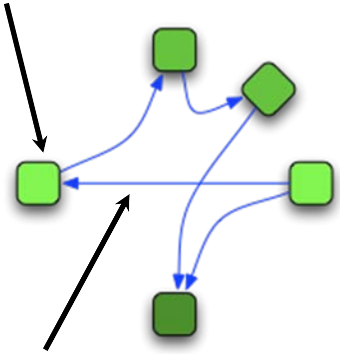
Component:
Communication
Quantities:
End-to-end QoS (bandwidth, delay, PER, **distance**)
Cost:
Abstraction of network cost (installation and maintenance)

Comm/Comp Trade-Off

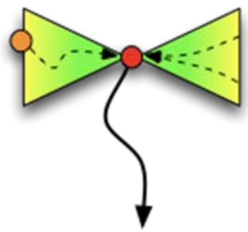
✓ Distribute control on ECUs
✓ Characterize performance and cost of controllers and communication effort
✓ Synthesis

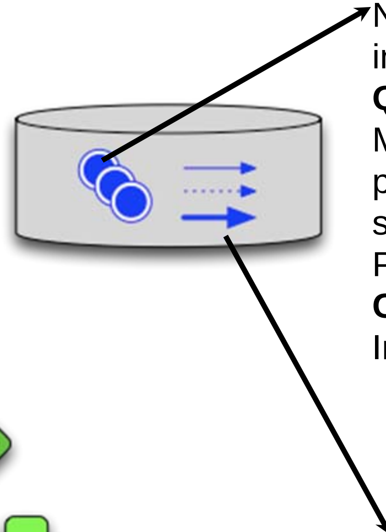
Courtesy: A. Pinto

Position



End-to-end Latency,
Bandwidth, BER
Redundancy





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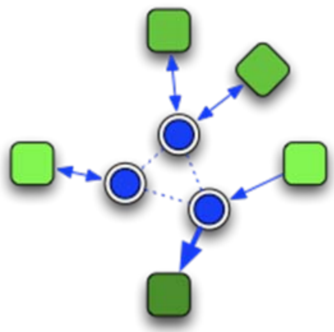

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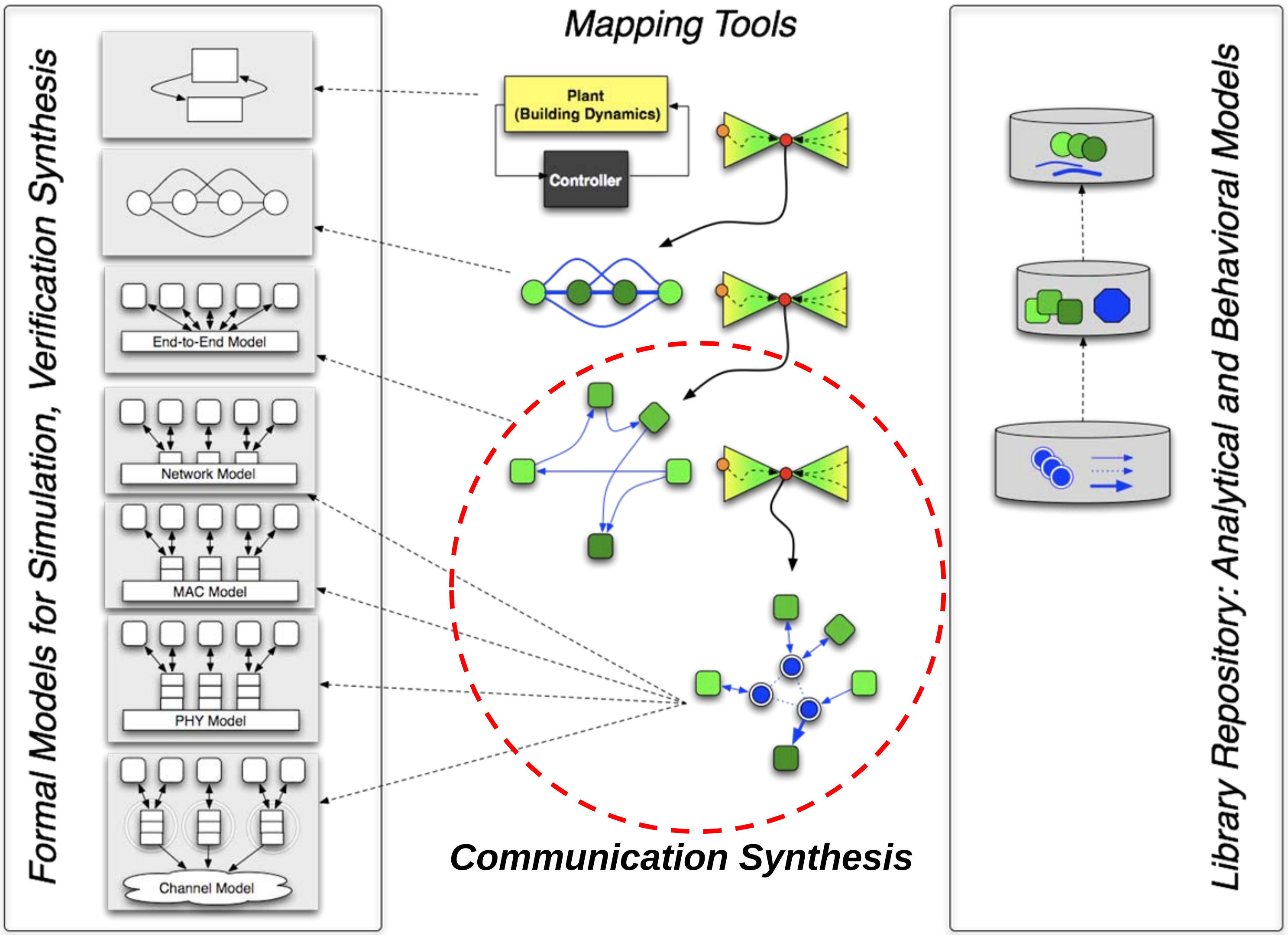
Communication Design

✓ Implement end-to-end communication on a multi-hop network
✓ Characterize components (nodes, links, sub-nets)
✓ Synthesis

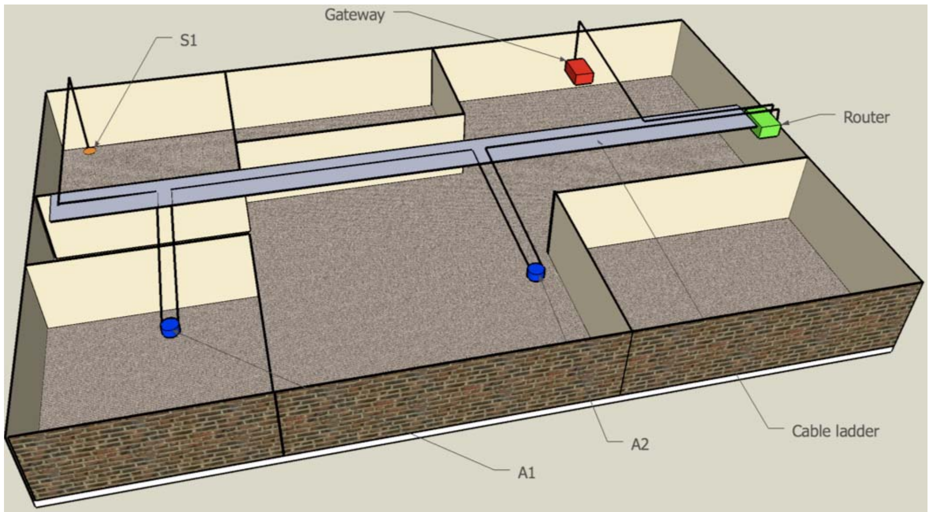
Courtesy: A. Pinto

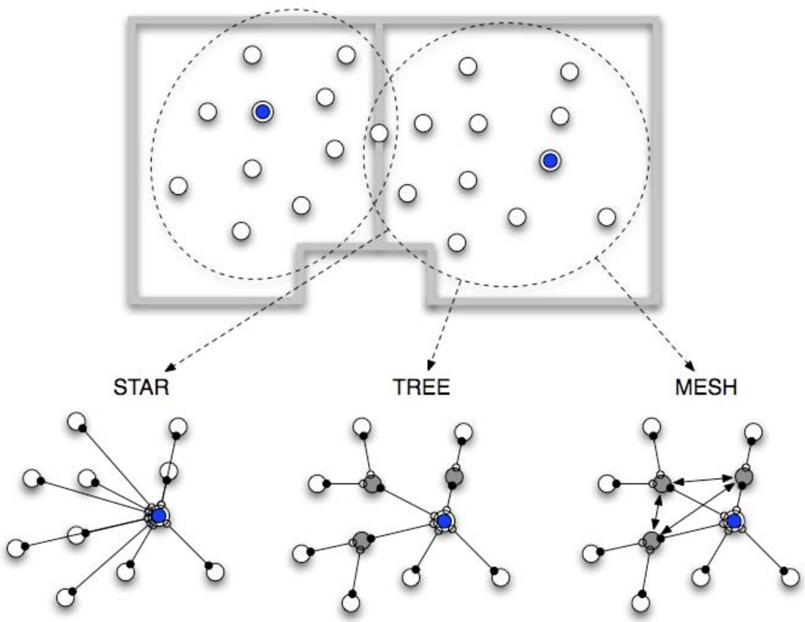


Putting It All Together

Proposed design flow for UTRC networked control systems

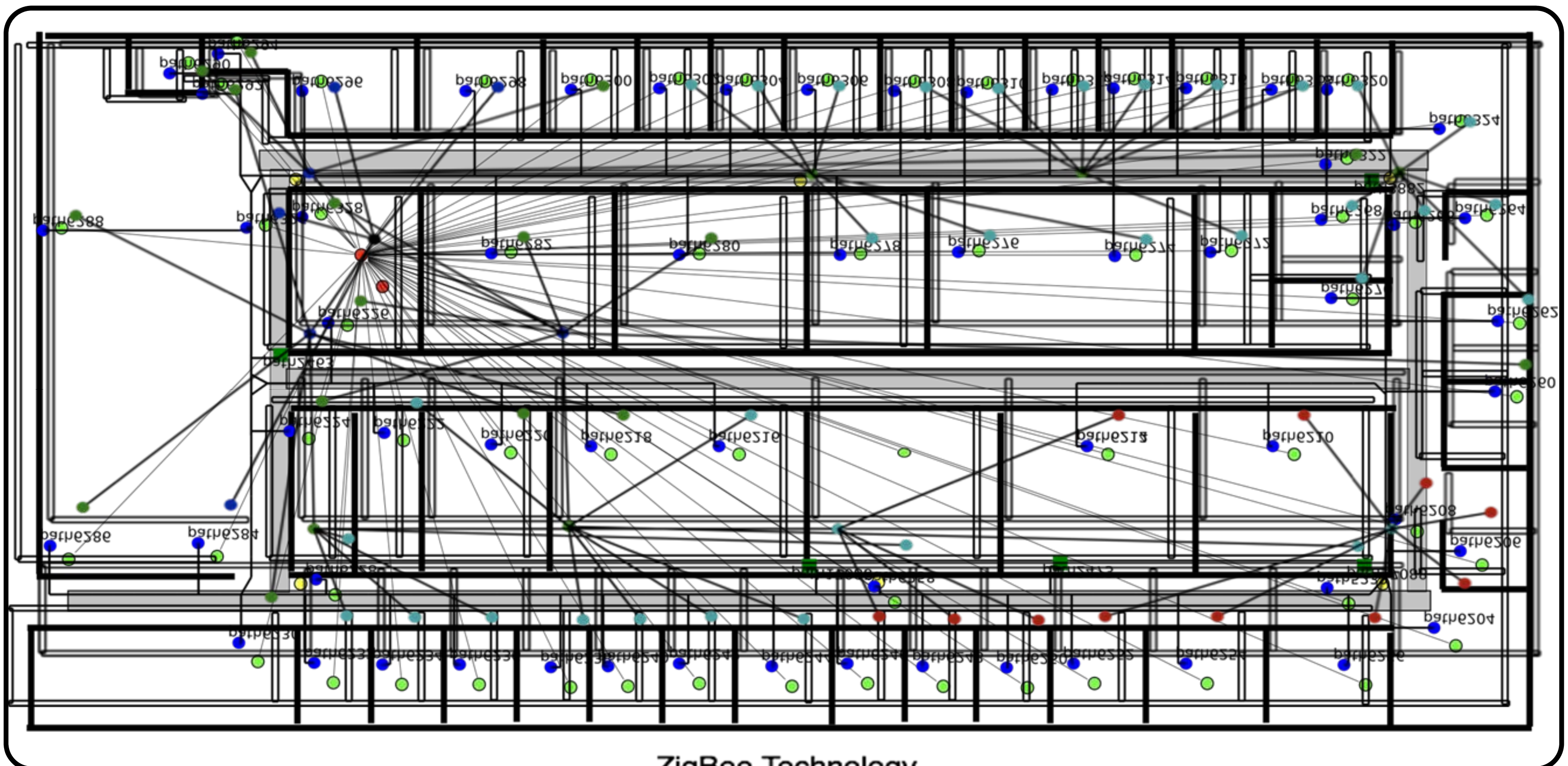
The Library of Communication Components





- Twisted-pair wires
  - Daisy-chain connection
  - ARCNET protocol (token ring bus)
- Wireless communication channels
  - Tree topology
  - ZigBee (802.15.4)

Examples



ZigBee Technology
BO = 7, SO = 3
$27000 over 20 yr
Max end-to-end latency = 2s
Max PER = 1e-5

Courtesy: A. Pinto

Results

- L-Buildings: 70 x 30 m^2, 64 nodes, period=0.1s, b=16 bits
- Big-box office: 60 x 56 m^2, 64 nodes, period=0.1s, b=16 bits

New

Building	Bw (Kb/s)	Max Length (m)	Max #devices	Max delay (ms)	Max Utilization (%)	Router ($)	Nodes ($)	Wires ($)	Total ($)
L-Building	78	1000	32	91	89%	3700	10240	5020	18960
	250	400	20	22	20%	5180	10240	4939	20359
Big-Box Office	78	1000	32	91	89	2220	10240	4317	16777
	250	400	20	19	20%	4440	10240	4131	18811

Retrofit

Building	Bw (Kb/s)	Max Length (m)	Max #devices	Max delay (ms)	Max Utilization (%)	Router ($)	Nodes ($)	Wires ($)	Total ($)
L-Building	78	1000	32	91	89%	5920	10240	12680	28844
	250	400	20	22	20%	5180	10240	13744	29198
Big-Box Office	78	1000	32	91	89	3700	10240	12044	25984
	250	400	20	19	20%	4440	10240	11855	26535

Conclusions

- A PBD-based design flow for CPS
  - Algorithmic analysis
  - Technology aware partitioning
  - Binding to computation resources
  - Communication synthesis
- Building automation system as an important application domain
- System for Off- and on-line management of large buildings as a final result