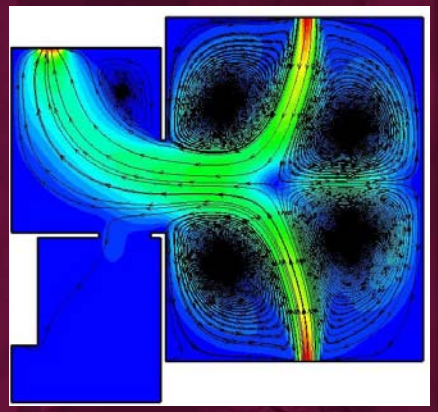
Design Specific Computational Tools for Energy Efficient Buildings



Air Flow in a Hospital Suite

J. A. Burns, E. M. Cliff, C. N. Rautenberg, L. Zietsman

VirginiaTech
Invent the Future

ICAM

Interdisciplinary **C**enter for **A**pplied **M**athematics

Fall Creek Falls Conference - Memphis
October 24 - 27, 2010

Technical Challenge

The general technical challenge was issued by the U.S. Secretary of Energy, Dr. Steven Chu:

> ***"We need to do more transformational research at DOE … including computer design tools for commercial and residential buildings that enable reductions in energy consumption of up to 80 percent with investments that will pay for themselves in less than 10 years."***
>
> **Secretary of Energy Dr. Steven Chu,**
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THE EMPHASIS IS ON

DESIGN – CONTROL – OPTIMIZATION TOOLS

NOT

"OPEN-LOOP SIMULATION"

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DESIGN – CONTROL – OPTIMIZATION TOOLS

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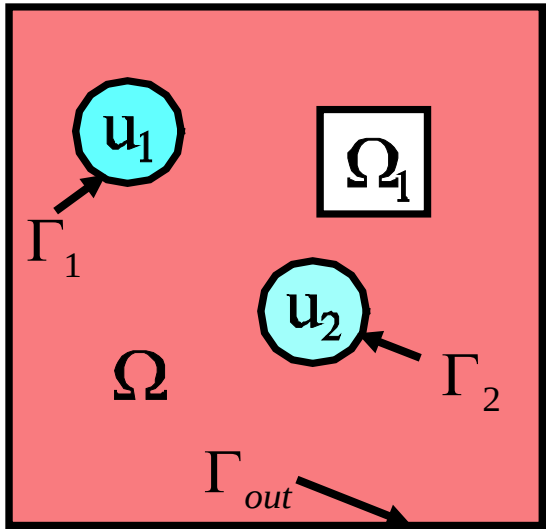
NOT

"SIMULATION BASED DESIGN"

Example - Non-Standard Equations

OPTIMAL FEEDBACK CONTROL OF A THERMAL SYSTEM

RICCATI PDES



$$\Delta_{(\vec{x})} p(\vec{x},\vec{y}) + \Delta^{*}_{(\vec{y})} p(\vec{x},\vec{y})\, p(\vec{x},\vec{y}) - \mathbf{N}(p(\vec{x},\vec{y})) + q(\vec{x},\vec{y}) = 0$$

Example - Non-Standard Equations

OPTIMAL FEEDBACK CONTROL OF A THERMAL SYSTEM

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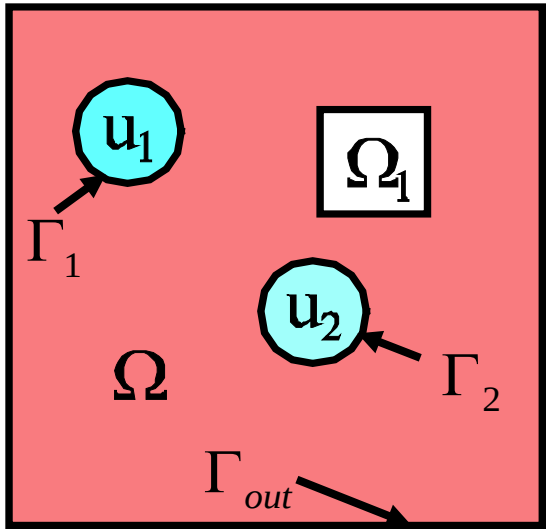


$$\Delta_{(\vec{x})} p(\vec{x},\vec{y}) + \Delta^*_{(\vec{y})} p(\vec{x},\vec{y})\, p(\vec{x},\vec{y}) - \mathbf{N}(p(\vec{x},\vec{y})) + q(\vec{x},\vec{y}) = 0$$

$$\mathbf{N}(p(\vec{x},\vec{y})) = \int_{\Omega\times\Omega} p(\vec{x},\vec{\xi})\, b(\vec{\xi})\, b(\vec{\zeta})\, p(\vec{\zeta},\vec{y})\, d\vec{\zeta}\, d\vec{\xi}$$

NON-LOCAL 2N – DIMENSIONAL PDES

Chandrasekhar Equations

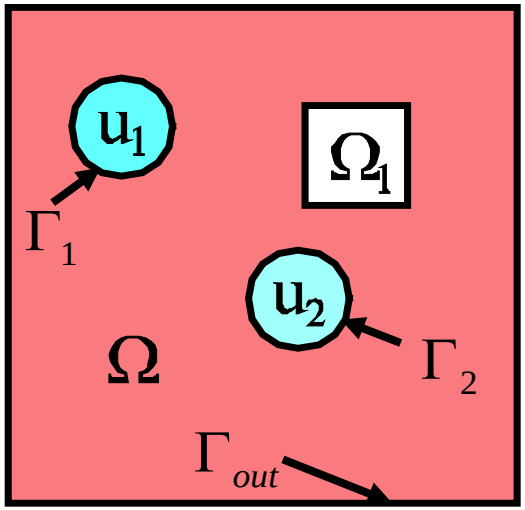
$$u(t,\vec{x}) = -KT(t,\bullet) = -\int_{\Omega} \mathbf{k}(t,\vec{x},\vec{y})T(t,\vec{y})d\vec{y}$$

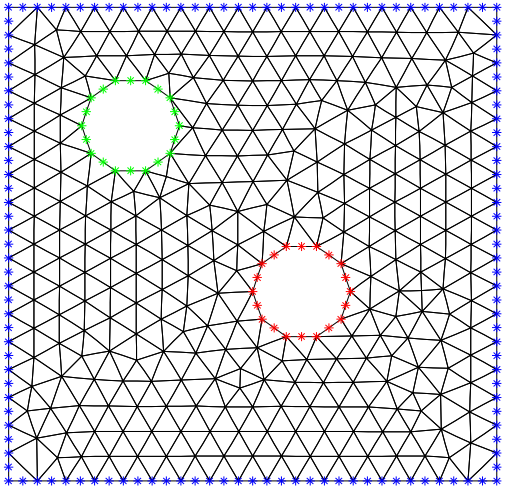
$$\begin{cases} \dfrac{\partial \mathbf{k}(t,\vec{x},\vec{y})}{\partial t} = \left[B^{*}\mathbf{h}(t,\cdot,\cdot)\right](\vec{x},\vec{y})\left[\mathbf{h}(t,\vec{x},\vec{y})\right]^{T} \\ \dfrac{\partial \mathbf{h}(t,\vec{x},\vec{y})}{\partial t} = -\left[\Delta^{*}_{(\vec{x},\vec{y})}\mathbf{h}(t,\cdot,\cdot)\right](\vec{x},\vec{y}) \\ \qquad\qquad + \mathbf{k}^{T}(t,\vec{x},\vec{y})\left[B^{*}\mathbf{h}(t,\cdot,\cdot)\right](\vec{x},\vec{y}) \end{cases}$$

$$\mathbf{k}(t_f,\vec{x},\vec{y}) = 0, \qquad \mathbf{h}(t_f,\vec{x},\vec{y}) = c(\vec{x},\vec{y})$$

$$\lim_{t\to-\infty} \mathbf{k}(t,\vec{x},\vec{y}) = \mathbf{k}(\vec{x},\vec{y})$$

Adaptive FE + New Algorithms



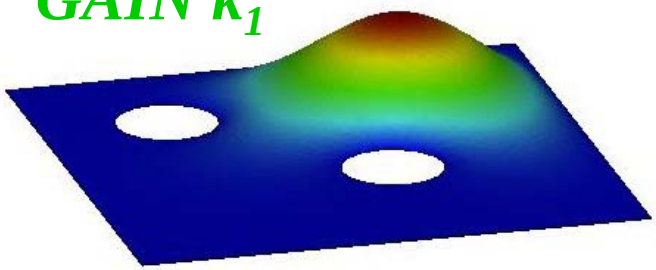


Mesh 0

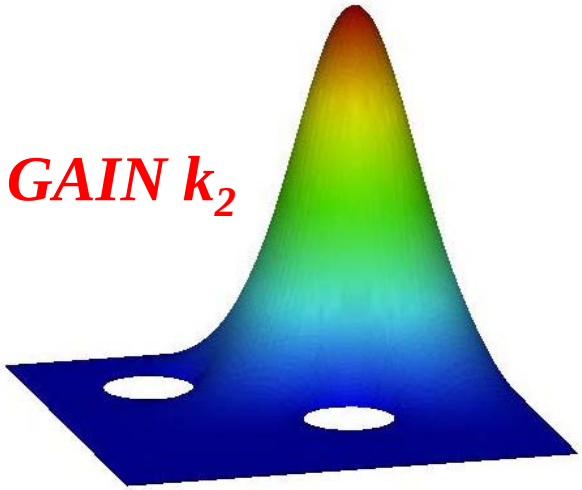
 # RIC EQ = 565,516

 # CHADRA EQ = 3,189

GAIN k_1



GAIN k_2



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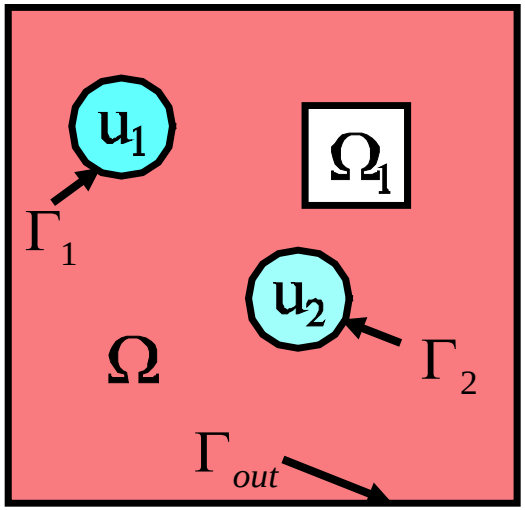

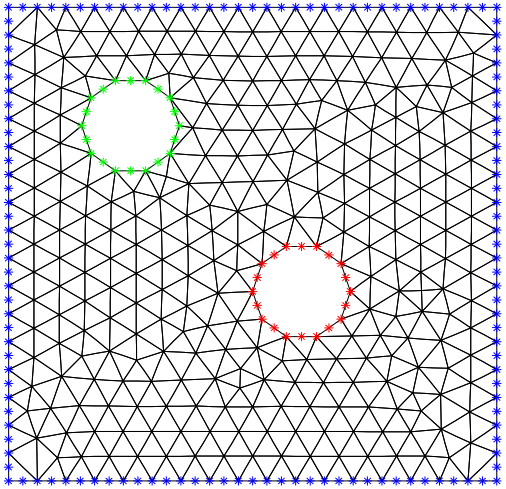

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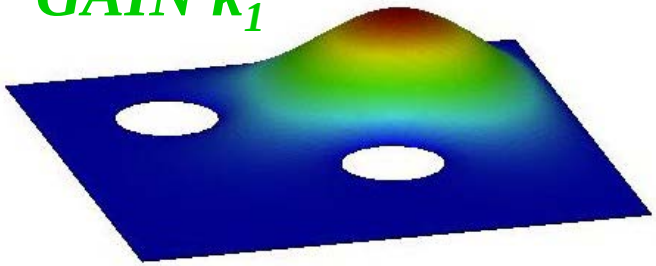
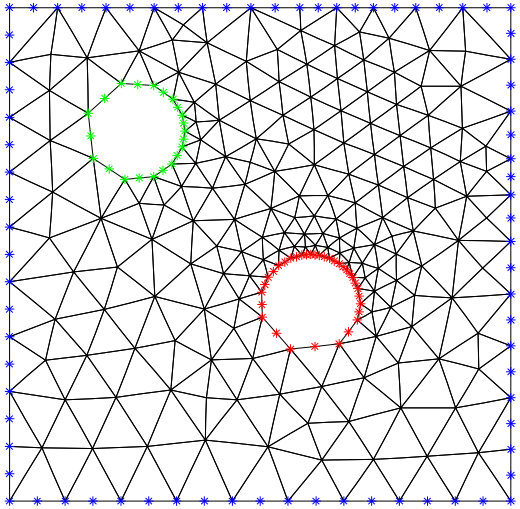
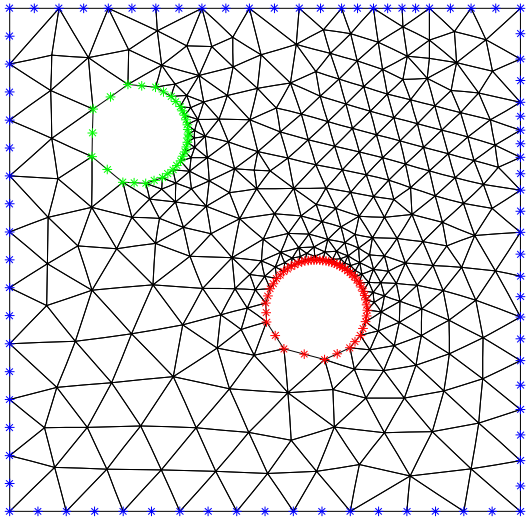


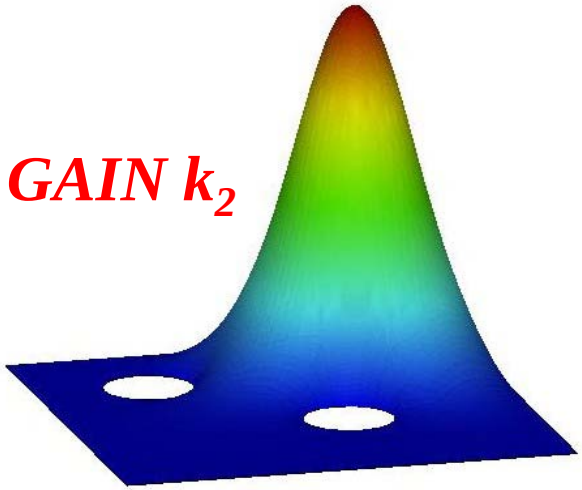


Mesh 3



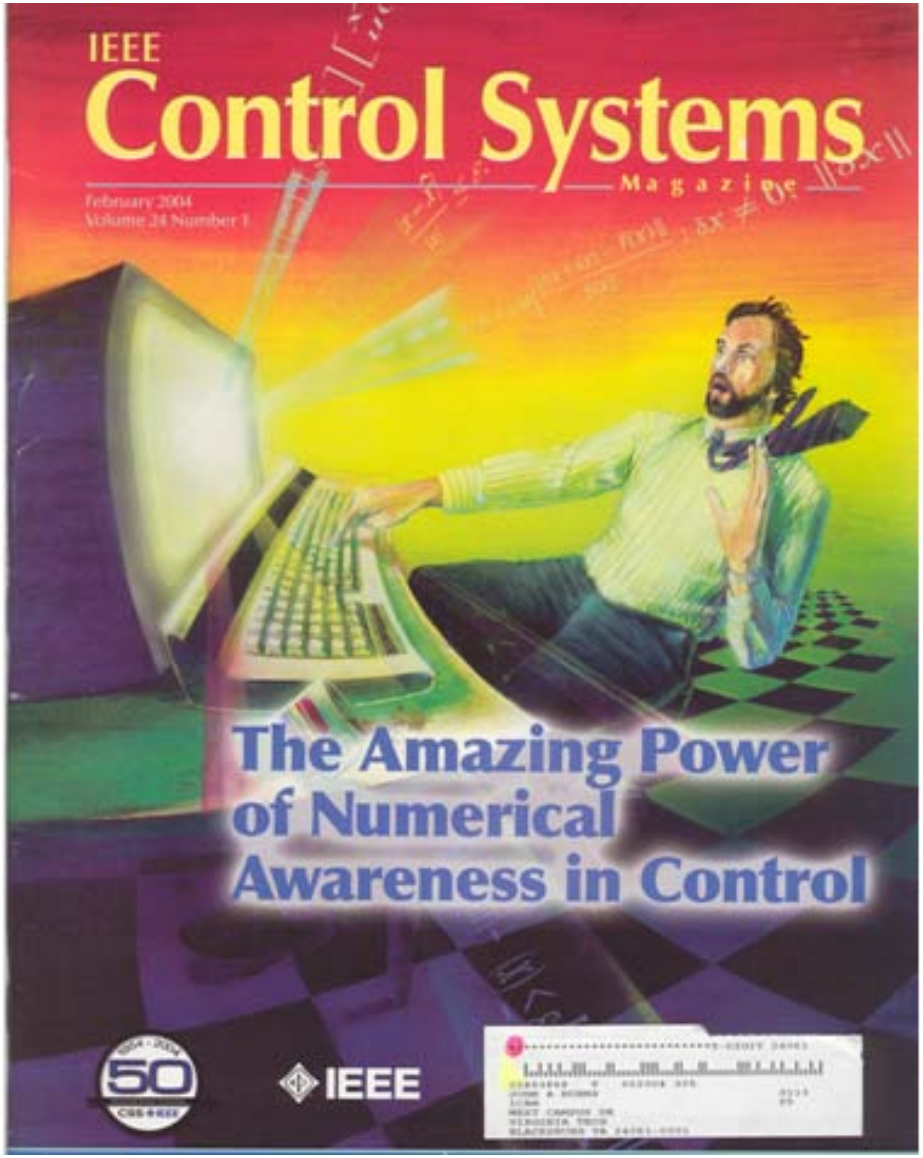
Mesh 5

GAIN k_2



574 Elements, 1231 Nodes, 1063 States

Control Sciences Embrace Computing



CONTROL COMMUNITY NOW UNDERSTANDS

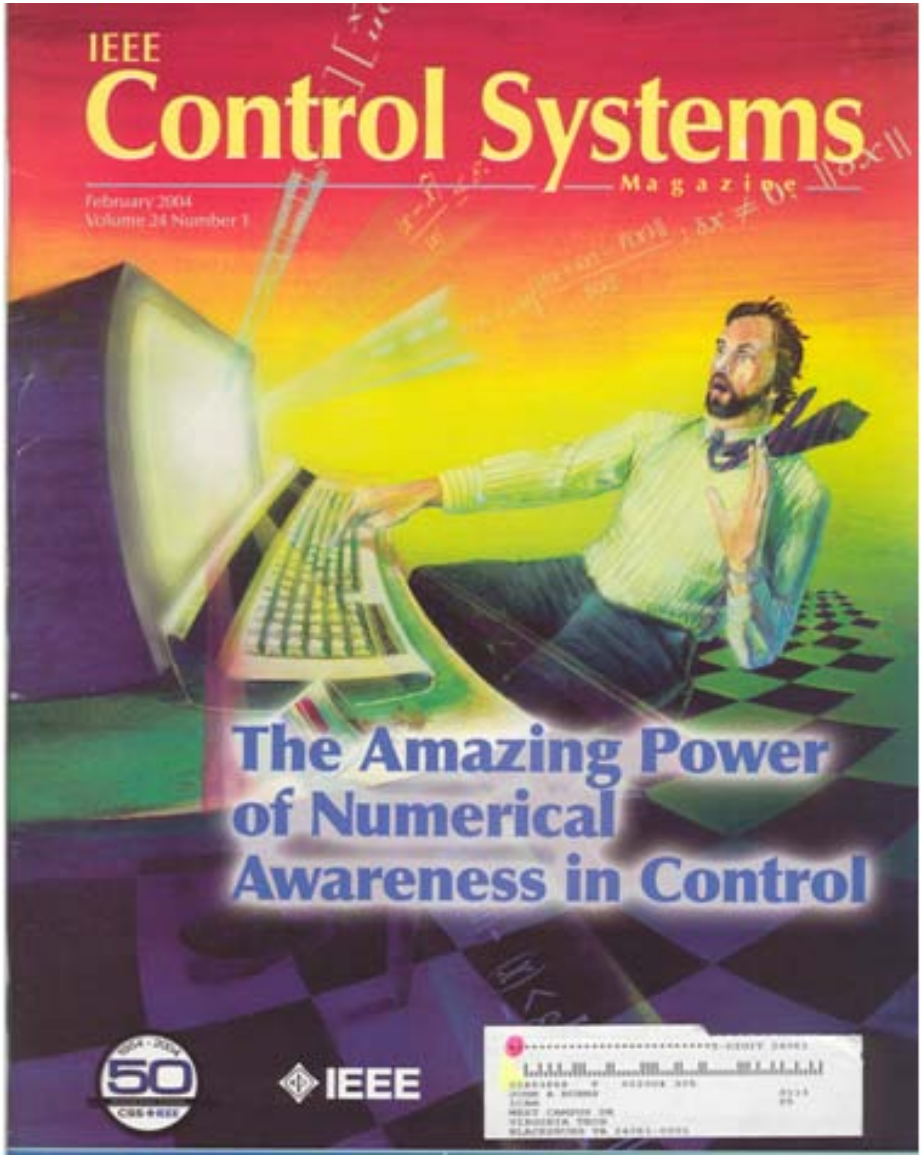
"The Amazing Power of Numerical Awareness"

ARTICLE MOTIVATED BY <u>FEEDBACK</u> CONTROL PROBLEMS IN

- **THERMAL PROCESSES**
- **FLUID FLOW**
- **INFLATABLES**
- **MATERIALS SCIENCE …**

PDE SYSTEMS

Control Sciences Embrace Computing



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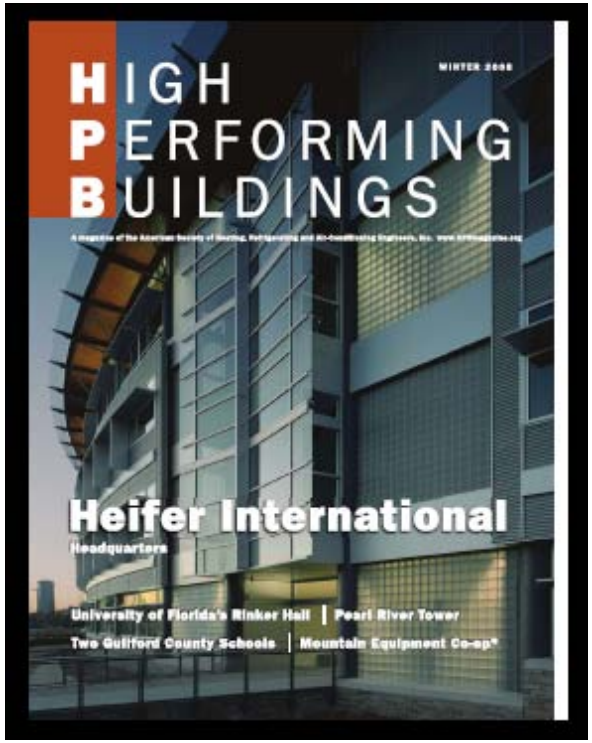
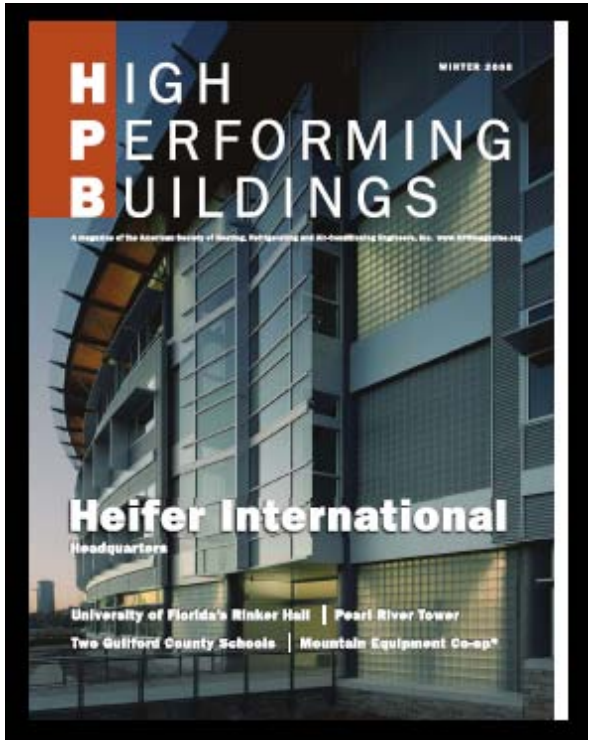
PDE SYSTEMS

Energy and Buildings



WHY BUILDINGS

Energy and Buildings



WHY BUILDINGS

AND NOT THIS

Impact of Energy Efficient Buildings

HUGE

- **A 50 percent reduction in buildings' energy usage would be equivalent to taking every passenger vehicle and small truck in the United States off the road.**
- **A 70 percent reduction in buildings' energy usage is equivalent to eliminating the entire energy consumption of the U.S. transportation sector.**

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DESIGN, CONTROL AND OPTIMIZATION OF WHOLE BUILDING SYSTEMS IS THE ONLY WAY TO GET THERE

? WHY ?

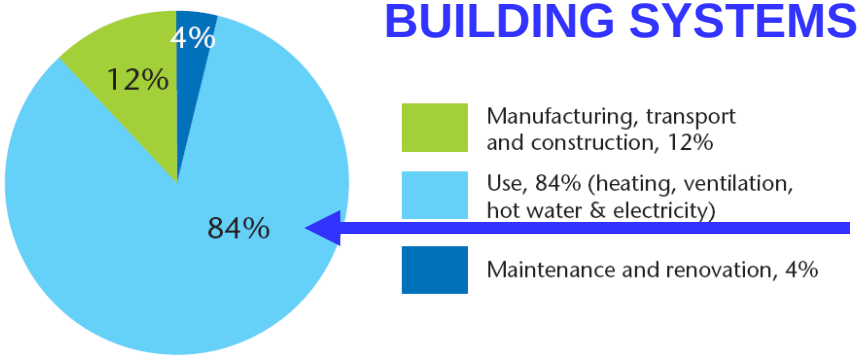

Figure 3.7: Life cycle energy use

84% of energy consumed in buildings is during the use of the building

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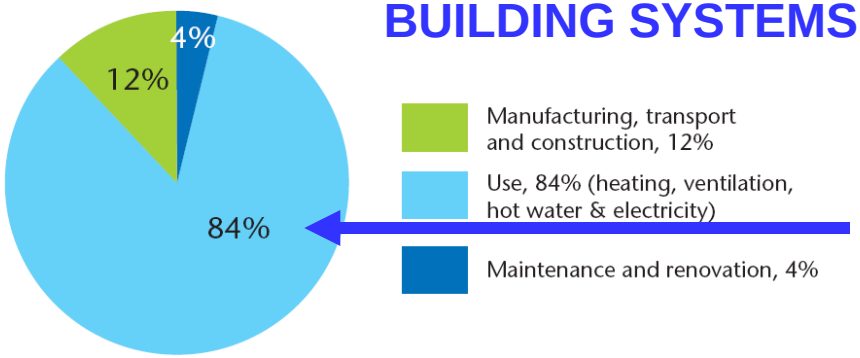


84% of energy consumed in buildings is during the use of the building

REQUIRES COMBINING - MODELING, COMPLEX MULTISCALE DYNAMICS, CONTROL, OPTIMIZATION, SENSITIVITY, HIGH PERFORMANCE COMPUTING …

Existence Proof

Energy Retrofit 10-30% Reduction

Cityfront Sheraton
Chicago IL
1.2M ft², 300 kWhr/m²
5753 HDD, 3391 CDD
VS chiller, VFD fans, VFD pumps
Condensing boilers & DHW

- Different types of equipment for space conditioning & ventilation
- Increasing design integration of subsystems & control

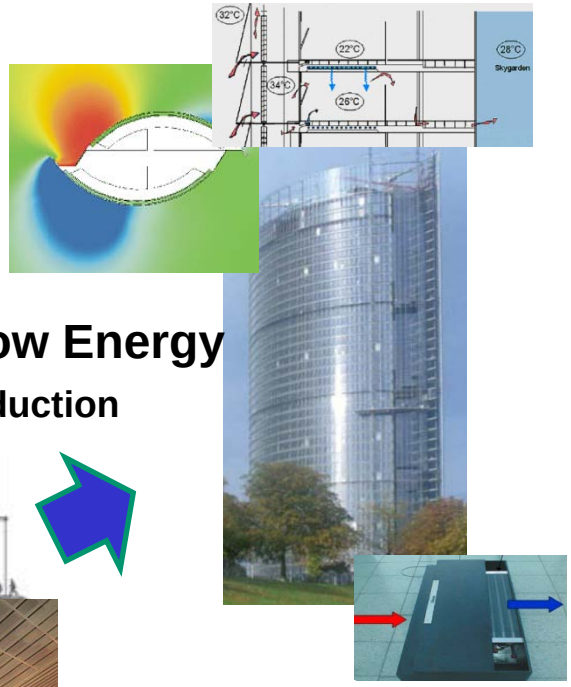
Tulane Lavin Bernie
New Orleans LA
150K ft², 150 kWhr/m²
1513 HDD, 6910 CDD
Porous Radiant Ceiling, Humidity Control Zoning, Efficient Lighting, Shading

LEED Design

20-50% Reduction

Very Low Energy

>50% Reduction

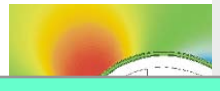


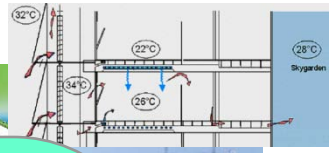
Bonn Germany
1M ft², 75 kWhr/m²
6331 HDD, 1820 CDD
No fans or Ducts
Slab cooling
Façade preheat
Night cool

Courtesy of Clas Jacobson UTC

Existence Proof

Energy Retrofit
10-30%
Reduction





ONE OFF PROJECTS

NO GENERAL DESIGN TOOLS

&

REQUIRES NEW PARADIGM

HPC SPECIFICALLY FOR DESIGN

OPTIMIZATION & CONTROL

<u>MODEL REDUCTION</u>

Cityf
C
1.2M f
5753 H
VS chiller, V
Condensi

- Diffe
equipr
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v
- Increas
integrat
subsystems & control

ermany
kWhr/m²
1820 CDD
or Ducts
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preheat
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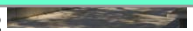

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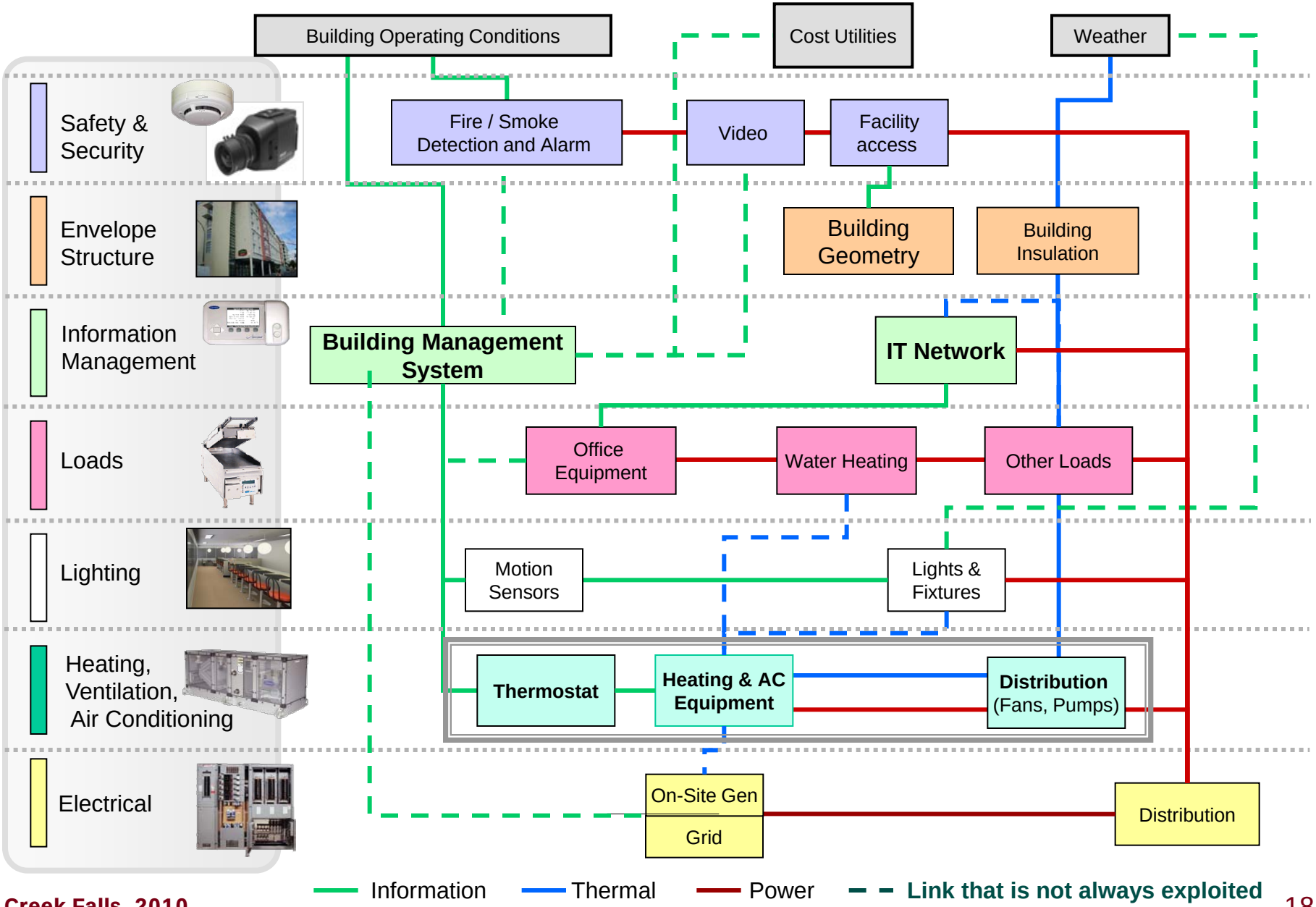
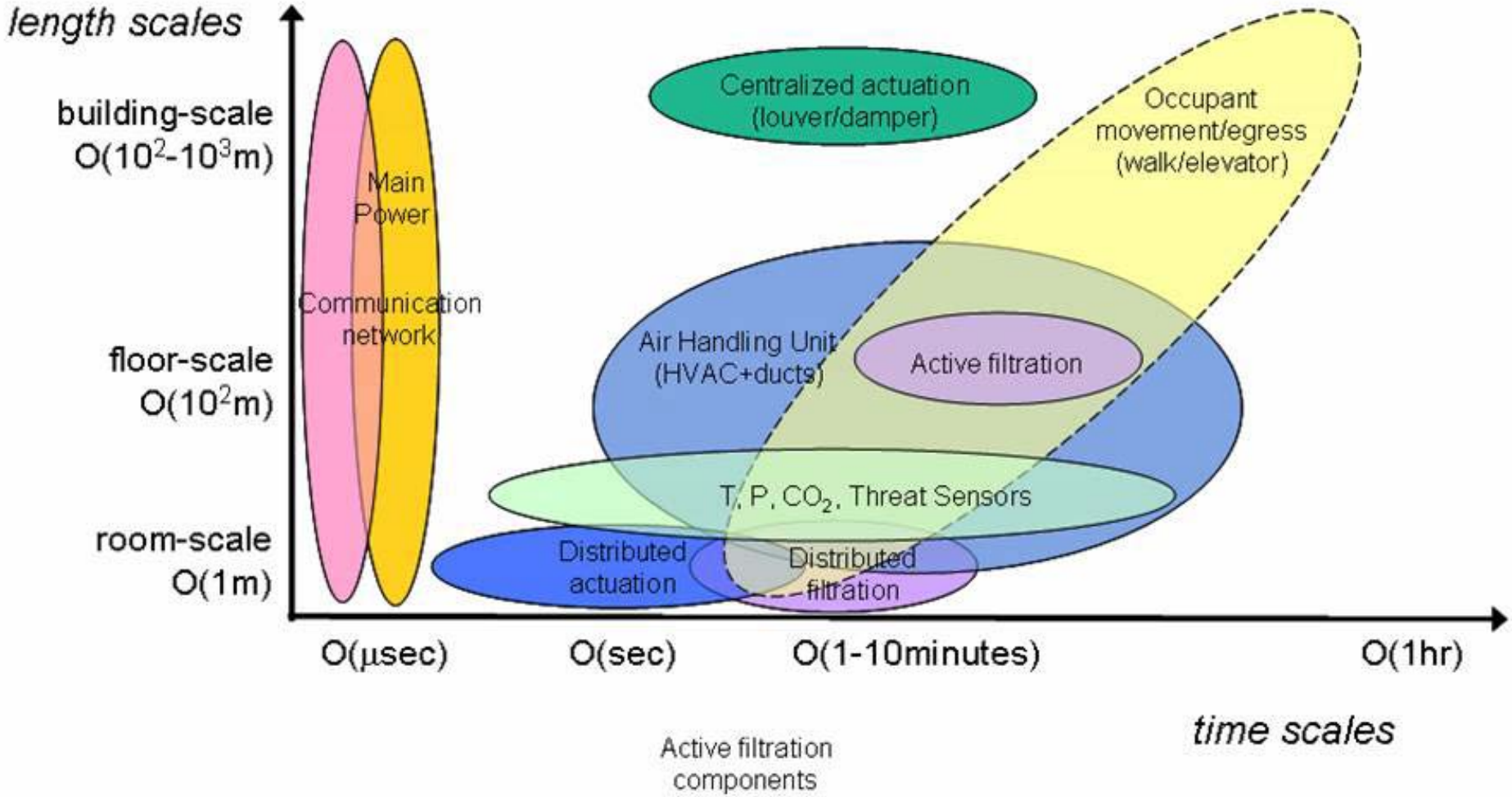
Whole Building Systems



Multi-Scale in Time and Space



Whole Buildings Are Complex Systems

A whole building system is a **complex system** because:

1. The system components do not necessarily have mathematically similar structures and may involve different scales in time or space;
2. The number of components may be large, sometimes enormous;
3. Components can be connected in a variety of different ways, most often nonlinearly and/or via a network. Furthermore, local and system wide phenomena may depend on each other in complicated ways;
4. The behavior of the overall system can be difficult to predict from the behavior of individual components. Moreover, the overall system behavior may evolve along qualitatively different pathways that may display great sensitivity to small perturbations at any stage.

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- **In addition to the above definition, even a single room can be a complex system if one is concerned with multi-physics dynamics such as coupled (chemically reacting) air flows, thermal profiles, energy flows, air quality, room geometry and the supervisory (closed-loop, possible human in the loop) control.**

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A whole building system is a **complex system** because:

MATHEMATICAL DEFINITION OF A COMPLEX SYSTEM

David L. Brown, John Bell, Donald Estep, William Gropp, Bruce Hendrickson, Sallie Keller-McNulty, David Keyes, J. Tinsley Oden and Linda Petzold, ***Appled Mathematics at the U.S. Department of Energy: Past, Present and a View to the Future***, DOE Report LLNL-TR-401536, May 2008.

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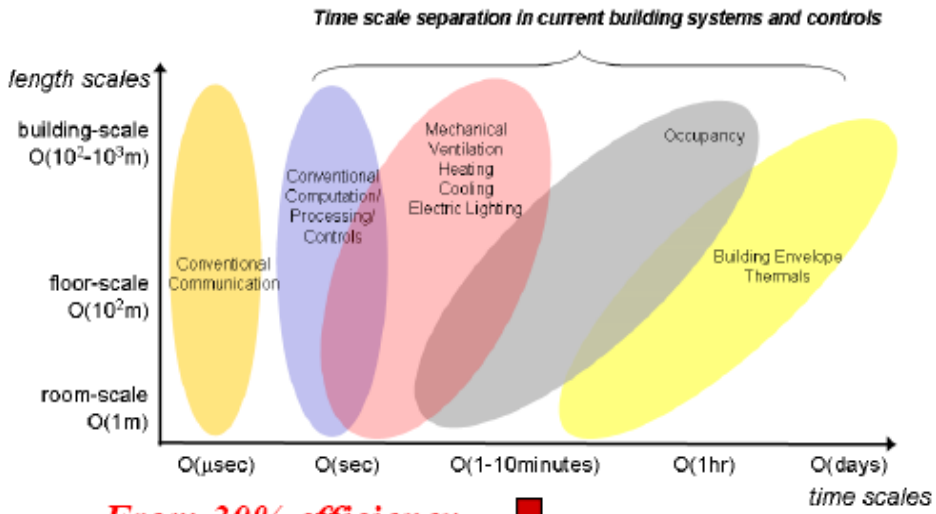
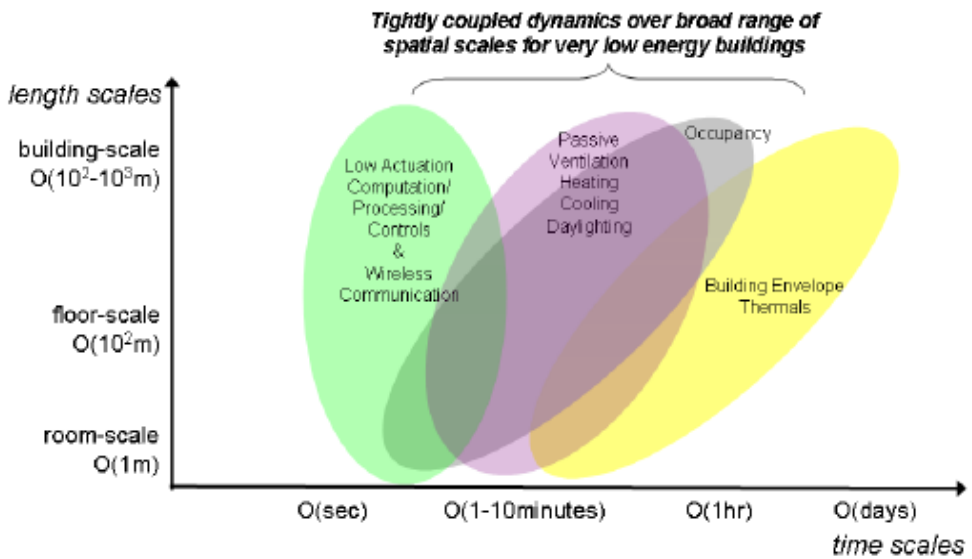
Technical Challenges



From 30% efficiency to 70-80% efficiency



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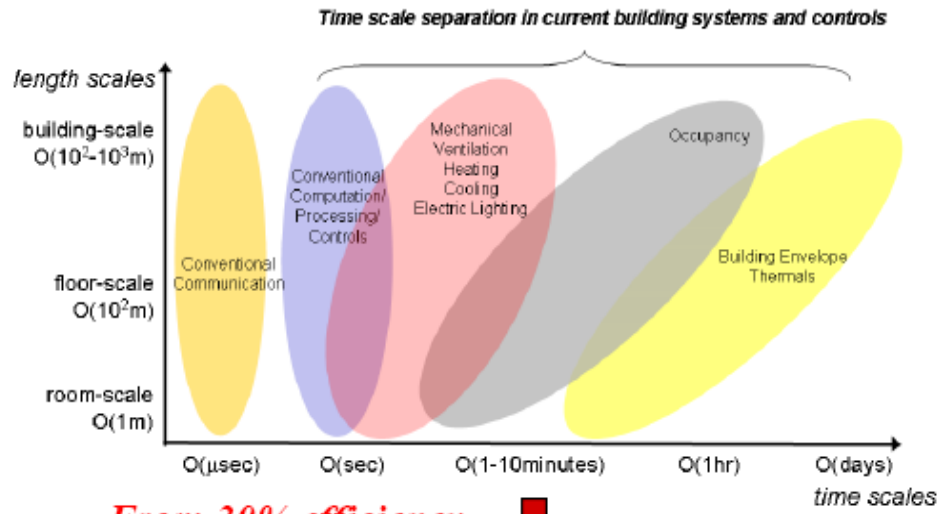

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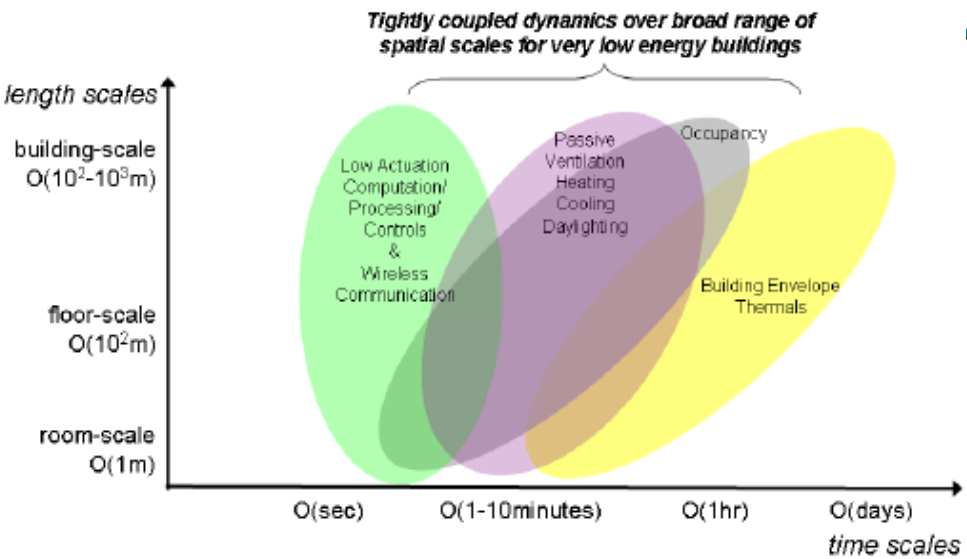

- **MODELING AND SIMULATION TOOLS THAT CAPTURE THE CORRECT BUILDING PHYSICS AT ALL KEY TIME AND SPATIAL SCALES ARE ESSENTIAL**
- **HOWEVER, BUILDING SIMULATION ALONE IS NOT SUFFICIENT**
- **MATHEMATICAL AND COMPUTATIONAL TOOLS MUST BE DEVELOPED SPECIFICALLY TO ALLOW INTEGRATION AND TO INTERFACE WITH:**
  - **DESIGN – CONTROL – OPTIMIZATION – SENSITIVITY – UNCERTAINTY TOOLS**
- **ALSO, REVOLUTIONARY ADVANCES WILL OCCUR ONLY IF THE ALGORITHMS AND COMPUTATIONAL TOOLS …**
  - **ENABLE "PLUG-AND-PLAY" FOR NEW COMPONENT TECHNOLOGIES**
  - **ARE BASED ON STATE OF THE ART COMPUTATIONAL SCIENCE**
  - **HAVE USER INTERFACES SUITABLE FOR BROAD BUILDING STOCKS**
  - **BE BUILT ON OPEN SOURCE SOFTWARE**
  - **TAKE ADVANTAGE OF MODERN COMPUTER AND COMPUTER SCIENCE TECHNOLOGY INCLUDING HIGH PERFORMANCE COMPUTING**

Barriers and Misconceptions

1. EXISTING BUILDING SIMULATION AND ENERGY TOOLS ARE NOT SUITABLE FOR DESIGN, OPTIMIZATION AND CONTROL OF WHOLE BUILDING SYSTEMS
   - THEY WERE NOT DESIGNED FOR THESE PURPOSES
   - THEY WERE DESIGNED TO RUN ON PC TYPE PLATFORMS AND HENCE FORCED TO USE CRUDE MODELS OF THE PHYSICS - CHEMISTRY
   - DO NOT TAKE ADVANTAGE OF STATE-OF-THE ART ALGORITHMS AND NEW COMPUTER PLATFORMS
   - OFTEN IGNORE SPATIAL FEATURES AND TIME SCALES THAT ARE ESSENTIAL TO OPTIMIZATION AND DESIGN TOOLS

2. EXISTING MODELS DO NOT ADDRESS UNCERTAINTY, MULTI-SCALE DYNAMICS AND REAL-TIME REQUIREMENTS

3. EXISTING SOFTWARE IS OFTEN BASED ON CRUDE MODELS, DOES NOT ALLOW FOR EASY INTEGRATION OF DESIGN AND CONTROL TOOLBOXES AND GUI's / USER INTERFACES DO NOT EXIST – "USED ONLY BECAUSE IT IS FREE"

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- IF I CAN SIMULATE A SYSTEM, THEN I CAN OPTIMIZE OR CONTROL IT <u>or</u>
- I MUST BE ABLE TO CONDUCT HIGH FIDELITY SIMULATIONS BEFORE I CAN DESIGN, OPTIMIZE OR CONTROL A SYSTEM
  - DESIGN, OPTIMIZATION AND CONTROL MAY REQUIRE 1,000's OF SIMULATIONS
  - SIMULATION ASSUMES ALL PARAMETERS, INPUTS, DISTRUBANCES ARE GIVEN
  - CONTROL DESIGN IS THE PROCESS OF FINDING OPTIMAL INPUTS
  - DESIGN AND CONTROL IS OFTEN DONE WITH REDUCED ORDER MODELS
- CONCATENATING THE "BEST SIMULATION TOOL" WITH THE "BEST DESIGN TOOL" PRODUCES THE BEST DESIGN OR CONTROL TOOL
- IF I CAN SIMULATE THE OPEN-LOOP SYSTEM, THEN I CAN SIMULATE THE CLOSED-LOOP SYSTEM
- THERE ARE NO THEORIES TO DEAL WITH MULTI-SCALE DISTRIBUTED PARAMETER CONTROL SYSTEMS

New DOE ub

August 22, 2010: The U.S. Department of Energy announced the establishment of a research hub for energy-efficient building technologies at the Navy Yard in South Philadelphia. The Energy-Efficient Building Systems Design Hub's mission will be to develop new energy efficient components for integration into whole building systems, new mathematical models and computer design tools that can be used for design and control of new buildings and to retrofit existing buildings. It also will analyze the role of policy, markets and behavior in the adoption and use of energy technology in buildings.

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Task 1: MODELING AND COMPUTATIONAL TOOLS SPECIFICALLY FOR DESIGN, OPTIMIZATION AND CONTROL OF HIGH PERFORMANCE BUILDINGS ….

Interdisciplinary Center for Applied Mathematics

Computational & Mathematical Issues

- NEW MATHEMATICAL AND COMPUTATIONAL TOOLS <u>SPECIFICALLY</u> FOR DESIGN – CONTROL - OPTIMIZATION – SENSITIVITY – UNCERTAINTY
  - BASED ON STATE OF THE ART COMPUTATIONAL SCIENCE
  - DEAL WITH MULTI-SCALE PHYSICS, CHEMISTRY AND COMPLEXITY
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POSSIBLE ROLES OF HIGH PERFORMANCE COMPUTING

- WHOLE BUILDING MODELING, SIMULATION AND HOLISTIC DESIGN
- HPC ENABLED MODEL REDUCTION
- HPC FOR PARALLEL OPTIMIZATION & DESIGN
- PREDICTIVE MODELING AND SIMULATION OF CLOSED-LOOP DYNAMICS
  - ENABLE "PLUG-AND-PLAY" FOR NEW COMPONENT TECHNOLOGIES
  - SHOULD "SOLVE" NON-STANDARD EQUATIONS –
    - NON-LOCAL (IN SPACE) COUPLED SYSTEMS
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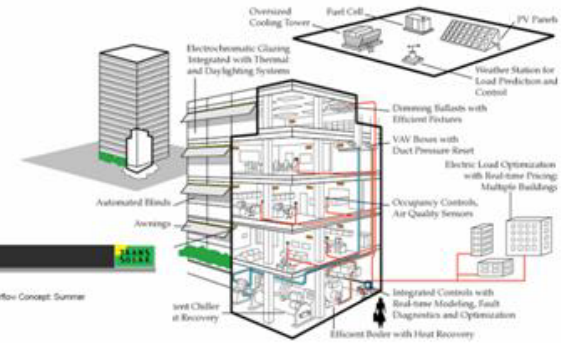
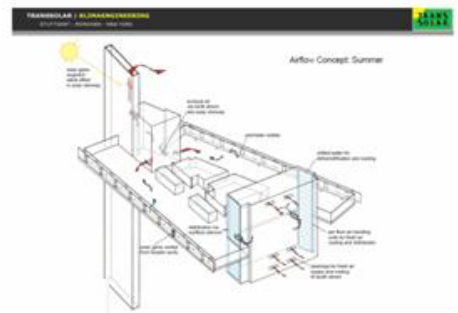
"RAW" HP2C REQUIREMENTS

Whole Building Simulations (complex geometry, multiple sub-systems, and realistic indoor - external uncertainties)



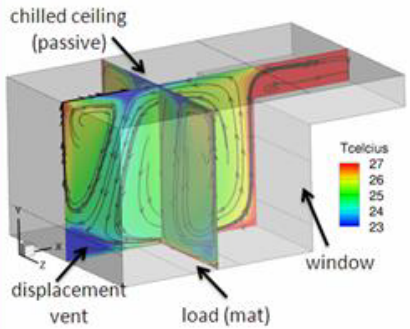
from LBNL

Multi-zone Building Simulation (simplified geometry and boundary conditions)



from Transolar Engineering

Thermal Environment in an Individual Zone/Room



from UTRC/VT

1 -10 TFlops machine* 1 PFlops machine* 10 PFlops machine*

* Less than 1hour turnaround for practical design calculations

"RAW" HP2C REQUIREMENTS

Whole Building Simulations

NOT POSSIBLE UNLESS ADVANCES ARE MADE IN

NEW ALGORITHMS

&

MODEL REDUCTION

SPECIFICALLY FOR DESIGN

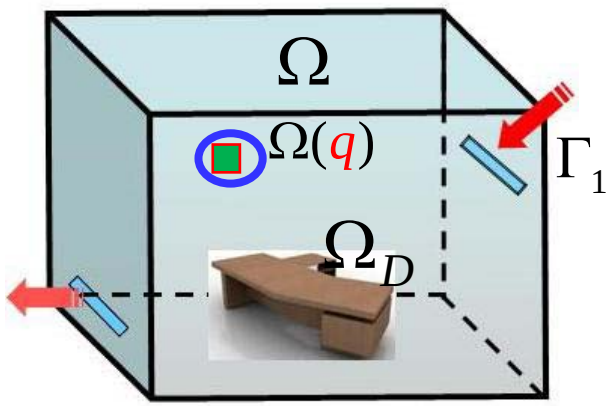
OPTIMIZATION & CONTROL

1 -10 TFlops machine* 1 PFlops machine* 10 PFlops machine*

* Less than 1hour turnaround for practical design calculations

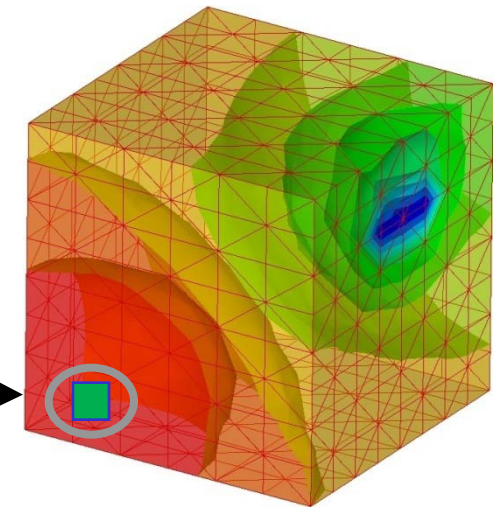
High Performance Computing for:

- **Holistic control design - optimal sensor placement**

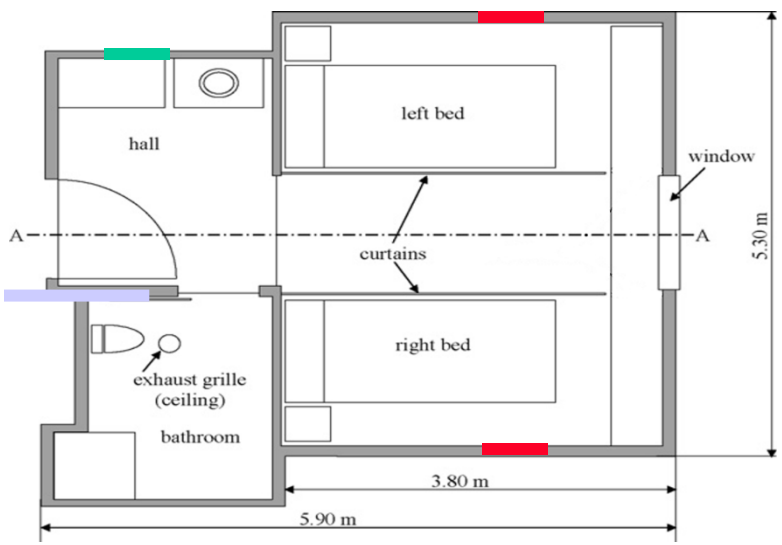


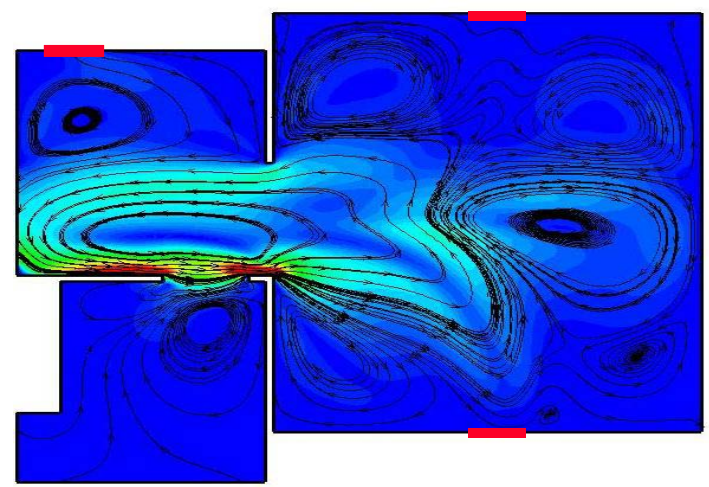
OBSERVER FUNCTIONAL GAIN

SENSOR ON LOWER SIDE WALL



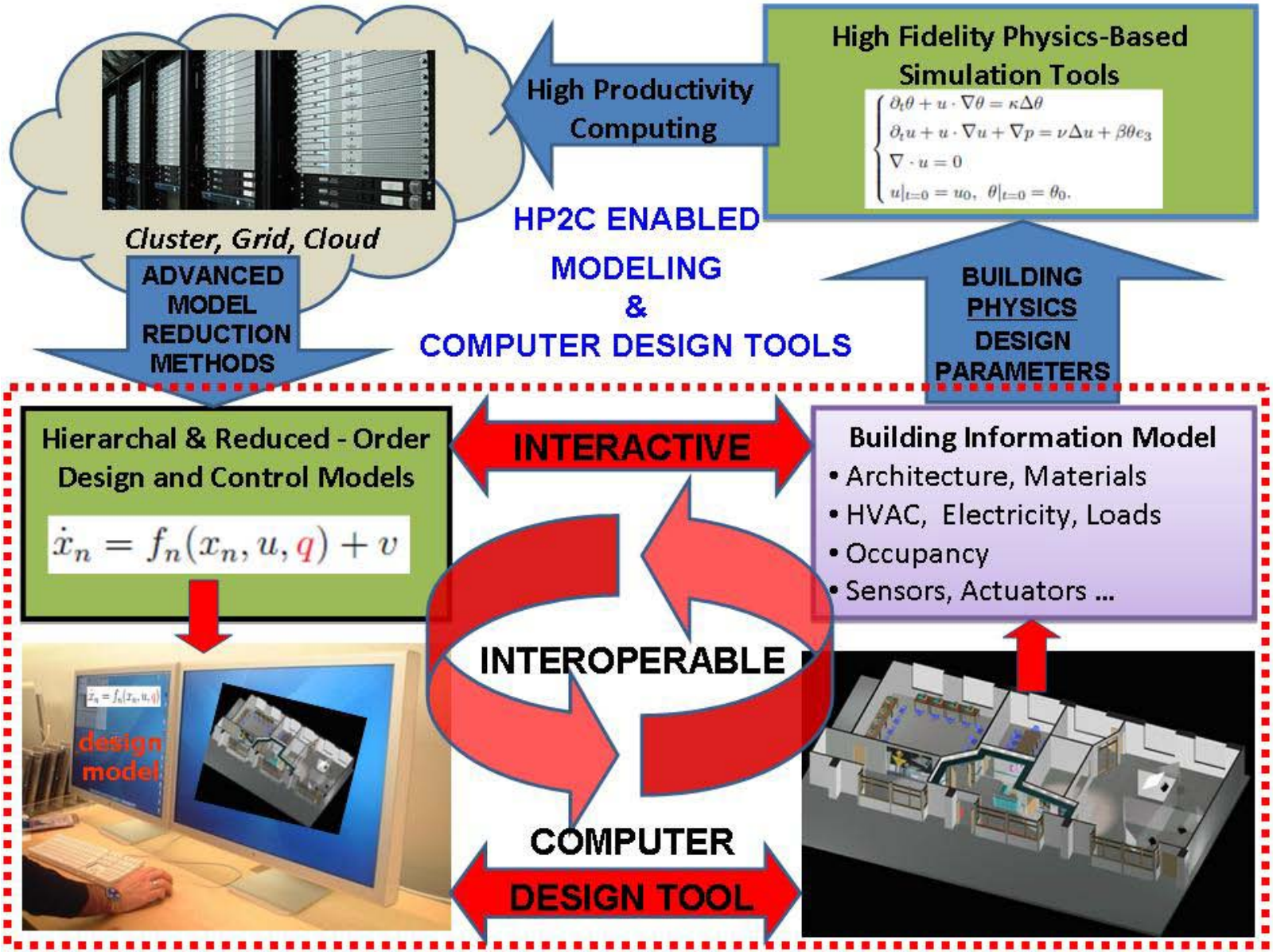
- **Shape sensitivity analysis and uncertainty**





SENSITIVITY WITH RESPECT TO WALL MOVEMENT

HP2C Enabled Model Reduction



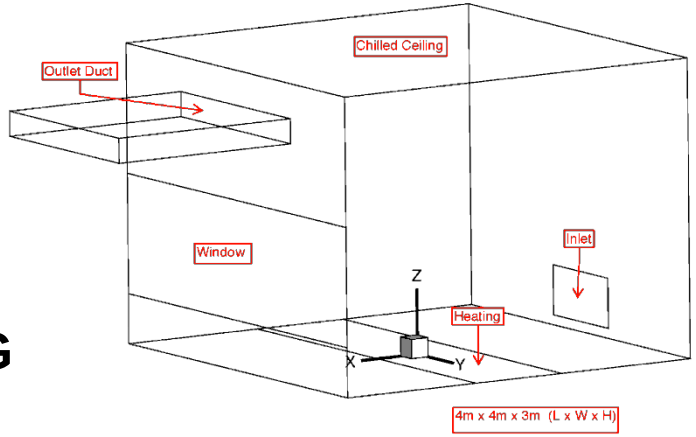
High Performance Computing for:

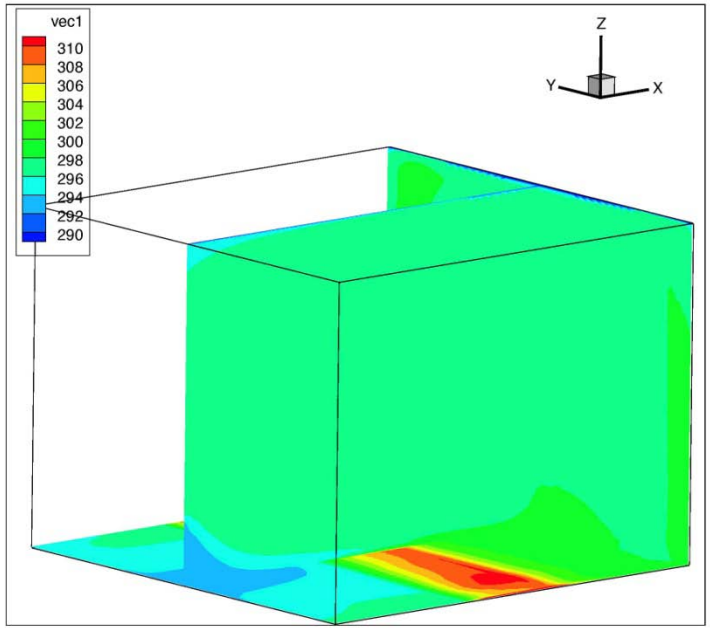
- **Model reduction**

CHILLED BEAMS

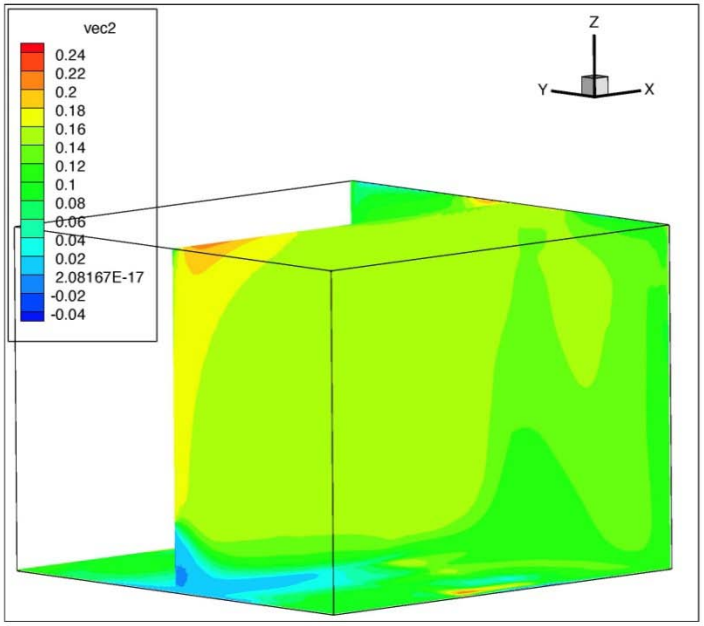
NATURAL VENTILATION

UNDERFLOOR HEATING



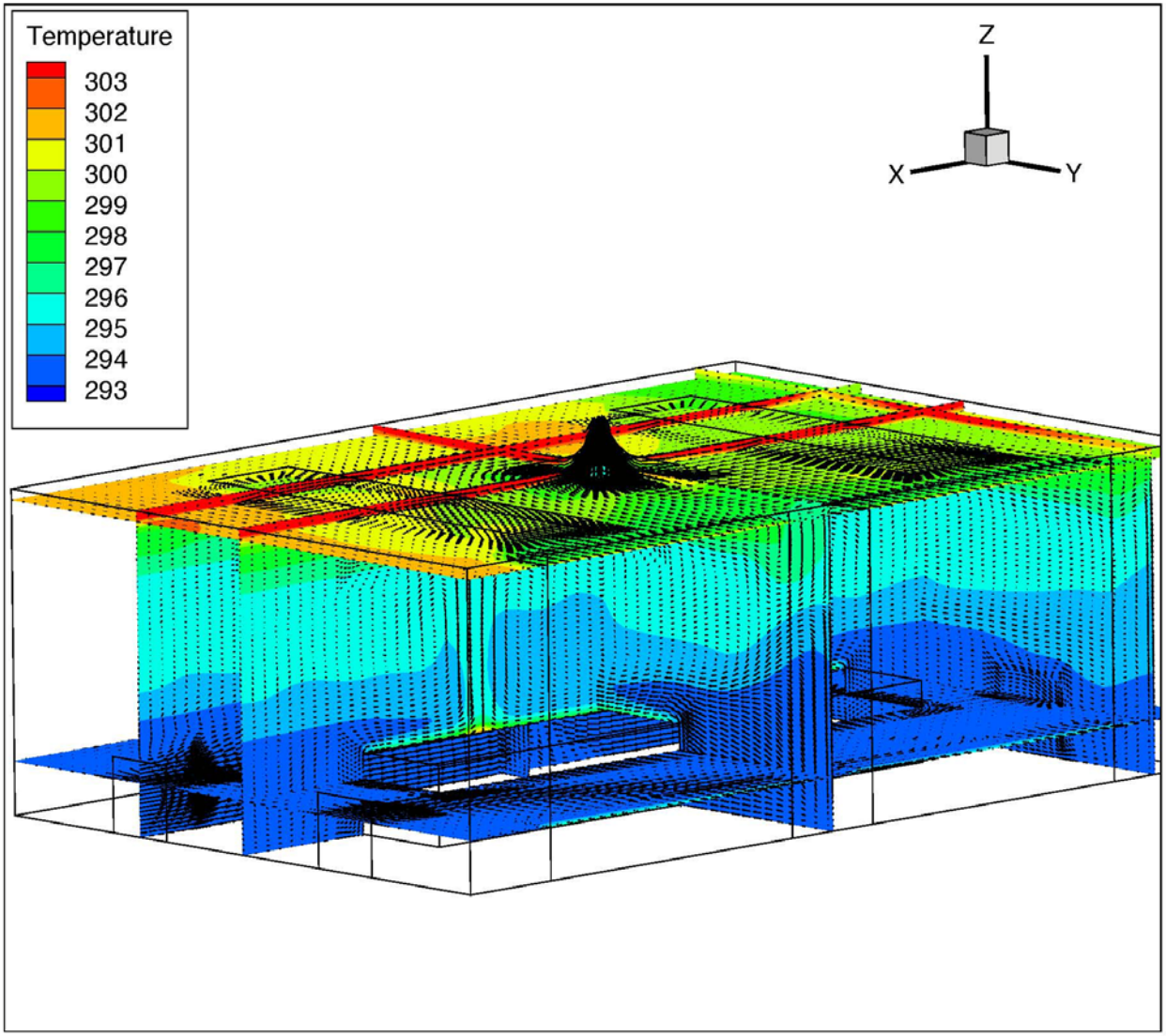


REDUCED BASIS 1

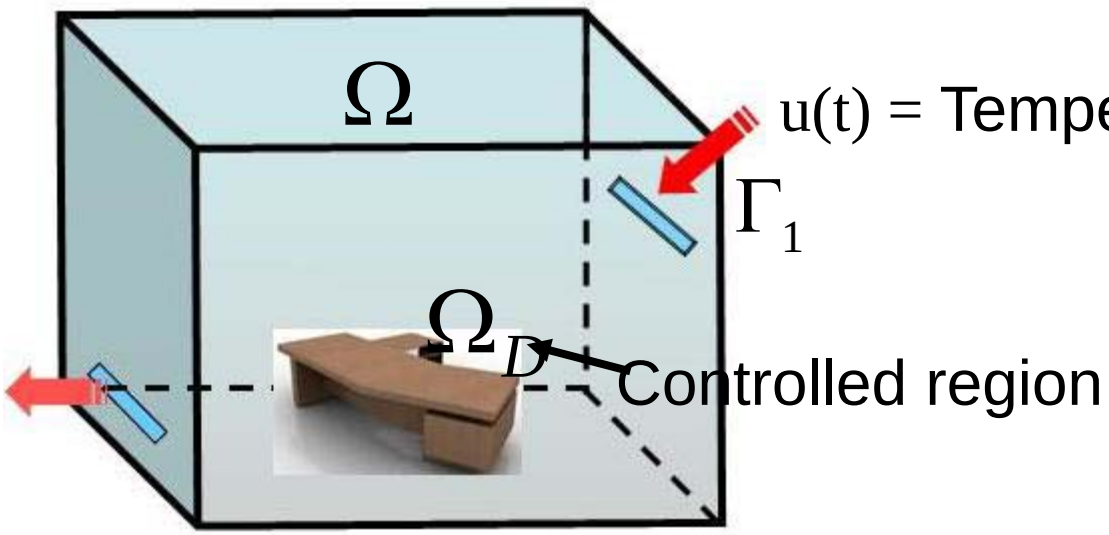


REDUCED BASIS 2

A Room with Uncertain Occupancy



Sensor Location Issues



u(t) = Temperature of inflow

Controlled region

$$\rho C\left(\frac{\partial}{\partial t}T(t,\vec{\mathbf{x}})+v(t,\vec{\mathbf{x}})\bullet\nabla T(t,\vec{\mathbf{x}})\right)=\kappa\nabla^2 T(t,\vec{\mathbf{x}})+g(\vec{\mathbf{x}})v(t)$$

$$T(t,\vec{\mathbf{x}})\big|_{\Gamma_1}=b(\vec{\mathbf{x}})u(t)$$

BOUNDARY CONTROL

$$\xi(t)=DT(t,\cdot)=\iiint_{\Omega_D} d(\vec{\mathbf{x}})T(t,\vec{\mathbf{x}})d\vec{\mathbf{x}}$$

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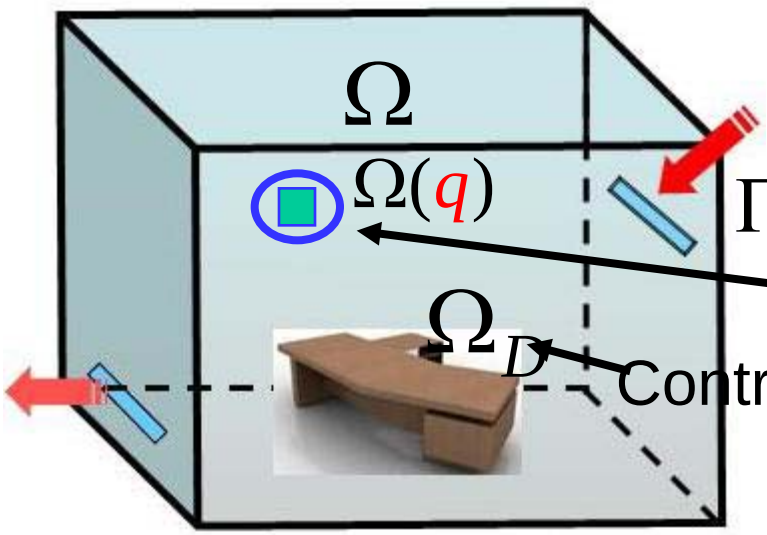

u(t) = Temperature of inflow

$$\Omega(q) = \left\{ x \in \Omega : \left\| q - \vec{\mathbf{x}} \right\| < \delta \right\}$$

Sensor region

Controlled region

$$\rho C \left(\frac{\partial}{\partial t} T(t,\vec{\mathbf{x}}) + v(t,\vec{\mathbf{x}}) \bullet \nabla T(t,\vec{\mathbf{x}}) \right) = \kappa \nabla^2 T(t,\vec{\mathbf{x}}) + g(\vec{\mathbf{x}}) v(t)$$

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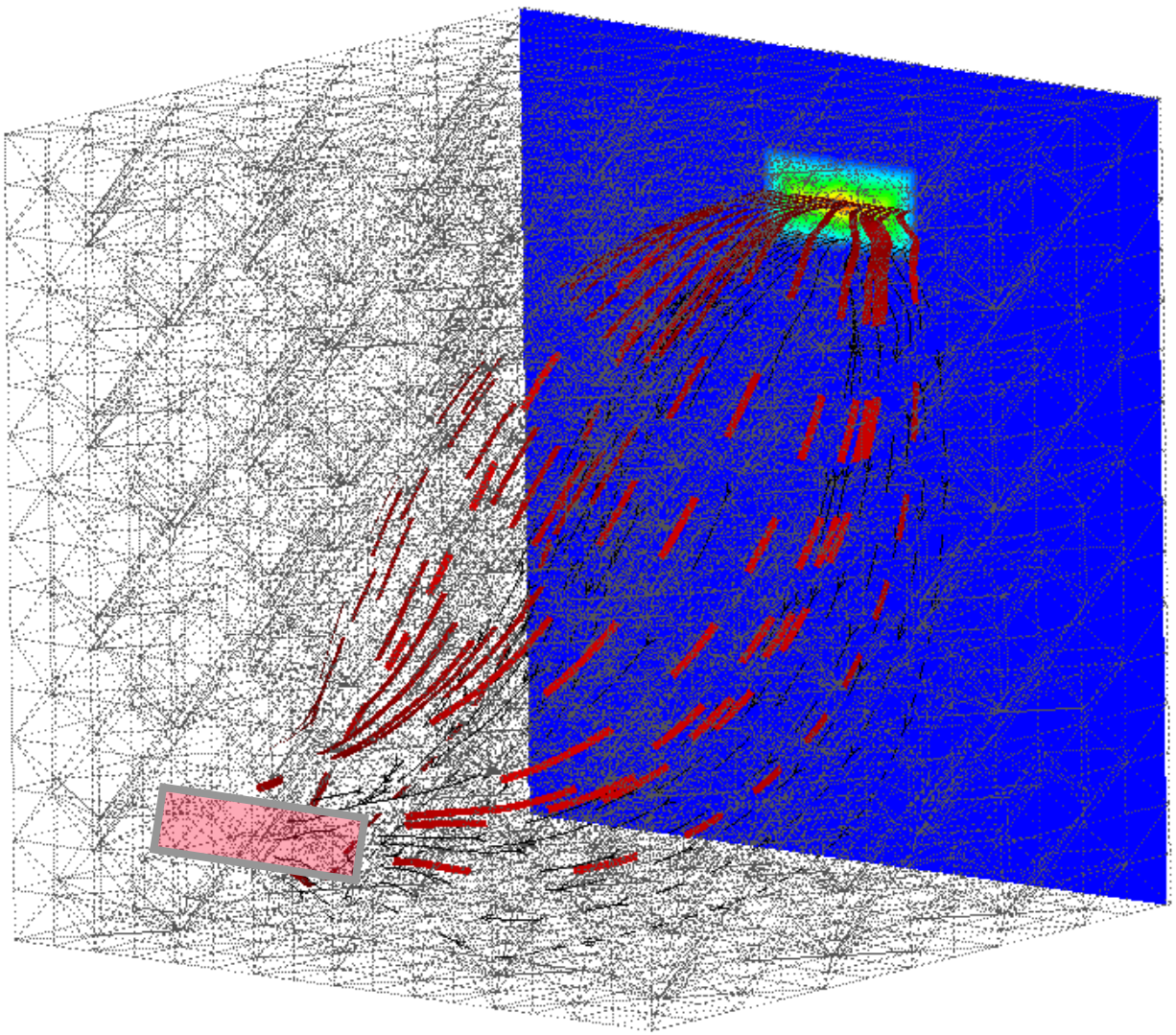
$$\xi(t) = DT(t,\cdot) = \iiint_{\Omega_D} d(\vec{\mathbf{x}}) T(t,\vec{\mathbf{x}}) d\vec{\mathbf{x}}$$

$$y(t) = C(q) T(t,\cdot) = \iiint_{\Omega(q)} c(\vec{\mathbf{x}}) T(t,\vec{\mathbf{x}}) d\vec{\mathbf{x}} + w(t)$$

Flow Field



Distributed Parameter Formulation

$$\dot{z}(t) = Az(t) + Bu(t) + Gv(t)$$ **LINEAR DP SYSTEM**

$$\xi(t) = Dz(t)$$ **CONTROLLED OUTPUT**

$$y(t) = C(q)z(t) + Ew(t)$$ **SENSED OUTPUT**

ALL CONTINUOUS (Hilbert-Schmidt) LINEAR FEEDBACK LAWS HAVE THE REPRESENTATION

$$u(t) = -Kz(t) = -\iiint_{\Omega} k_T(\vec{\mathbf{x}})T(t,\vec{\mathbf{x}})d\vec{\mathbf{x}}$$

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FEEDBACK FUNCTIONAL GAIN

Dynamic Controller

$$u(t) = -Kz(t) = -\iiint_{\Omega} k_T(\vec{\mathbf{x}})T(t,\vec{\mathbf{x}})d\vec{\mathbf{x}}$$

$$\hat{u}(t) = -K\underline{z_e(t)} = -\iiint_{\Omega} k_T(\vec{\mathbf{x}})\underline{T_e(t,\vec{\mathbf{x}})}d\vec{\mathbf{x}}$$

$$\dot{z}_e(t) = A_e z(t) + F(q)[y(t) - C(q)z_e(t)]$$

$$[F(q)y](\vec{\mathbf{x}}) = f_T(q,\vec{\mathbf{x}})y$$

Dynamic Controller

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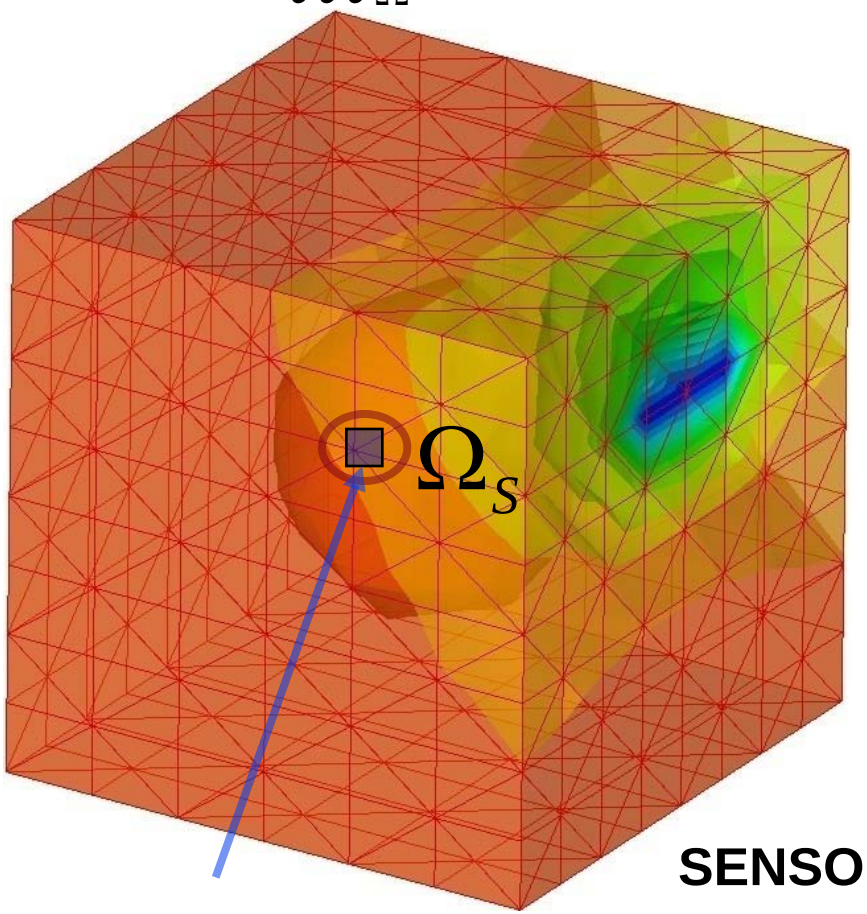
OBSERVER FUNCTIONAL GAINS

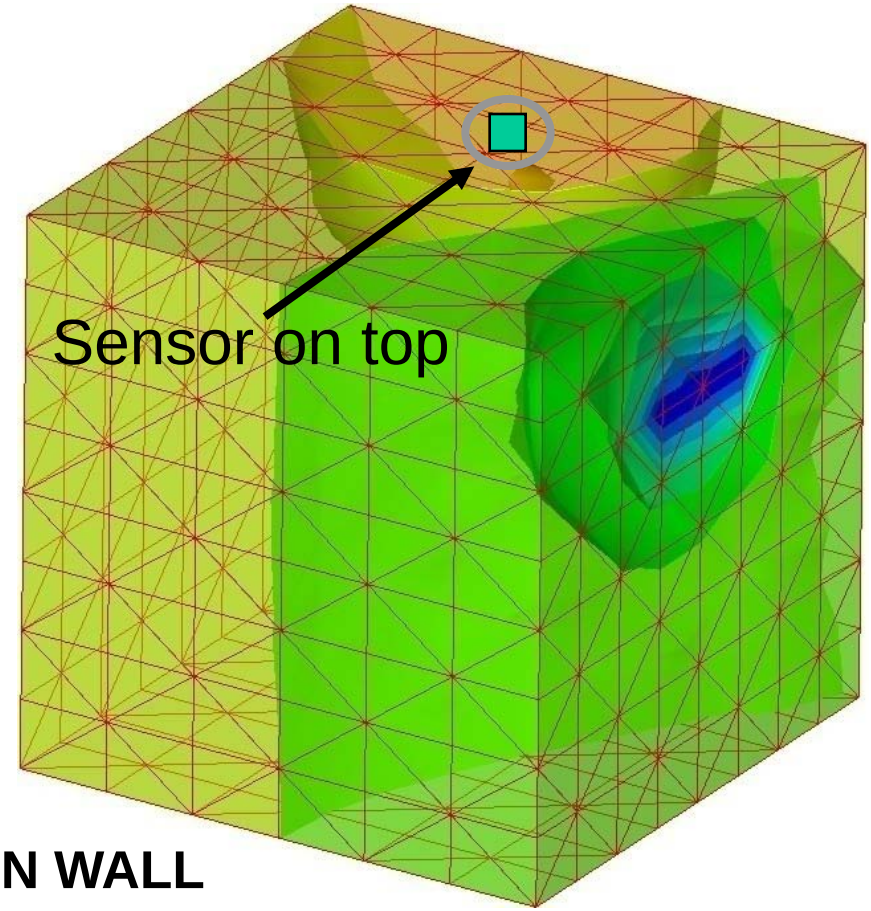
? WHAT DO THESE FUNCTIONAL GAINS TYPICALLY LOOK LIKE ?

Functional Gains

$$u(t) = -\iiint_{\Omega} k_T(\vec{\mathbf{x}}) T(t, \vec{\mathbf{x}}) d\vec{\mathbf{x}}$$

$$[F(q)y](\vec{\mathbf{x}}) = f_T(q, \vec{\mathbf{x}}) y$$





SENSOR ON WALL

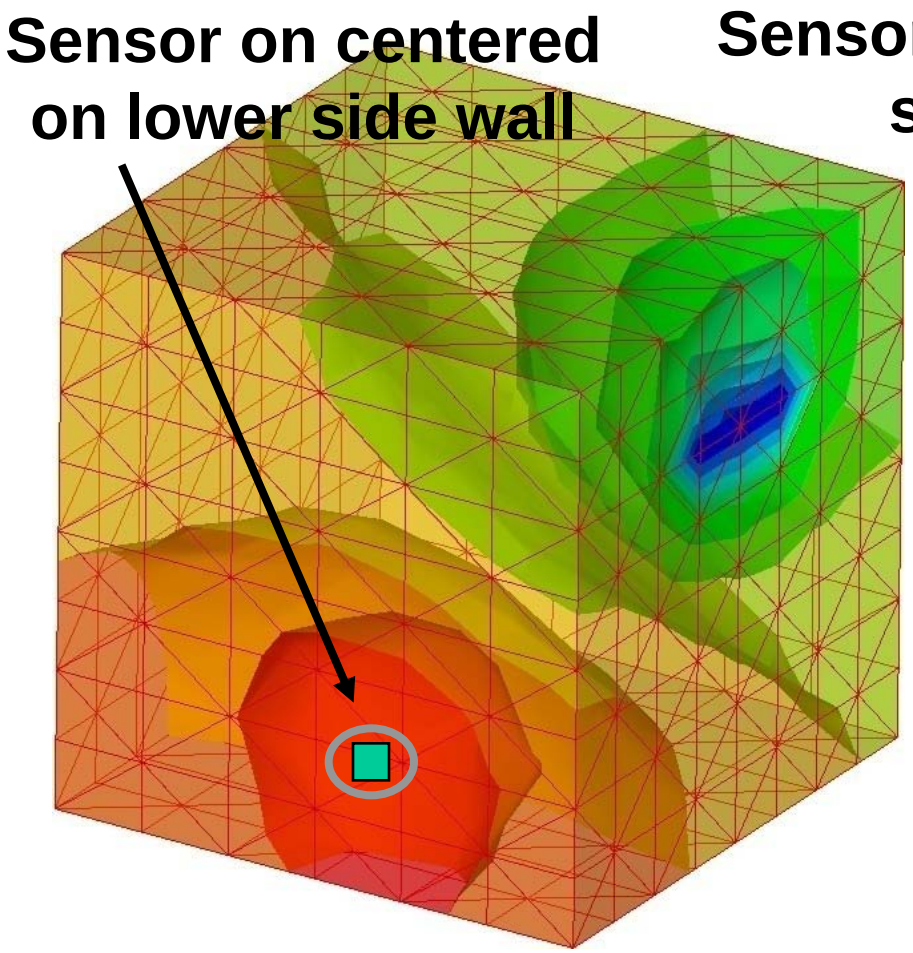
PLACE SENSOR ON DESK

FEEDBACK FUNCTIONAL GAIN

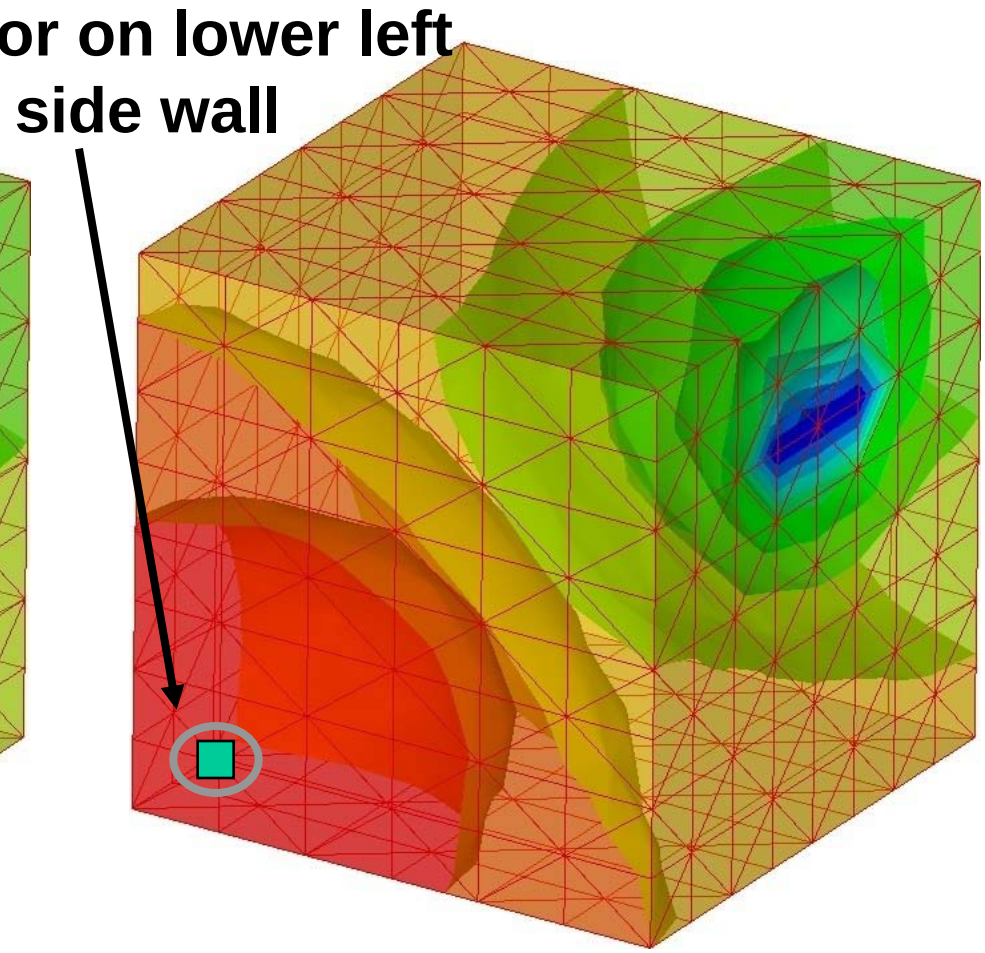
WHICH WALL AND WHERE

OBSERVER FUNCTIONAL GAIN SENSOR ON TOP WALL

Observer Functional Gains



OBSERVER
FUNCTIONAL GAIN
SENSOR ON SIDE WALL

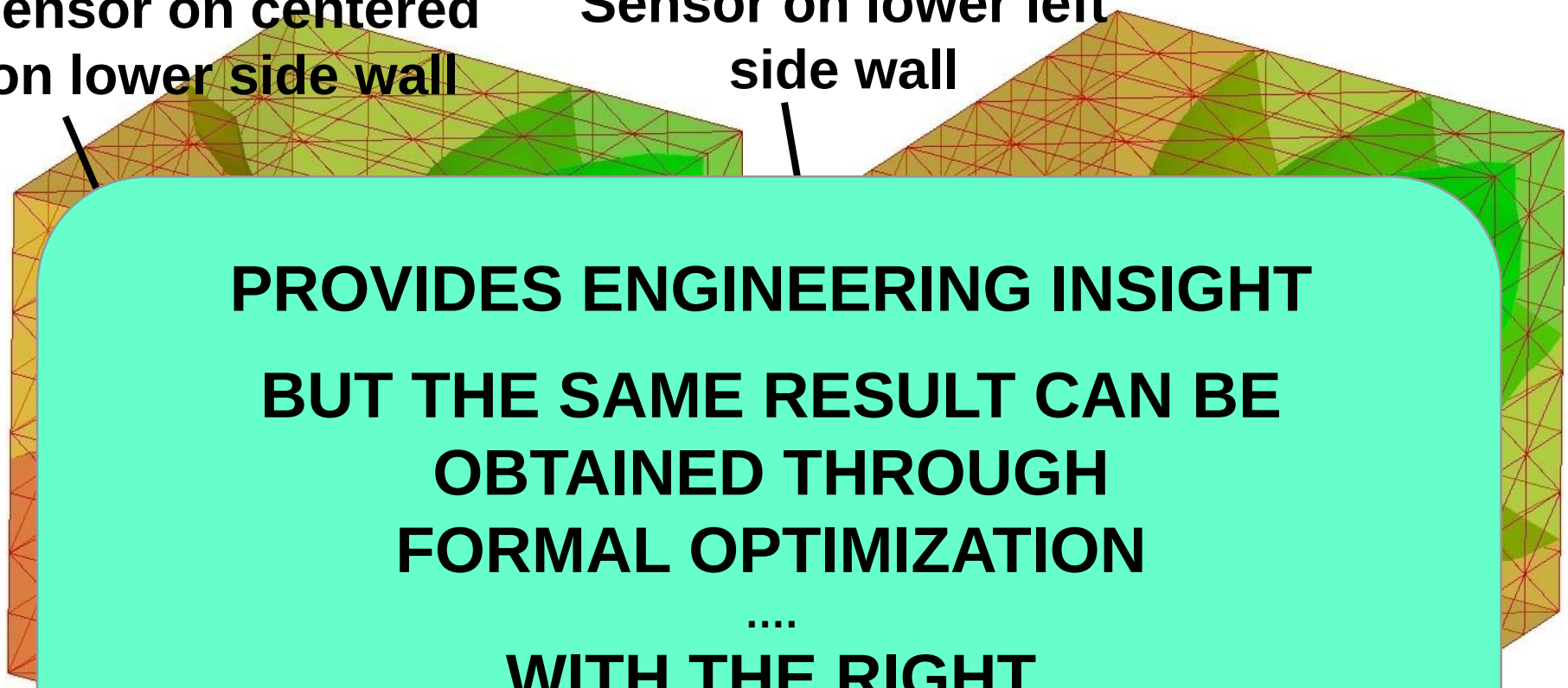


OBSERVER
FUNCTIONAL GAIN
SENSOR ON SIDE WALL

Observer Functional Gains

Sensor on centered on lower side wall

Sensor on lower left side wall



PROVIDES ENGINEERING INSIGHT

BUT THE SAME RESULT CAN BE OBTAINED THROUGH FORMAL OPTIMIZATION

....

WITH THE RIGHT COMPUTATIONAL TOOLS

OBSERVER FUNCTIONAL GAIN SENSOR ON SIDE WALL

OBSERVER FUNCTIONAL GAIN SENSOR ON SIDE WALL

Closing Remarks

- THESE ARE HARD CS&E PROBLEMS IDEAL FOR HP2C
  - WE NEED A BASIC UNDERSTANDING THE DYNAMICS AND PHYSICS OF THE INTERCONNECTED SYSTEMS IN A WHOLE BUILDING
  - EXISTING MODELING AND ANALYSIS TOOLS FOR THE TYPE OF COMPLEX SYSTEMS DEFINED BY WHOLE BUILDINGS ARE NOT SUFFICIENT FOR DESIGN AND REAL TIME CONTROL
  - …
- NEW PARADIGMS, ALGORITHMS AND COMPUTATIONAL SCIENCES ARE ESSENTIAL
  - A HOLISTIC APPROACH MIGHT PROVIDE NEW INSIGHT
  - HYBRID AND SIMULATION BASED DESIGN ALGORITHMS WILL PLAY AN IMPORTANT ROLE
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- A WHOLE BUILDING IS AN UNCERTAIN COMPLEX SYSTEM
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- A WHOLE BUILDING IS AN UNCERTAIN COMPLEX SYSTEM
  - CONTROL (OPTIMAL AND FEEDBACK) WILL BE AN ENABLING SCIENCE FOR HPB DESIGN AND OPERATION OF ENERGY EFFICIENT BUILDINGS
  - … NEED HPC SENSITIVITY AND UNCERTAINTY ANALYSIS TOOLS

THANK YOU

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