SinBerBEST
Singapore-Berkeley Building Efficiency and Sustainability in the Tropics

2019 Symposium: People, Buildings & Data – Shaping a Sustainable Future
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Uncertainty Quantification & Hybrid Simulation for Energy Efficient Building Envelopes

Extreme Events

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National Science Foundation — Where Discoveries Begin
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Caltrans
ciee California Institute for Energy and Environment
California Department of Conservation
BEARS | Berkeley Education Alliance for Research in Singapore Limited

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We Will Talk About:

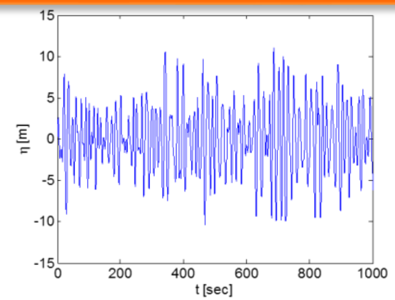
- ✓ Uncertainties
- ✓ Daylighting
- ✓ Hybrid Simulation (**H**ardware-**i**n-the-**L**oop: **HiL**)
- ✓ **S**imulation of **L**ight through **A**ctive **B**uildings: **SLAB**

Uncertainties

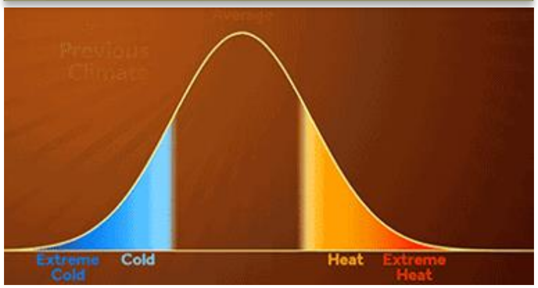
Sources:

- **Natural Hazard** (Haze, Rain, Flood, Wave, Wind, Earthquake, …)
- **Weather** (Temperature, Humidity, Solar radiation, …)
- **Use** (Human occupancy, Energy consumption, …)
- **Modeling** (Assumptions, Material behavior, …)
- …

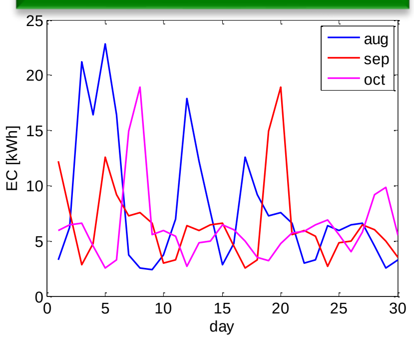
Natural Hazard (e.g. Wave)

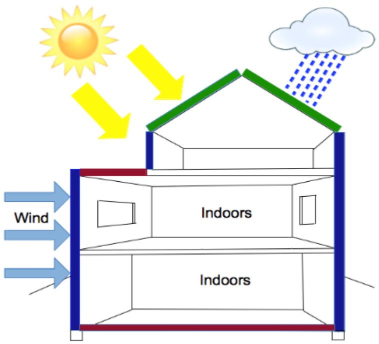


Weather (e.g. Temperature)



Energy consumption





Quantifying Tools:

- Stochastic Processes
- Random Fields
- Machine Learning (ML)
- Deep Learning (ANN, CNN, RNN)
- Reinforcement Learning (RL)

Information Theory for Uncertainty Quantification (UQ)

Relative Entropy →

- Marginal Distributions
- Joint Distributions

Kullback-Leibler (KL) Divergence

$$D[f(x) \parallel f_m(x;\boldsymbol{\vartheta})] = \int f(x) ln \frac{f(x)}{f_m(x;\boldsymbol{\vartheta})} dx$$

Model PDF: $f_m(x;\boldsymbol{\vartheta})$

Target PDF: $f(x)$

Parameters of a model distribution

$$D[f(x) \parallel f_m(x;\boldsymbol{\vartheta})] = \int f(x) ln[f(x)]dx - \int f(x) ln[f_m(x;\boldsymbol{\vartheta})]dx$$

KL divergence gives the lost information in representing $f(x)$ through $f_m(x;\boldsymbol{\vartheta}^*)$

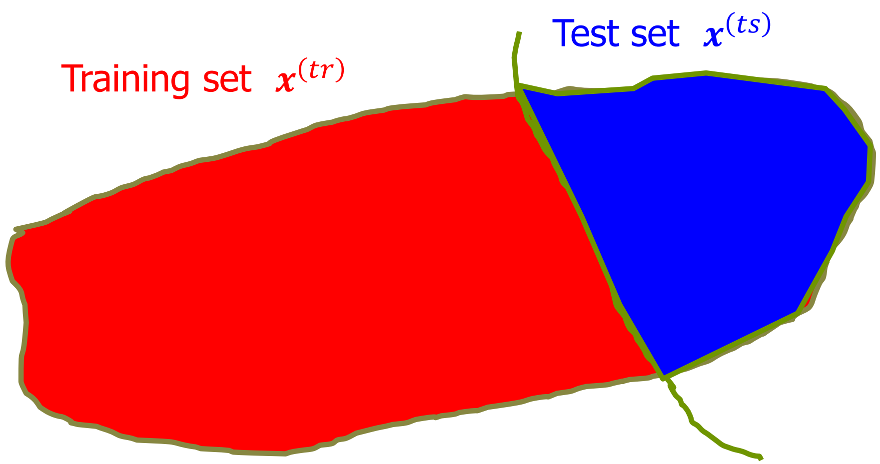
$$\min_{\boldsymbol{\vartheta}} D[f(x) \parallel f_m(x;\boldsymbol{\vartheta})] = \max_{\boldsymbol{\vartheta}} \int f(x) ln[f_m(x;\boldsymbol{\vartheta})]dx = \max_{\boldsymbol{\vartheta}} E[ln\{f_m(x;\boldsymbol{\vartheta})\}]$$

$$\boldsymbol{\vartheta}^* = \max_{\boldsymbol{\vartheta}} \left(\frac{1}{n} \sum_{i=1}^{n} ln[f_m(x^{(i)};\boldsymbol{\vartheta})] \right)$$

Maximum Likelihood Estimation (MLE)

The minimum divergence between $f(x)$ underlying the data & the model $f_m(x;\boldsymbol{\vartheta})$ is equivalent to MLE of the model

Algorithm for Model Selection



1. $m = 1,2,3, \dots$ (Ex. LN, Weibull, …)

- **a.** *Choose model* $f_m(x; \boldsymbol{\vartheta})$
- **b.** $\boldsymbol{\vartheta}^* = \boldsymbol{\vartheta}^*\left[\boldsymbol{x}^{(tr)}\right]$
- **c.** $f_m(x) = f_m(x; \boldsymbol{\vartheta}^*)$

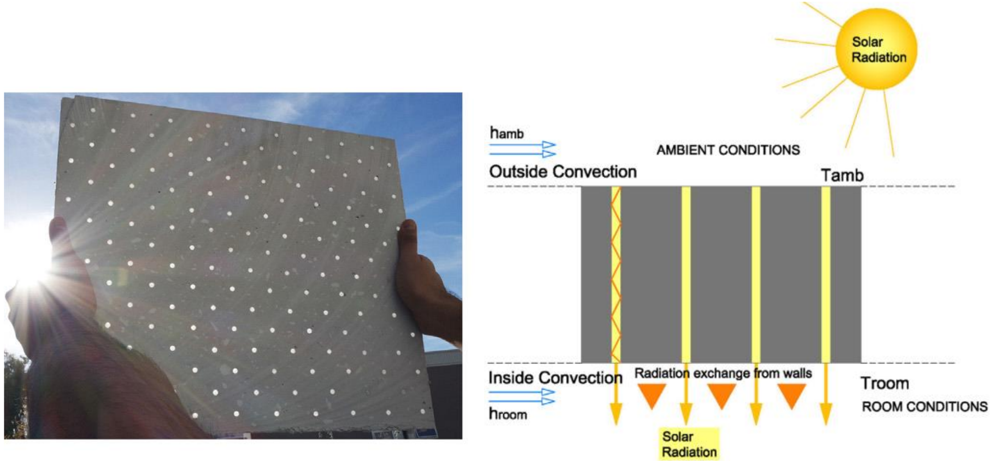
2. $D_m = D\left[f\left(\boldsymbol{x}^{(ts)}\right) \parallel f_m\left(\boldsymbol{x}^{(ts)}, \boldsymbol{\vartheta}^*\right)\right]$

3. $f_{opt}(x) = argmin\{D_1, D_2, D_3, \dots\}$

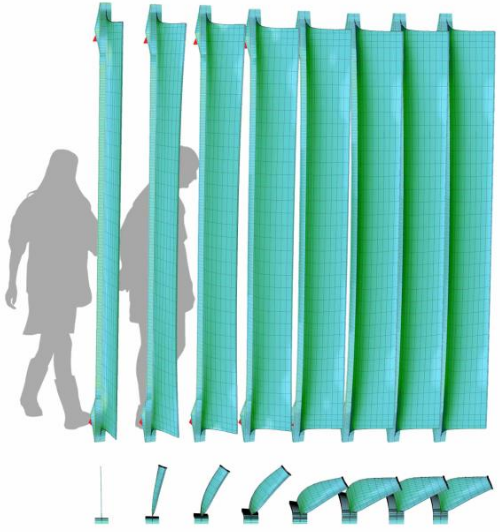
Difficulties in Daylighting Analysis of Complex Fenestration Systems (CFS)

Light-transmission properties of new façade systems are complex:

- ✓ Involving complex light-propagation mechanism
- ✓ Changing state according to environment and/or commands (active/adaptive)



Translucent Concrete Panels (TCPs): A novel fenestration with complex optical path [Ahuja & Mosalam, 2017].



An adaptive façade system [Schleicher et al., 2011]

Importance & Approaches of Daylighting Analysis

Daylighting is an important part of the overall building performance with impacts on:

Occupants wellbeing/productivity
- Visual comfort, e.g. glare
- Productivity loss due to insufficient daylight

Energy use of buildings
- Lighting load from lack/excess of daylighting
- Cooling/heating load

Numerical simulation

Ray tracing:
- ✓Backwards ray tracing
- ✓Photon mapping
- ✓Monte-Carlo ray tracing

Finite element radiosity method

Physical testing

Full scale tests

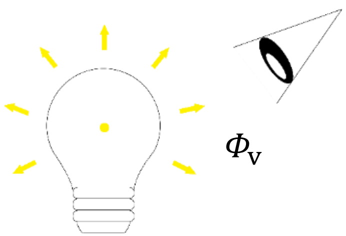
Ex.: FLEXILAB at Lawrence Berkeley National Laboratory (LBNL)

Reduced scale tests

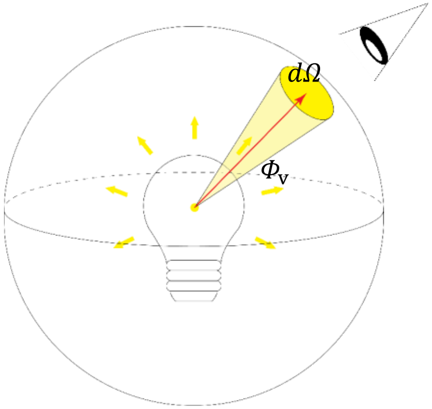
Ex.: SinBerBEST scanning heliodon

Basic Definitions in Daylighting Analysis

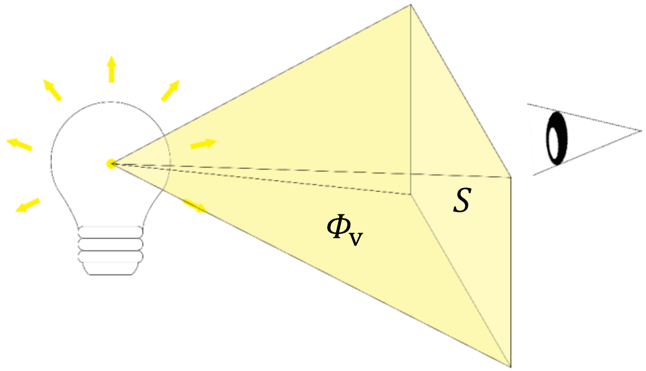
Luminous flux $\boldsymbol{\Phi_\mathrm{v}}$: weighted (perceived by human eyes) power of light emitted by a light source [**Lumen**].



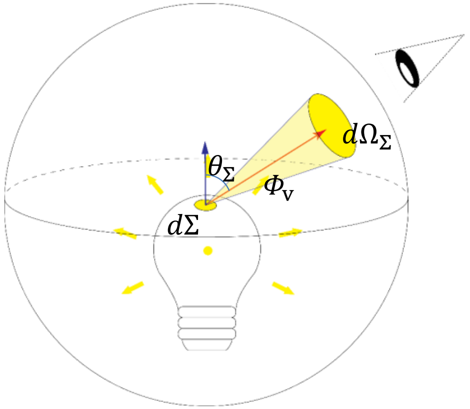
Luminous intensity $\boldsymbol{I_v} = \frac{d\Phi_v}{d\Omega}$: luminous flux emitted by the entire light source in one direction per solid angle Ω [**Candela**].



Illuminance $\boldsymbol{E_v} = \frac{d\Phi_v}{dS}$: total luminous flux from all directions incident on a surface S per unit area [**Lux**]. Reflected luminance from a surface is proportional to illuminance the surface receives and its reflectance.



Luminance $\boldsymbol{L_v} = \frac{d^2\Phi_v}{d\Omega_\Sigma d\Sigma \cos\theta_\Sigma}$: luminous intensity per unit area of the light source Σ [**Candela/$\boldsymbol{m^2}$**] "perception of brightness".

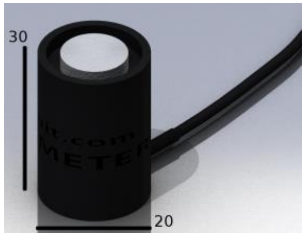


Sensing Technology in Daylighting Research (1/2)

- Luminous flux measurement (Integrating Spheres)
  - ✓ Internal near-ideal diffusively reflective (Lambertian) coating scatters light uniformly "integrating luminous flux" in all directions.
  - ✓ Measure the output power of lights but **costly**.

The integrating sphere
https://en.wikipedia.org/wiki/Integrating_sphere

- Illuminance measurement (Meters)
  - ✓ Ubiquitous in engineering to estimate light distribution in a space.
  - ✓ Loses the **directional information** of incident light.



Illuminance sensor
©Beta Nit™

Sensing Technology in Daylighting Research (2/2)

- Luminance/luminous intensity distribution
  - Luminance meters
    - ✓ Measures luminance in **single solid angles**.
  - Digital cameras
    - ✓ Use High Dynamic Range Image (HDRI) method by **costly** digital cameras or **cheap** Raspberry Pi (RPi) cameras.
    - ✓ Need **calibration** in advance.
  - Goniophotometer
    - ✓ Accurate measurements of emitted luminance distribution of materials to calculate their transmission functions.
    - ✓ Slow and **expensive**.

luminance meter https://gossen-photo.de/en/mavo-spot-2-usb/

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Ubiquitous luminance sensing using the Raspberry Pi and Camera Module system

The Society of Light and Lighting

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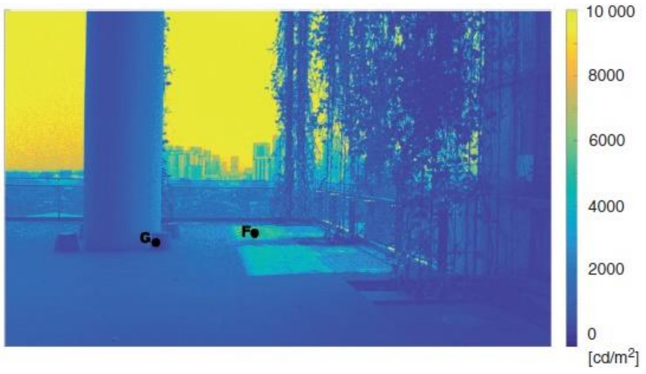
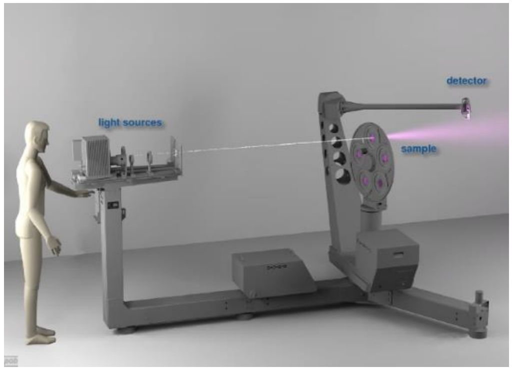




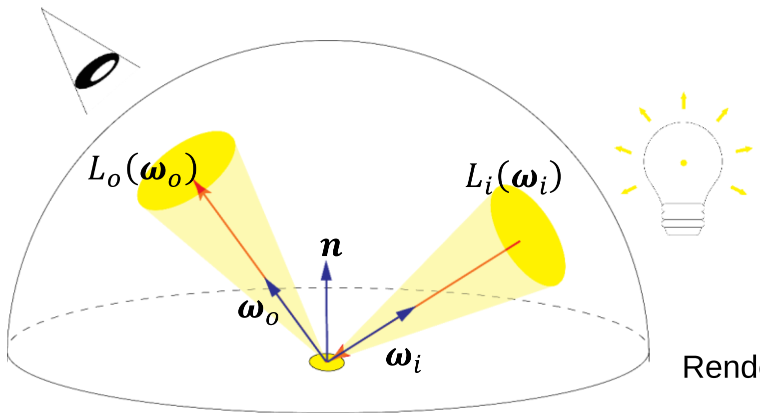
A model of Goniophotometer used by LBNL & Solar Energy Research Institute of Singapore, http://www.pab.eu/

Goal of Numerical Methods for Daylighting Simulation

Solve the fundamental rendering equation (Immel et al., 1986; Kajiya, 1986):

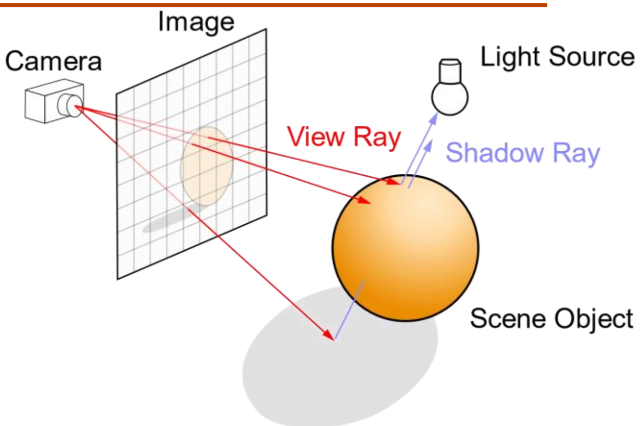
$$L_o(\boldsymbol{\omega}_o) = L_e(\boldsymbol{\omega}_o) + \int_\Omega f_r(\boldsymbol{\omega}_o, \boldsymbol{\omega}_i)\, L_i(\boldsymbol{\omega}_i)\, (\boldsymbol{\omega}_i \cdot \boldsymbol{n})\, d\boldsymbol{\omega}_i$$

$L_o(\boldsymbol{\omega}_o)$: output (reflected & emitted) luminance in direction $\boldsymbol{\omega}_o$;
$L_e(\boldsymbol{\omega}_o)$: luminance emitted by the surface;
$f_r(\boldsymbol{\omega}_o, \boldsymbol{\omega}_i)$: reflective transmission function (relating reflected luminance to incident one);
$L_i(\boldsymbol{\omega}_i)$: incident luminance in direction $\boldsymbol{\omega}_i$; and
$\boldsymbol{n}$: normal vector to the surface.



Rendering Equation

Numerical Methods for Daylighting Simulation



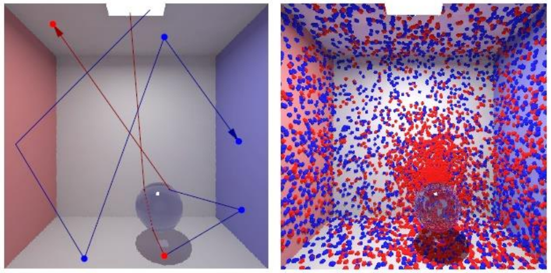
Backward ray tracing method
https://en.wikipedia.org/wiki/Ray_tracing_(graphics)#/media/File:Ray_trace_diagram.svg

Backwards ray tracing method [Whitted, 1980]

- shooting "view rays" from an observer to surfaces & simulating light propagation (reflection, refraction & scattering).
- unable to handle scenarios with complex reflections & refractions, e.g. indirect diffuse reflections.

Photon mapping method [Jensen, 1996 & 1997]

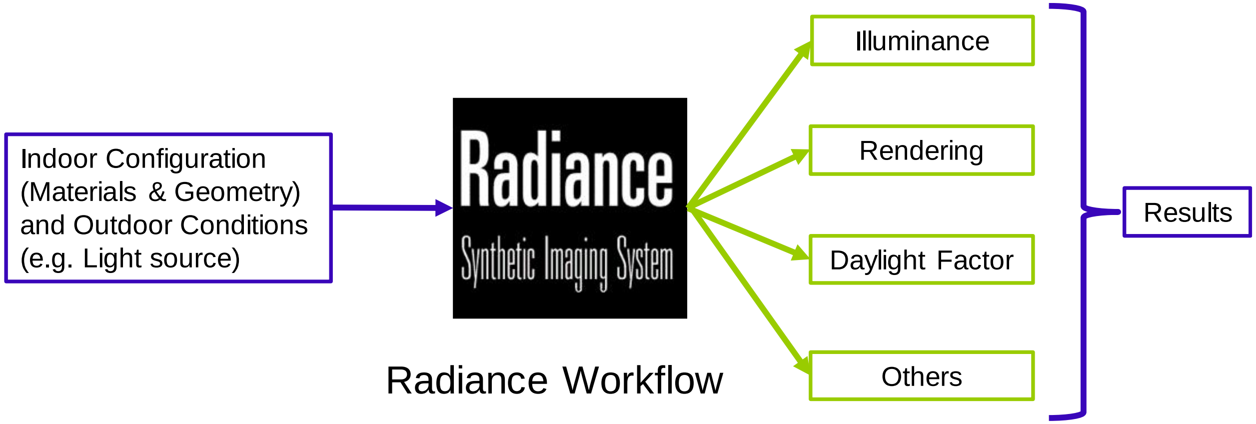
- forward step: photons emitted from all sources & reflected, refracted or absorbed probabilistically.
- backward step: view rays shot from an observer "ray tracing" & illuminance calculated as a density estimation of photons.
- Can handle indirect diffuse illuminations.



Photon mapping method. Left: forward step for two photons.
Right: density distribution of photons at end of forward step.
https://www.radiance-online.org/learning/documentation/photonmap-user-guide

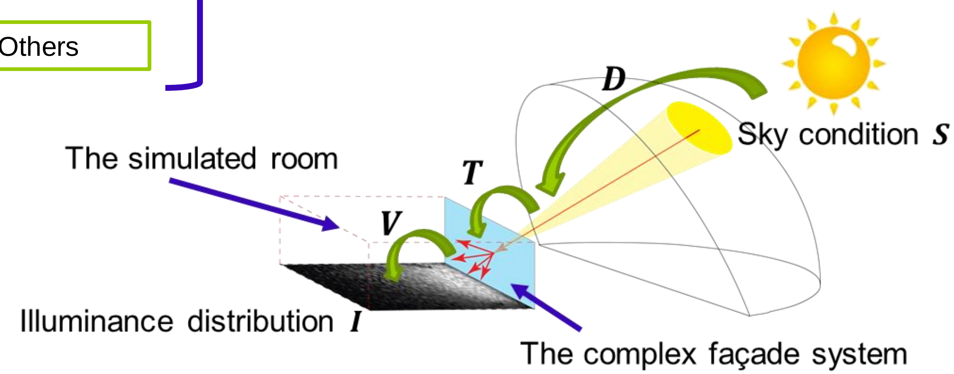
Radiance & Three Phase Simulation Methodology for Daylighting Analysis

Radiance [Ward, 1994]: Industry main tool for geometric optics using backwards ray tracing & photon mapping.



Radiance Workflow

Three-phase method [McNeil, 2013] developed for **annual simulation of CFS** (suitable for HiL simulation).



Basic equation: $I = VTDS$ with matrices:

I: **illuminance distribution** of space in question (points in space × time steps "***n***")

S: **sky condition** of a location at ***n*** (sky patches in 145 Tregenza, 580 Reinhart MF:2, or 2,305 Reinhart MF:4 divisions "***p***" × ***n***)

D: **daylight** maps ***p*** to a luminance component incident on façade surface (luminance components in 145 Klems basis × ***p***)

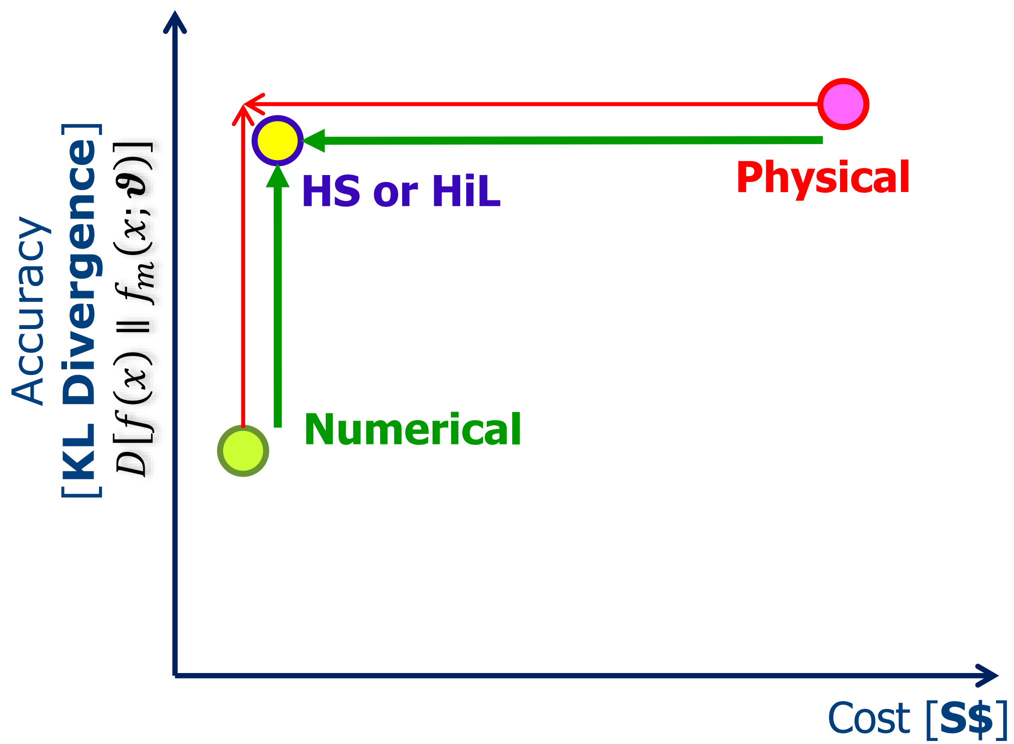
T: **façade transmission** maps incident to output luminance (emitted × incoming luminance components in 145 Klems basis)

V: **view** maps output façade luminance to room illuminance distribution (points in space × emitted luminance components)

Physical Testing Approaches & Comparisons

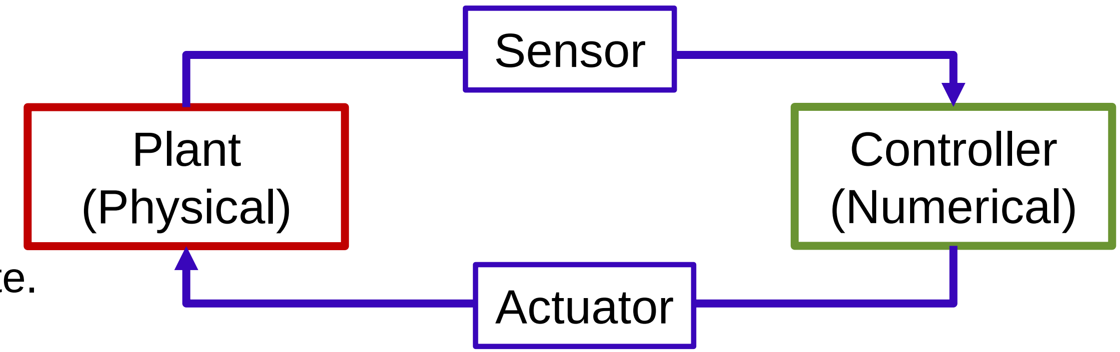
	Advantages	Disadvantages
Numerical Simulation	• Versatile (multi-physics abilities) • Fast & cost-effective	• Uncertainties from model assumptions • Difficult to simulate complex systems
Physical Testing	• Eliminating modeling & computational errors • Can test complex systems	• Cost, slow & needs expertise • Laws of similitude limit geometry & material choices of the experiments

A Hybrid Simulation (HS) or Hardware-in-the-Loop (HiL) approach combines merits of the two!



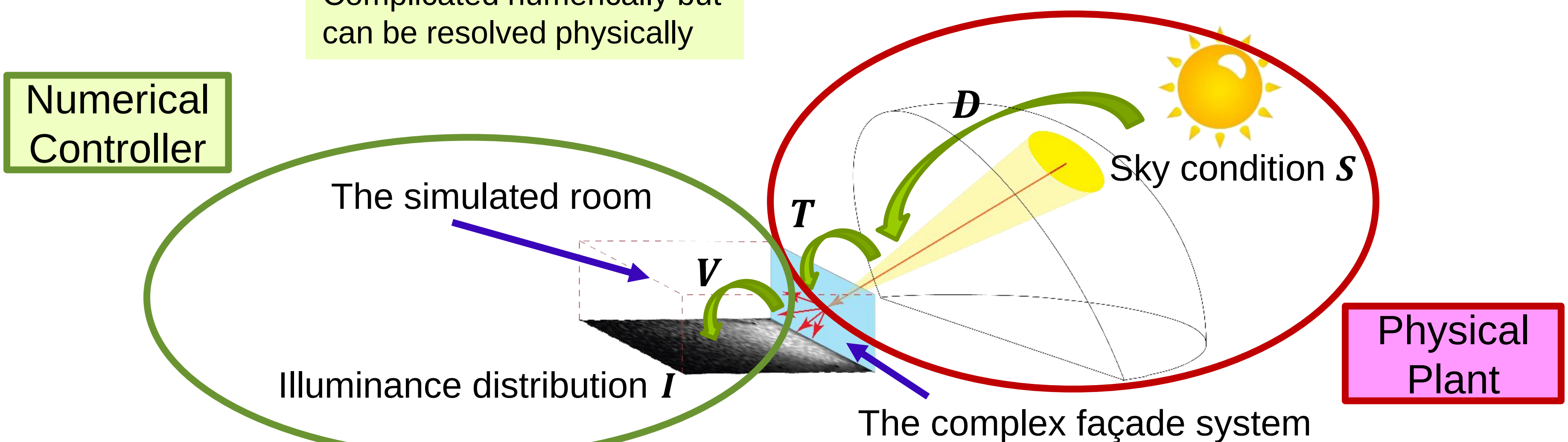
Hardware-in-the-Loop (HiL) Approach in Daylighting Analysis

- Architecture of HiL simulation:
  - **Controller** simulates the mathematical model.
  - **Plant** consists of the physical model, usually difficult to simulate.



- In daylighting analysis, the computationally most difficult part is the transmission of light energy through the CFS: $\boldsymbol{I} = \boldsymbol{V}\underbrace{\boldsymbol{TDS}}$

Complicated numerically but can be resolved physically

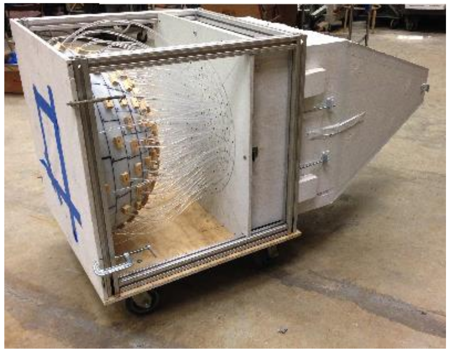


Simulator of Light into Active Buildings (SLAB)

Motivation & Objectives:

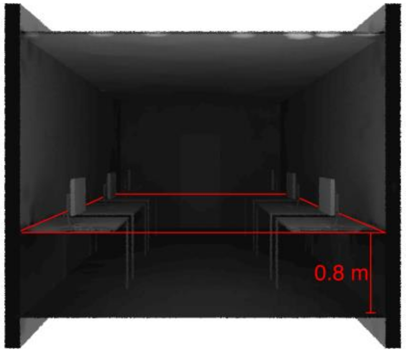
- Few platforms are available to perform cyber-physical validation of daylighting performance of ***complex building façades including outdoor conditions***.
- CFS (material, geometry & mechanisms) are challenging for ***numerical simulations*** considering daylighting, thermal performance, etc.

- Develop a ***testbed*** for CFS (typically, require large-scale testing).
- Develop a parallel luminance sensor as a ***portable*** Goniophotometer.
- Develop a ***HiL platform for performance-based design*** of CFS including ***UQ***.



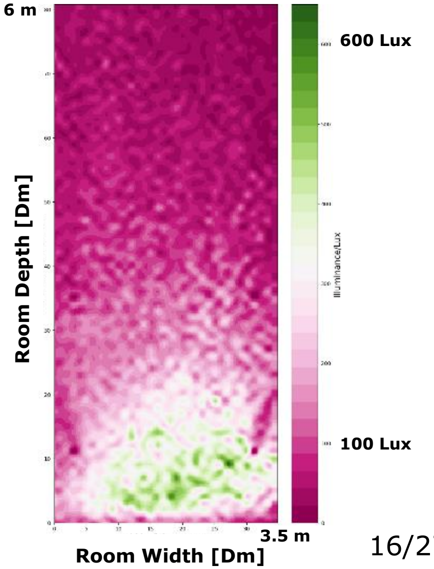
Optical component of SLAB

In-field operation of SLAB

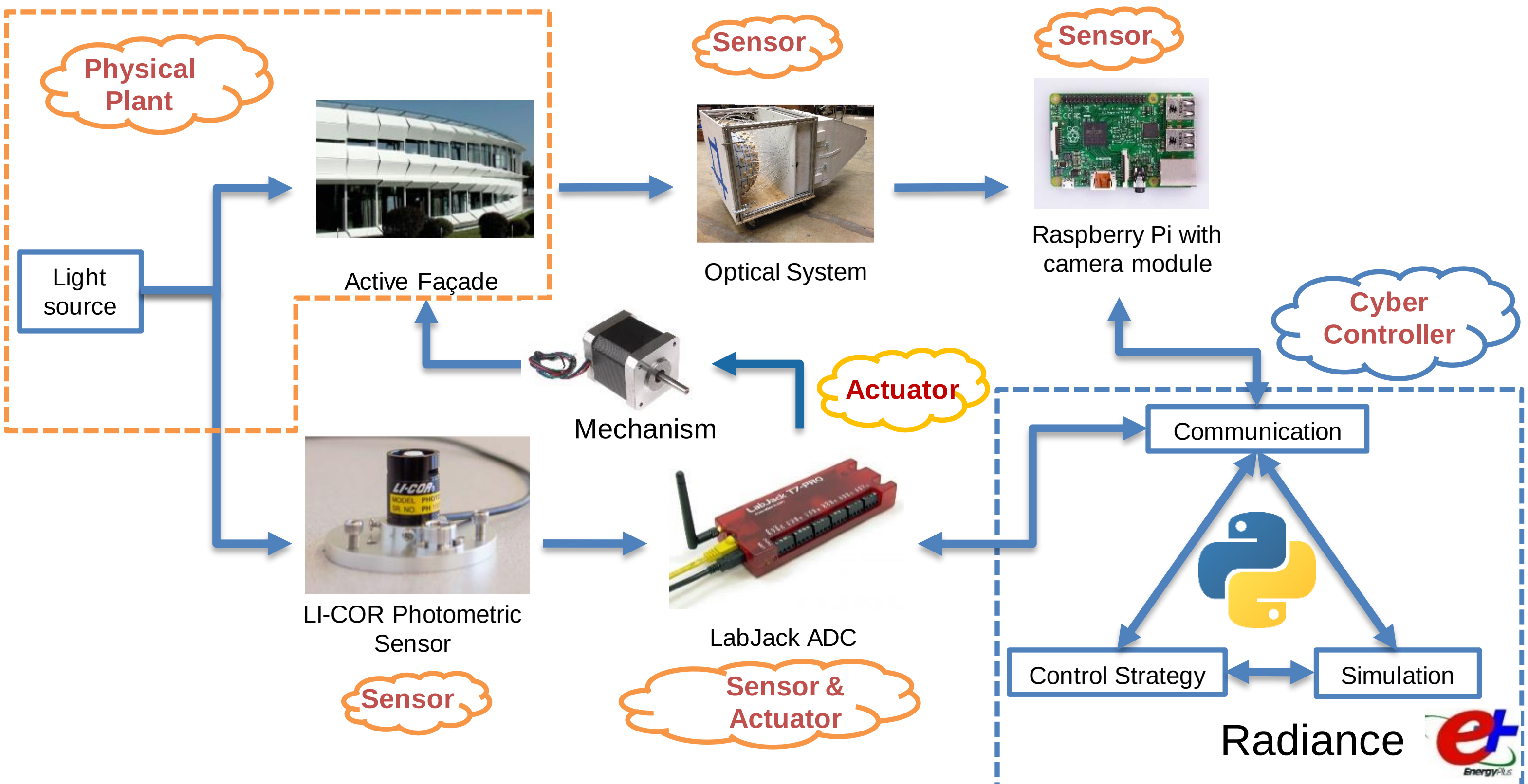


Computational component of SLAB: Radiance model

Simulated room illuminance distribution



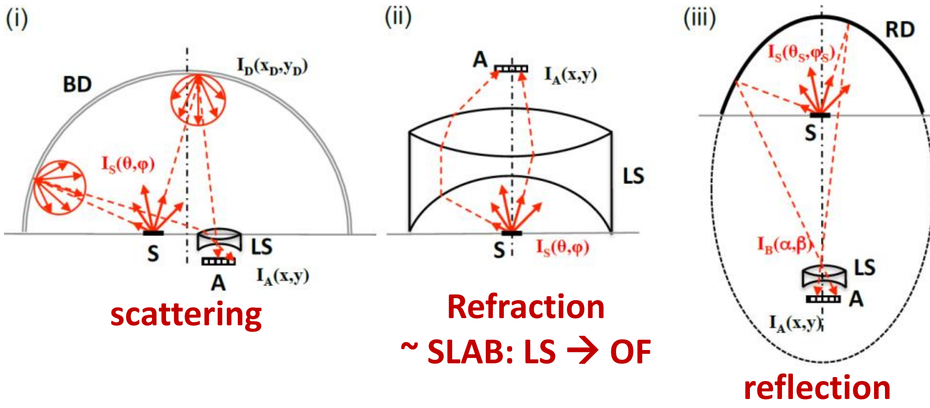
HiL Architecture of SLAB



- HiL: controllers (computational models) & plant (physical model).
- Sensors & actuators: interface between physical & cyber spaces.
- Controller – Daylighting (Radiance), energy (EnergyPlus) simulation & control strategies.
- Plant – CFS (difficult to simulate computationally).
- Actuator – LabJack analogue-to-digital converter (ADC) & active parts of CFS.
- Sensors – Photometric sensors & optical system of SLAB.

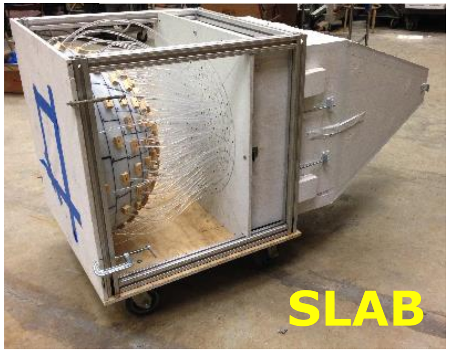
The Optical Sensor of SLAB (1/2)

- A parallel Goniophotometer to simultaneously measure all emitted luminance components from a source is a complex optical system.



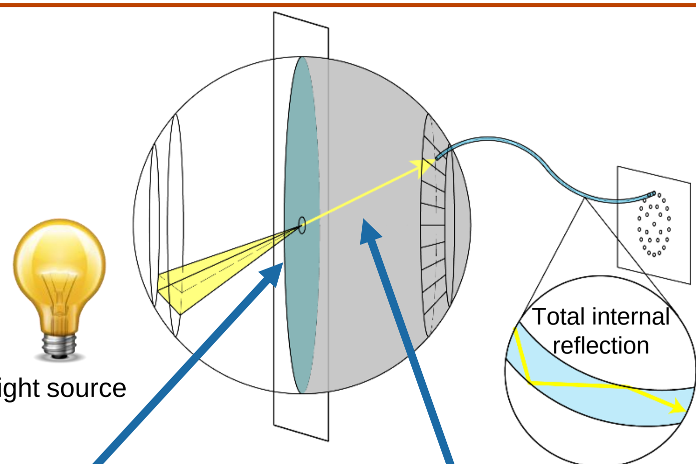
Parallel Goniophotometers: **S** – Source, **A** – Detector Array, **LS** – Lens, **BD** – Back-scattering Dome, **RD** – Reflecting Dome [Karamata & Andersen, 2013]

- SLAB is a simplified parallel Goniophotometer:
  - 145 Klems bases to discretize the 2π hemisphere.
  - OFs guide light to a sensor instead of complex LS.
  - Luminance level of each patch sampled at the OF.

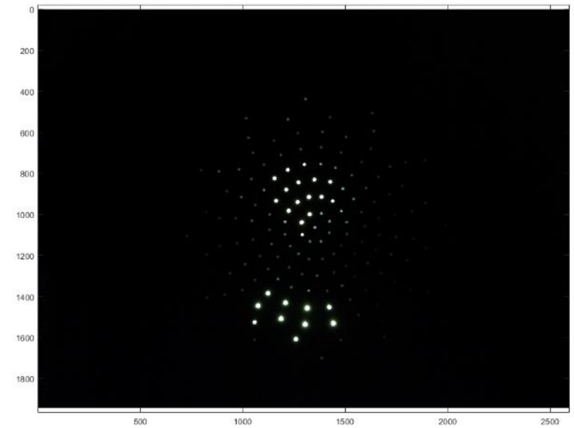


Left: Klems bases divide the sampling dome.
Right: OFs connected to the dome of SLAB.

The Optical Sensor of SLAB (2/2)



RPi with the camera module

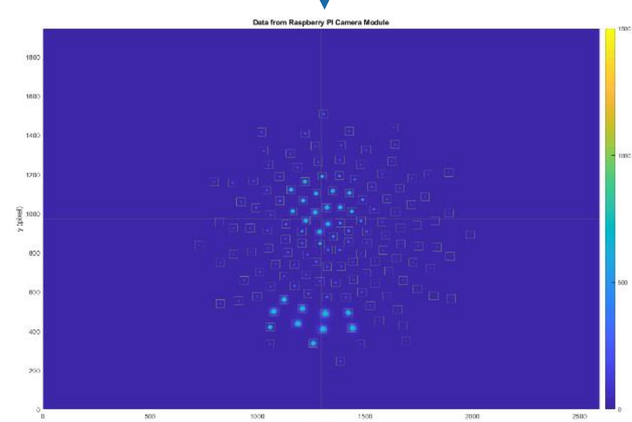


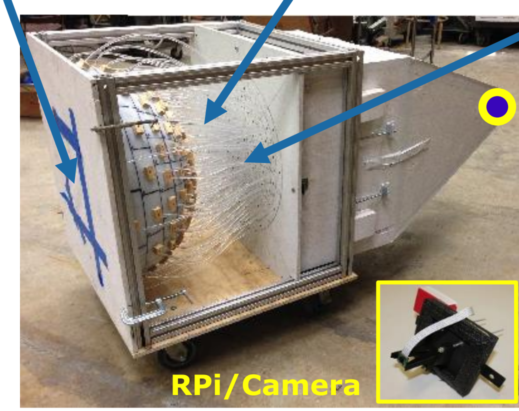
1. Light propagates to the aperture of the SLAB.

2. Light propagates to the back of the dome and is picked up by the Optical Fibers (OFs) array.

3. Light propagates to the back through the OFs, where a RPi camera picks up the light signal.

4. A High Dynamic Range Image (HDRI) produced by the RPi camera

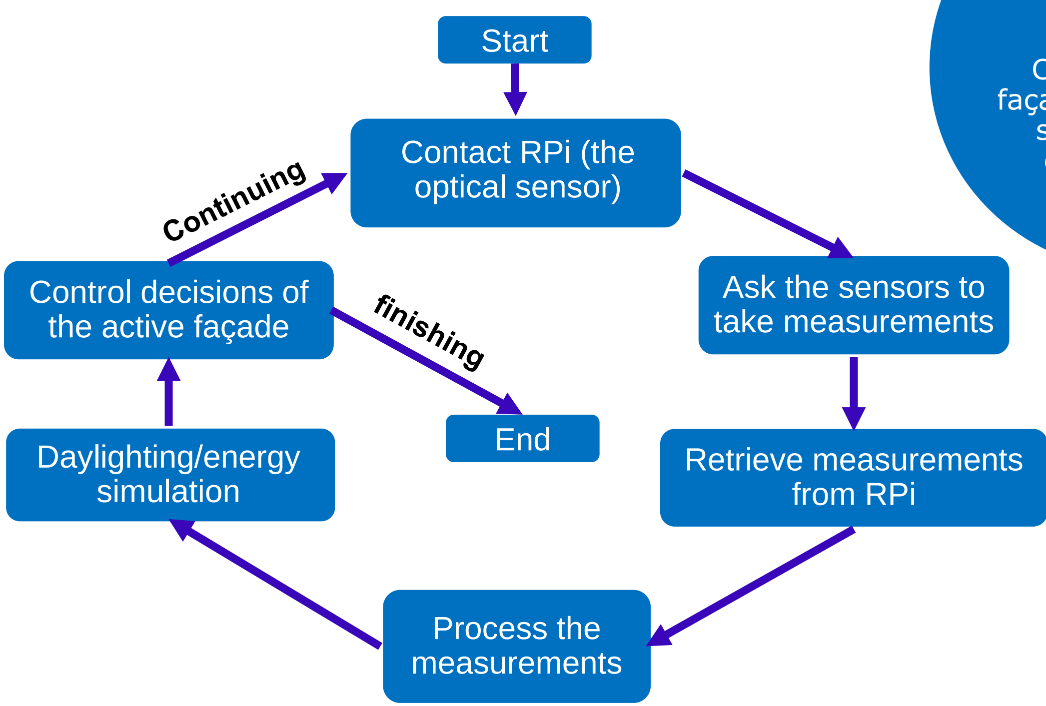


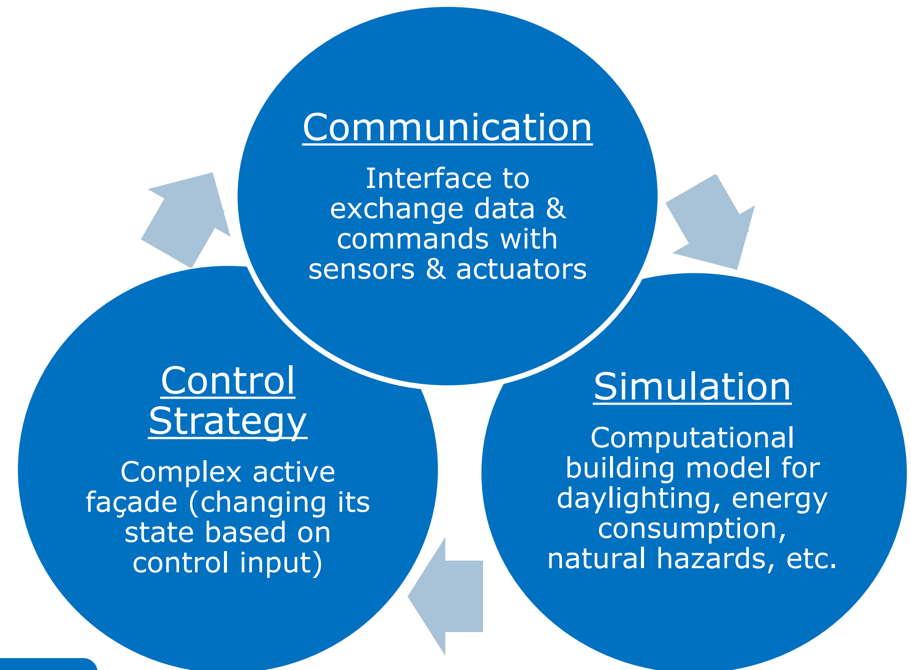


5. The photo is further processed to extract luminance information.

The Cyber Components of SLAB

Key Requirements:
1. **Accuracy** ← Parallel Goniophotometer
2. **Speed** ← Three-phase simulation
3. **Reliability** ← Finite-state machine





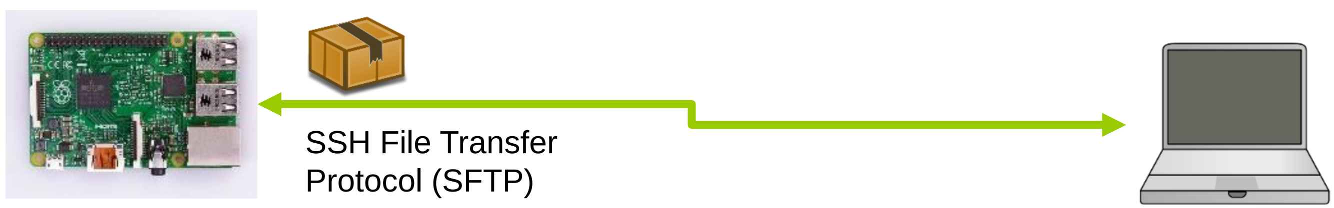
The Communication Solution

The Raspberry Pi (RPi) optical sensor: **Server** & PC running main program: **Client**.

- **Step 1**: RPi sets up communication channels using Python “socket” library & starts listening.

- **Step 2**: PC sets up a socket to RPi’s address & sends an inquiry. The RPi sends a reply & starts taking measurements, then RPi starts listening again.

- **Step 3**: Knowing that measurements occurred, data is obtained from RPi.



The Daylighting Simulation Capability

- The daylighting simulation is conducted using the three-phase method: $\boldsymbol{I = VTDS}$

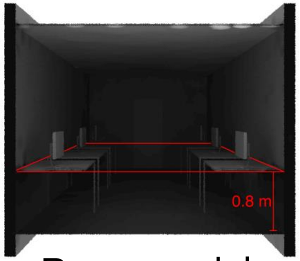
- Instead of calculating the emitted luminance $\boldsymbol{L_o = TDS}$ of the façade, the SLAB system directly measures the output $\boldsymbol{L_o}$ from the façade → Accurate high-speed simulation.

Complex façade

Sensor system

Measured luminance $\boldsymbol{L_o}$

$\boldsymbol{I = VL_o}$

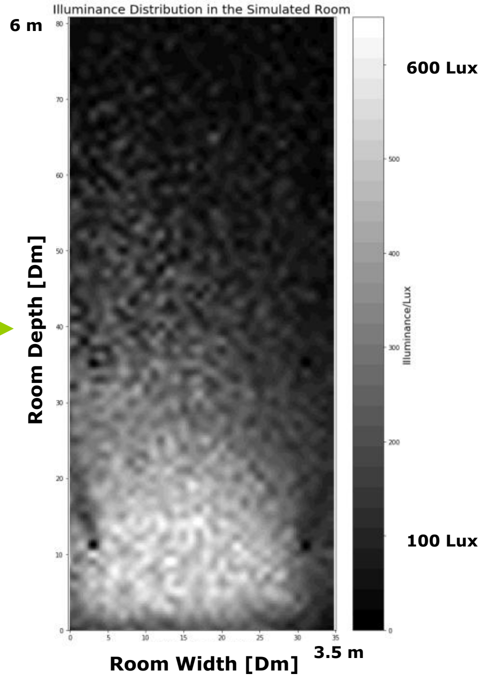


Room model

Radiance
Synthetic Imaging System

Daylighting simulation software

Simulated view matrix $\boldsymbol{V}$



Illuminance distribution

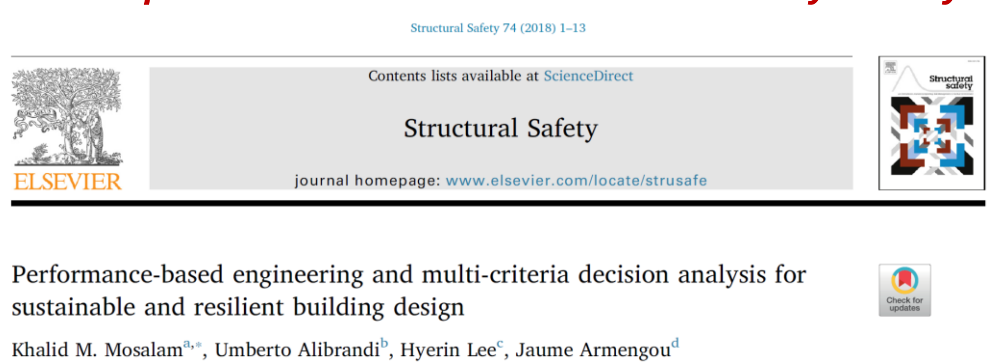
Prospect of Simulation Capabilities

Daylighting simulation can be combined with other issues, e.g. energy simulation & UQ analysis.

Decision-making variables

- Energy Consumption
  - **Material Properties:**
    Factors that can cause variabilities are:
    - Temperature changes (external/internal);
    - Moisture content variation (absorption/desorption);
    - Aging;
    - Uncertainties in material properties.
  - **Weather Conditions**
  - **Human Occupancy**
    - Widely recognized as a major contributing factor to uncertainty of building performance.
- Cost
  - **Financial Market**
    - Initial construction
    - Lifecycle
- CO2 emission
- Human comfort

Time-dependent Stochastic Processes + Utility Theory!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Performance-based engineering and multi-criteria decision analysis for sustainable and resilient building design

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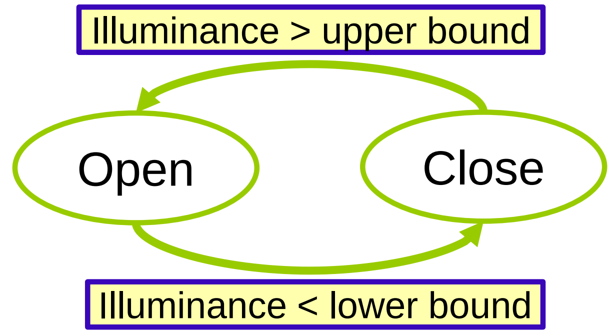
The Control Strategy

SLAB can implement & test many types of control strategies, depending on choice & goal of active façade.

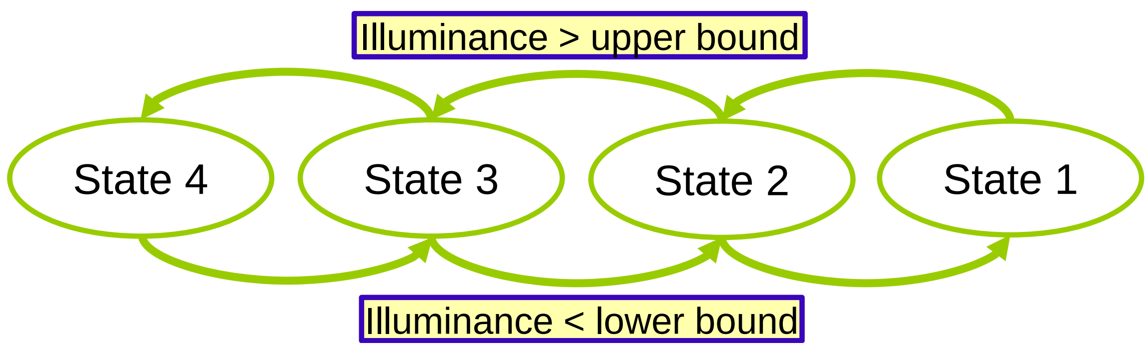
- A façade with only ***two states*** (open/close), a bang-bang controller is implemented based on daylight condition in a room.



- A façade with **multiple states**, a finite-state machine is used (***Demo***) or with **continuous shifting states**, more sophisticated controllers, e.g. PID, can be used.

Demo: A façade with 4 transmittance states (discrete model of an electrochromic glass) tested in SLAB.

Four-state façade with selectable transmittance of 100%, 80%, 40% & 20% (step motor is also shown)



State diagram of a finite-state-machine controller: State 1 has highest transmittance & State 4 has the lowest.

Simulator of Light into Active Buildings (SLAB)

A Demonstration

Jiawei Chen

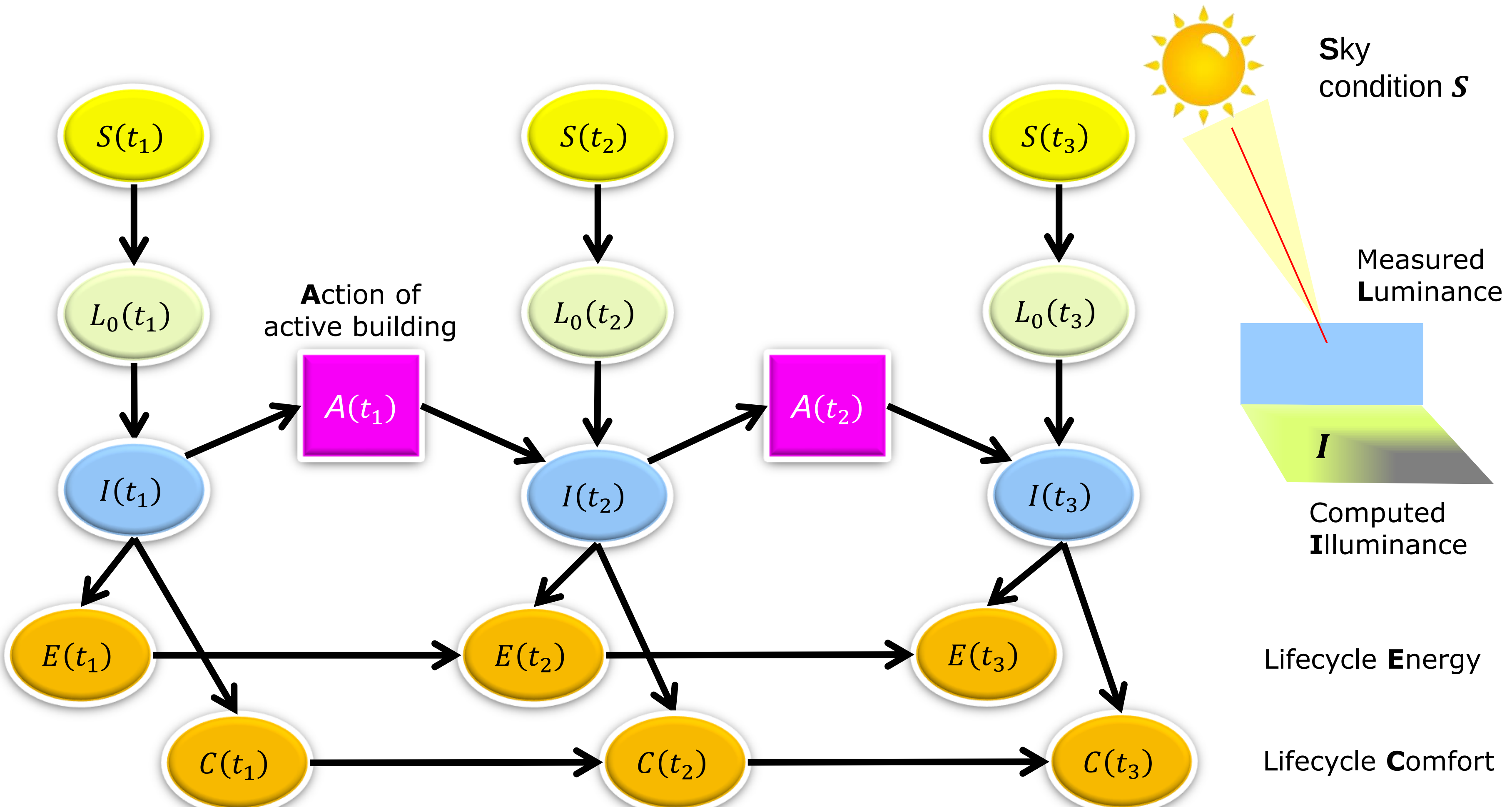
Morgan J. Wilder

SinBerBEST

Building Efficiency and Sustainability in the Tropics

http://sinberbest.berkeley.edu/slab

Prospect of SLAB Capabilities: Lifecycle Analysis Using Bayesian Networks



t = time

Concluding Remarks

- HiL (e.g. using SLAB) is an economical and accurate testing method that can complement other pure testing & simulation methods.
- The benefits of HiL increase when used in conjunction with uncertainty qualification for performance-based engineering solutions.
- HiL can be conveniently applied to a variety of "real" engineering problems (e.g. active façades), ranging widely in the underlying physics including problems involving multi-physics phenomena.
- Work is being carried out to further reduce the size of the SLAB system and increase its accuracy for the use with the Heliodon for a variety of applications including lifecycle analysis using BNs.

Thank you! Questions?