Energy Efficient, Smart Optical Windows

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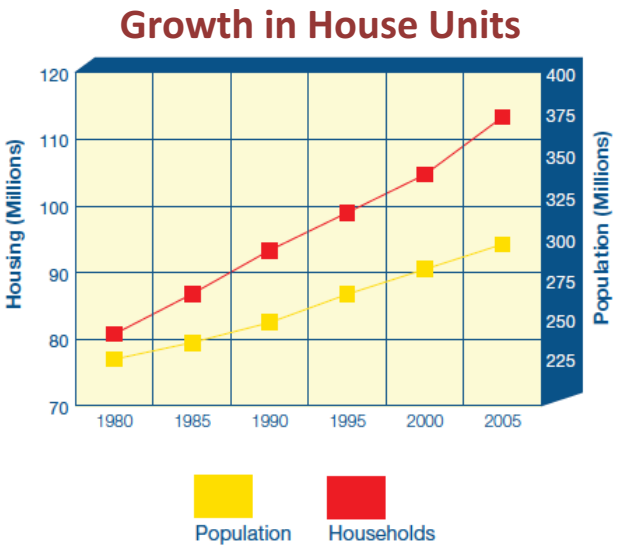
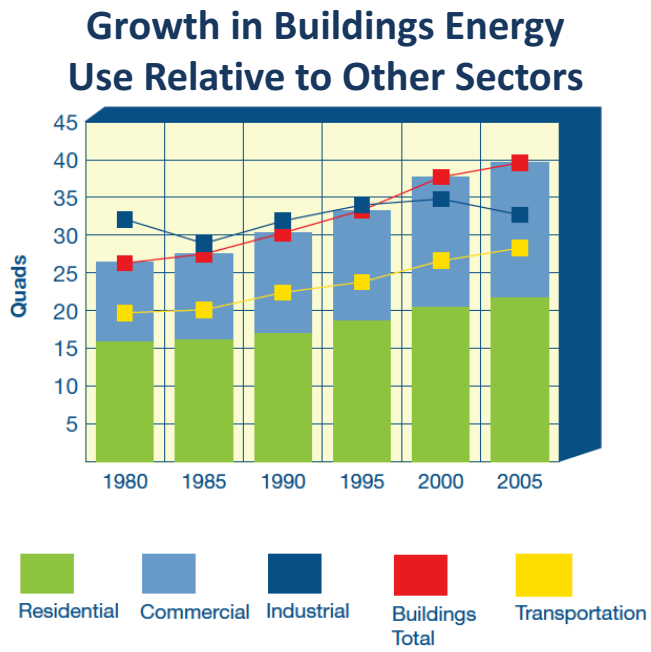
Energy Consumption in Residential and Commercial Buildings in US





Today, the nation's 114 million households and more than 4.7 million commercial buildings consume nearly 40 % of total U.S. energy use.

- Electricity is the largest energy source for buildings.
  - 70% generated by burning coal, petroleum, or natural gas
- Natural gas is the second largest
- Petroleum (predominantly heating oil) is a distant third

DOE report


Mode-Gakuen Spiral Towers
Nagoya, Japan

Building Features

- **Transparency**

  Light illumination

- **Thermal Insulation**

  Keeping room temperature stable

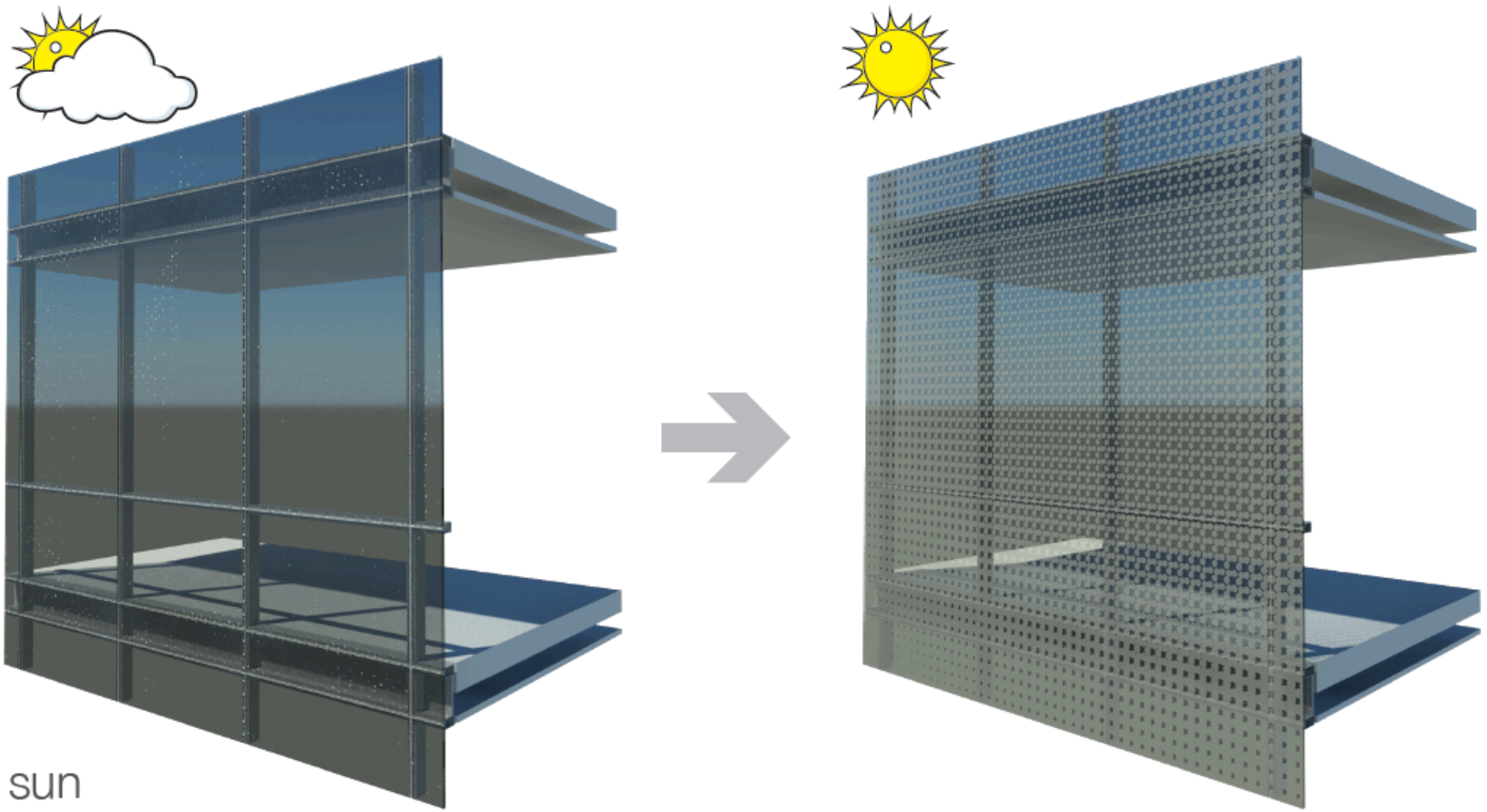
- **Aesthetic Effect**

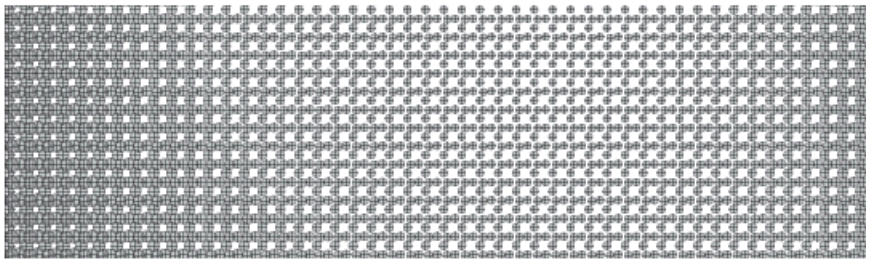
  Colorful and adaptive

- **Others**

  Self-cleaning, water harvesting, noise insulation, human interactions …

An Environmentally Responsive Window

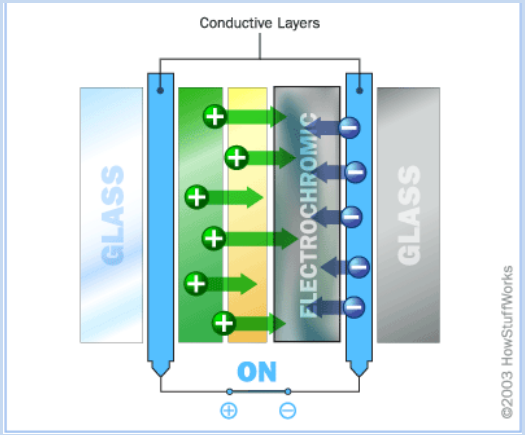


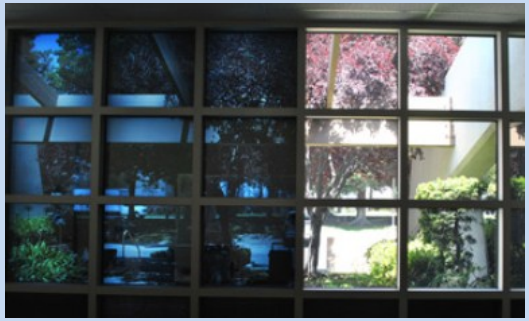


Mark Nicol, Jenny Sabin (Penn Design)

Current Smart Window Technologies

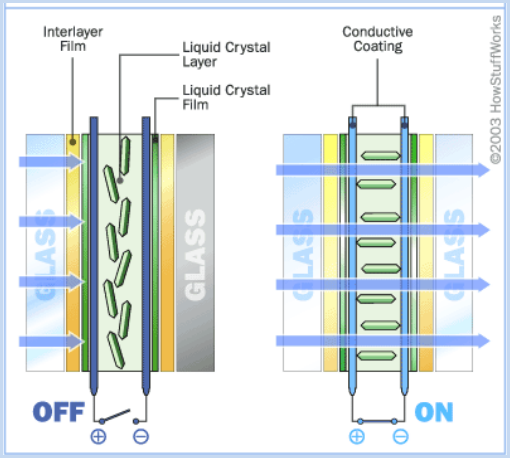
Electrochromic



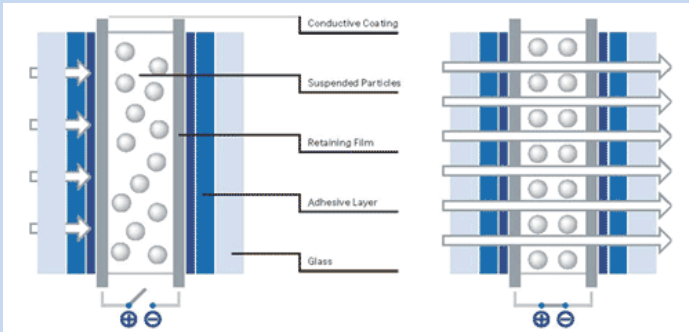


- Expensive
- Chemically unstable
- **Initial state is not transparent**
  - **Transparency requires use of electricity**

Polymer Dispersed LCs

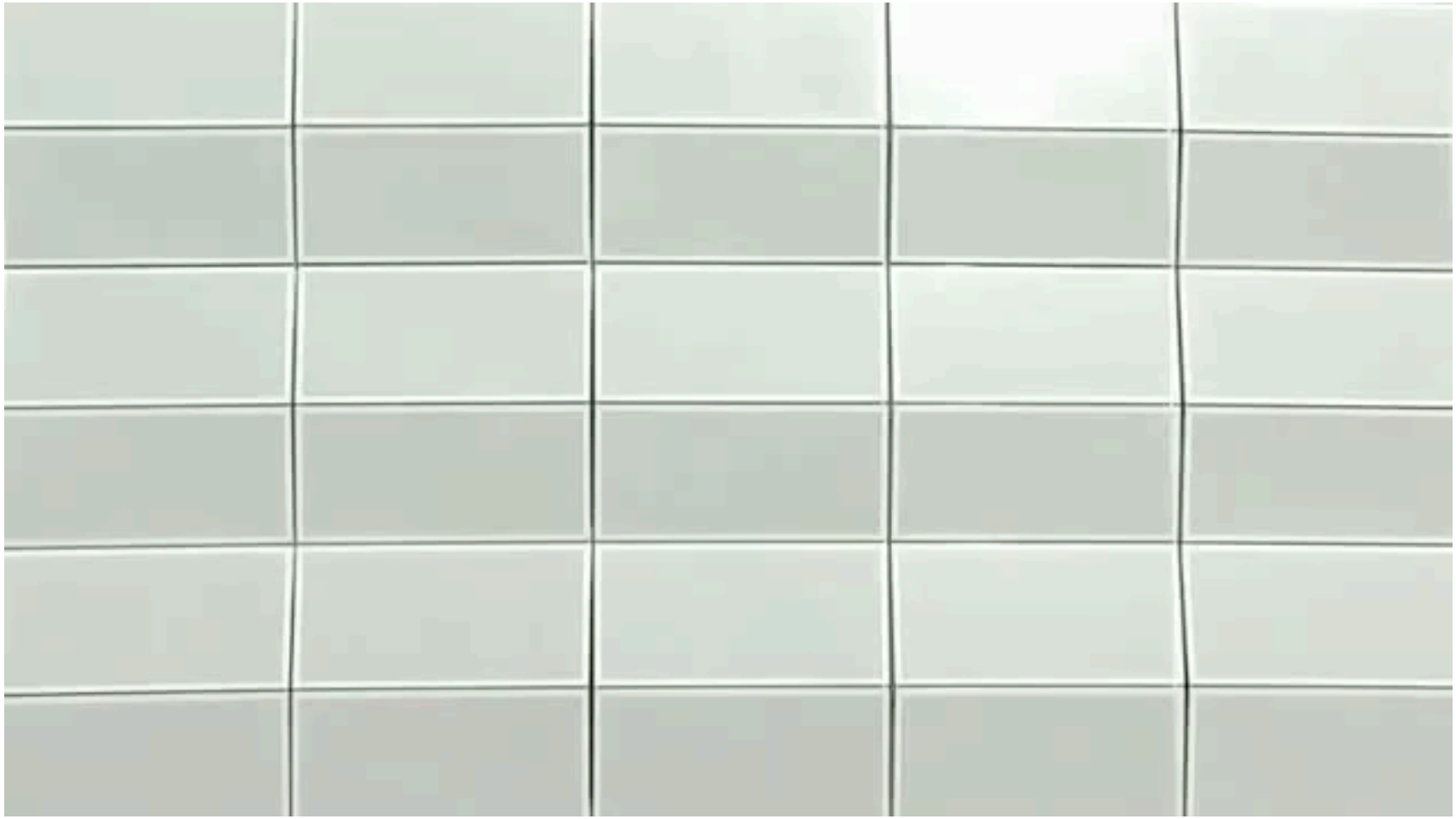


Suspended Particle Displays



www.spdcontrolsystems.com; www.smartglassmedical.com; www.ics.ele.tue.nl/~akash/maartje/getSystemDetail.php?ID=1084

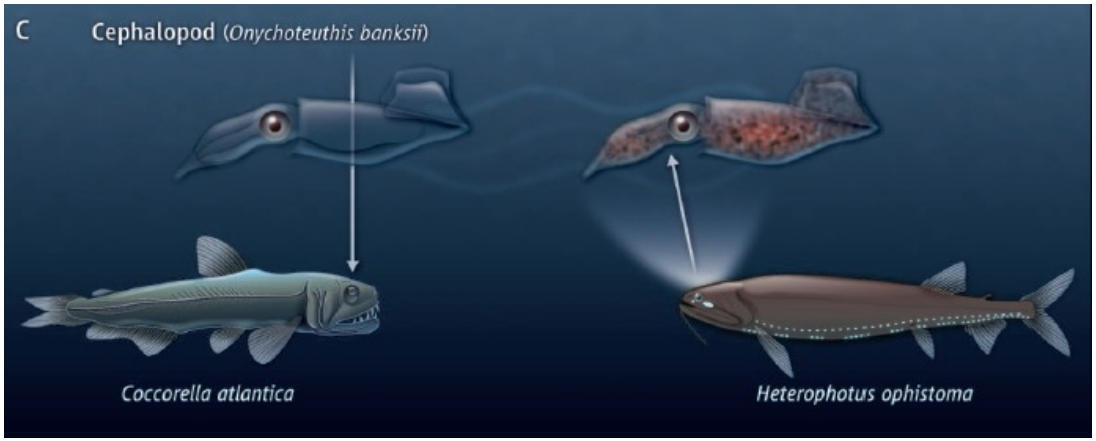
A Dynamic Façade Design



by Giselbrecht + Partner

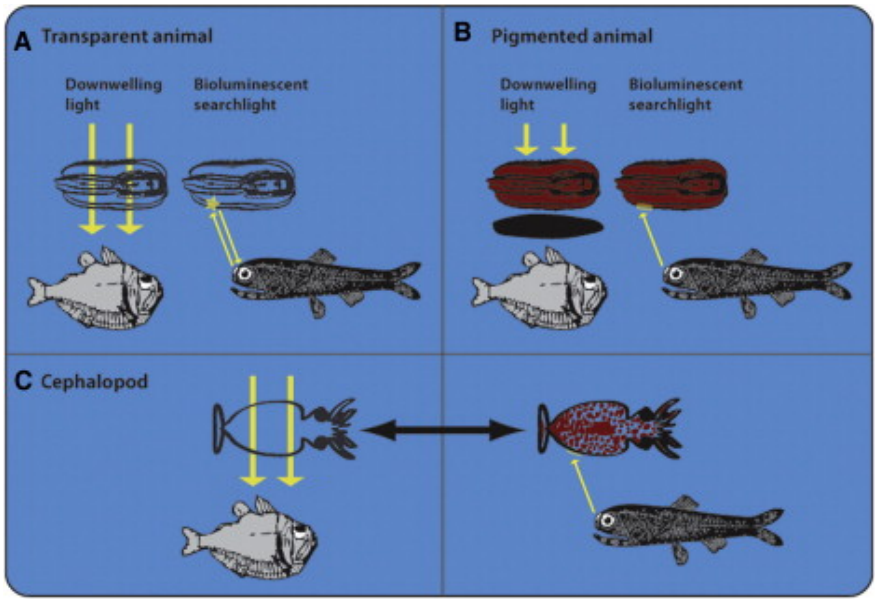
http://www.minimalisti.com/architecture/exterior-design-architecture/01/dynamic-facades-design.html

Camouflage and Display
Switching between Color and Transparency

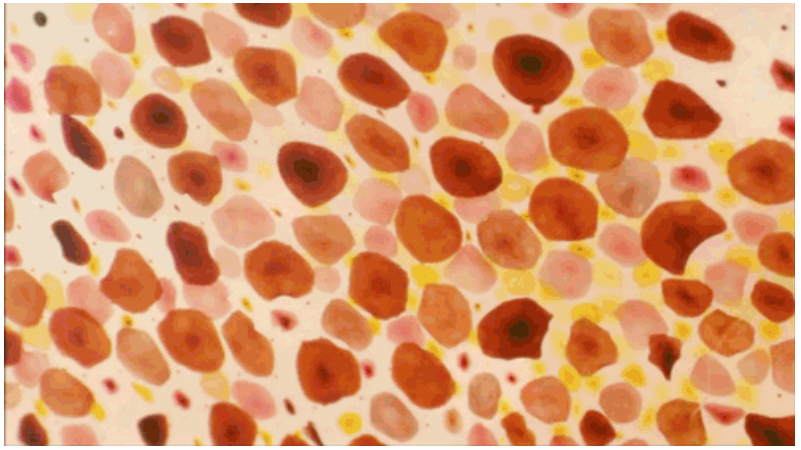


Pennisei, *Science* 2012

Deep Water Camouflage



Zylinski, S. and Johnsen, S. (2011). Curr. Biol. 21: 1937.



- Cephalopods switch bet transparent and pigmented states to avoid specific predators
- Stretch/contract skin to **reveal/hide** chromatophores (pigment-containing cells)

Initial state is TRANSPARENT!

Venetian Blinds: Most Popular

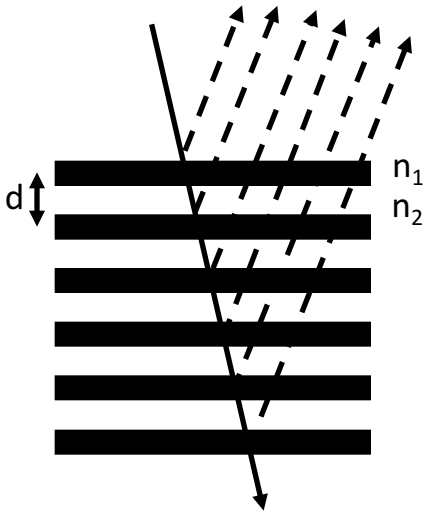
Can we design venetian blinds-like smart windows that can switch transparency?

Horizontal blinds + a string system

- Is cheap and easy to use
- Requires very low maintenance
- Occupants have completely control of how much light will come through
- Requires a small footprint

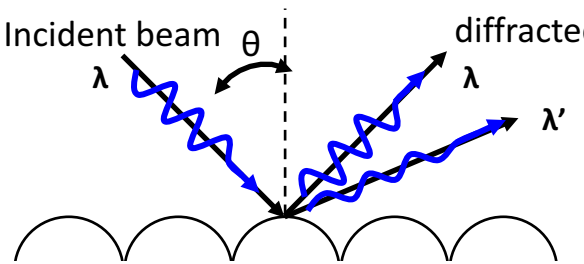
Background: Structural Colors

multilayer reflection

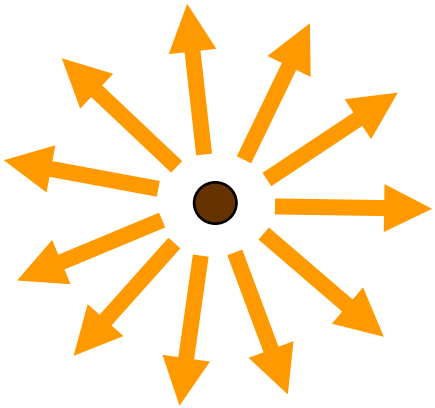


diffraction gratings

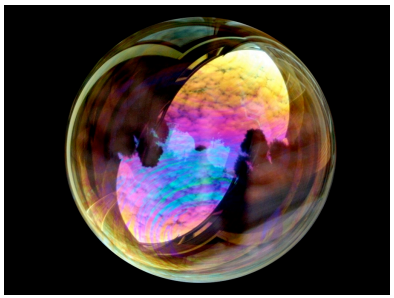
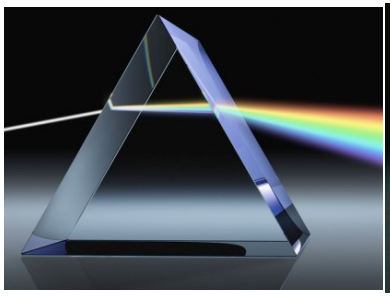
$$d\left(\sin\theta_m + \sin\theta_i\right) = m\lambda.$$

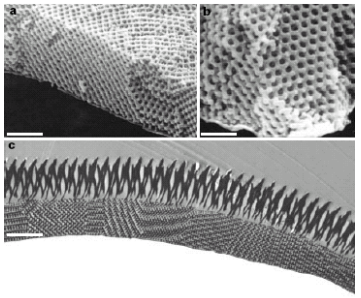


scattering

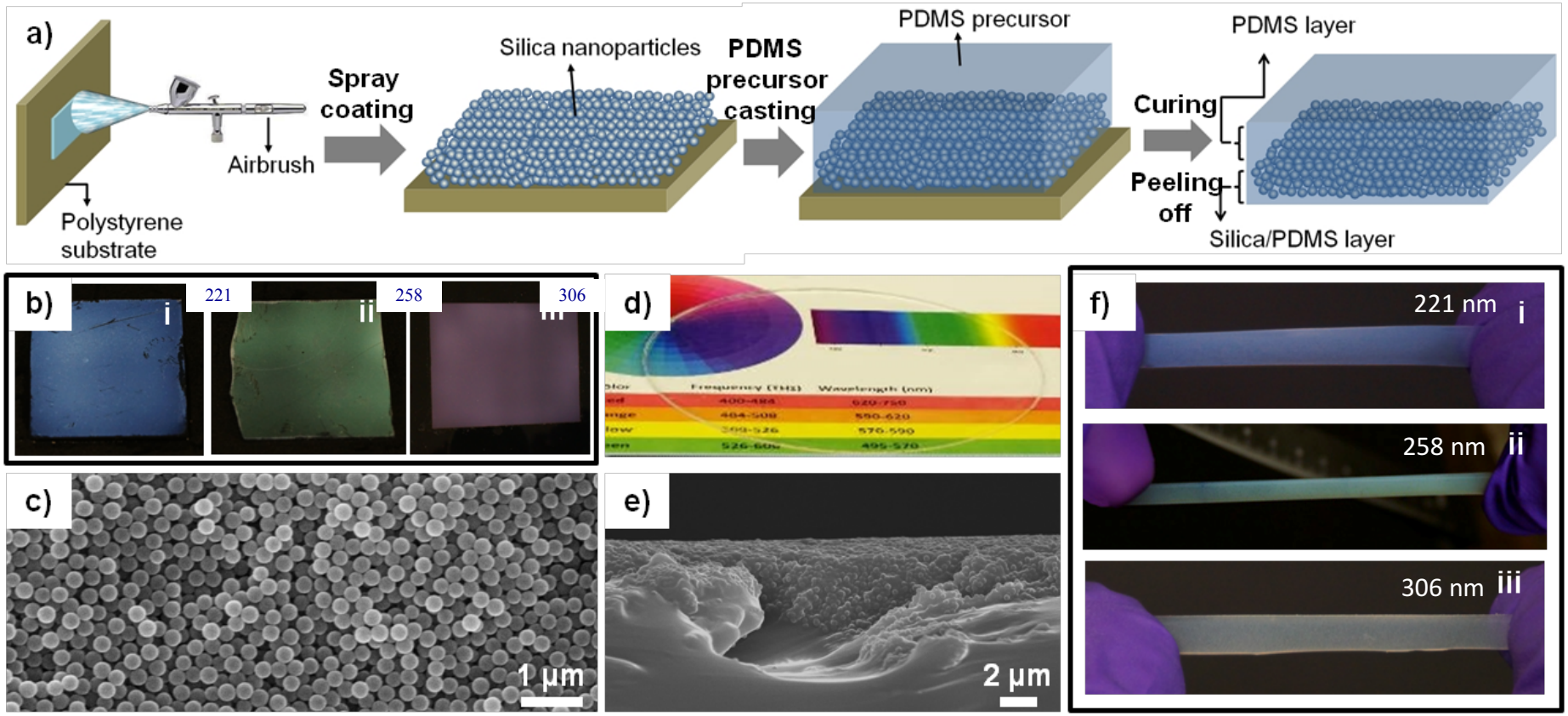


Structural colors often appear considerably brighter than those of pigments, whose colors are caused by selective absorption by chemical substances.

Switching from Transparent to Opaqueness/Color



Reflectance

$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$$

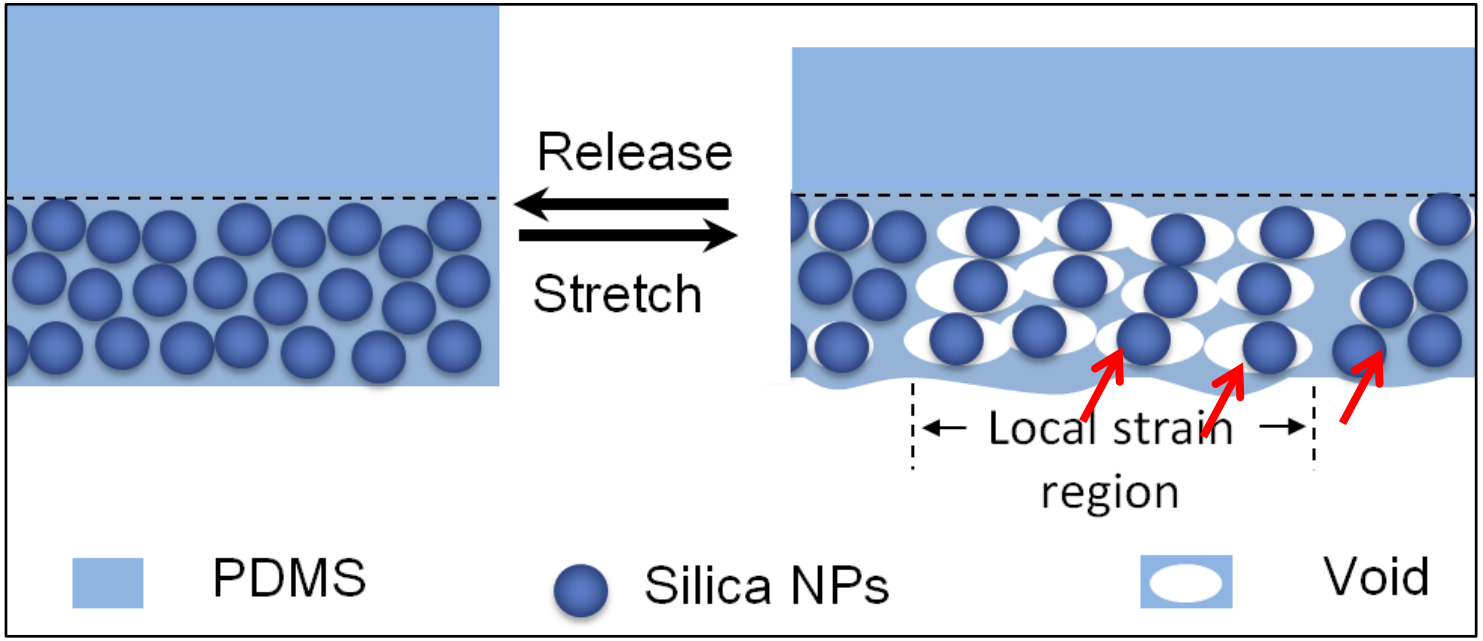
n_{silica}=1.457 at 632.8nm
n_{PDMS}=1.423 at 632.8nm
n_{void}=1

Silica nanoparticle array thickness: 4-5 μm

PDMS thickness: 500 μm

Ge, D.† and Lee, E.,† Yang, L., Cho, Y., Li, M., Gianola, D.S., and Yang, S. *Adv. Mater*.2015

Mechanism



formation of nano- to micro-sized voids around the nanoparticles act like light scatters to "reveal" the embedded structural colors upon stretching

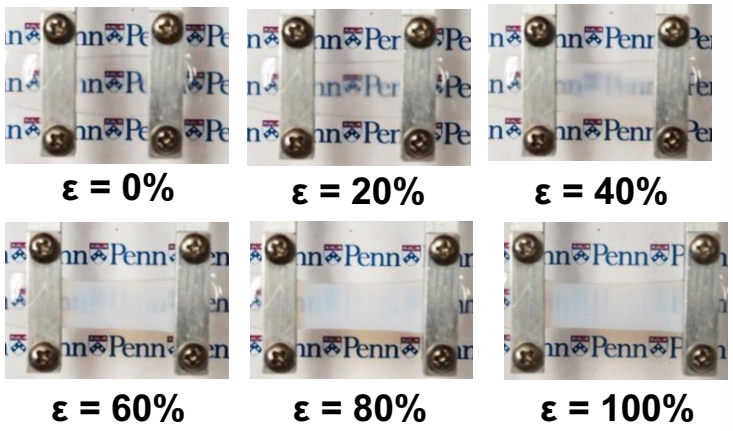
Reflectance changed by x100 times

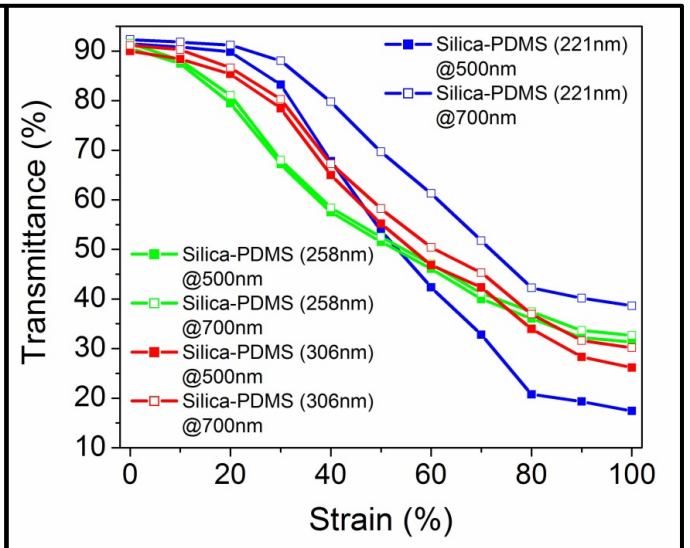
$R_{\text{silica-PDMS}}$= 0.014%
$R_{\text{silica-void}}$= 3.46%
$R_{\text{PDMS-void}}$= 3.05%

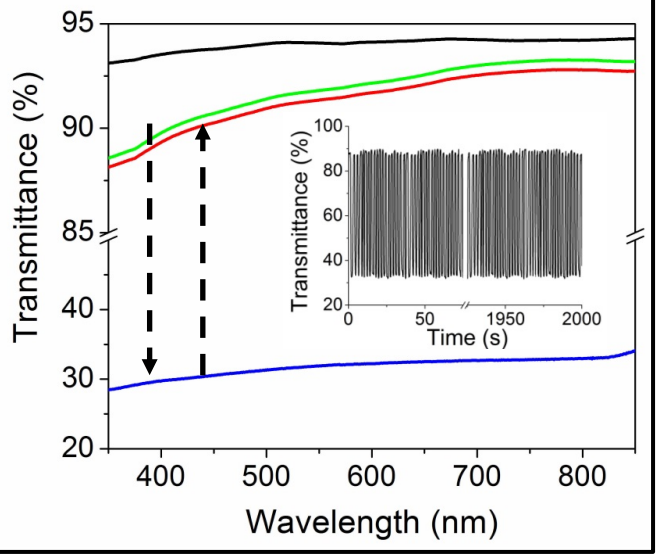
$$R = \frac{(n_1 - n_2)^2}{(n_1 + n_2)^2}$$

Ge, D.† and Lee, E., † Yang, L., Cho, Y., Li, M., Gianola, D.S., and Yang, S., (2015) Adv. Mater., 27: 2489

Transmittance as a Function of Mechanical Stretching







Over 1000 cycles

Ge, D.† and Lee, E.,† Yang, L., Cho, Y., Li, M., Gianola, D.S., and Yang, S. *Adv. Mater*.2015

Innovation of Our Smart Window Technology

Importantly,

It is simple and requires no use of electricity, → energy efficient and reliable

1. The initial state is truly transparent
2. The change of transmittance in the vis-NIR region is very large, from > 90% to 30%
3. It offers angle-independent color display upon stretching whereas most stretchable smart windows in literature display angle-dependent colors
4. The displayed color is independent of stretching strain, but dependent on nanoparticles size and materials nature

   → there is still room for further improvement of performance
5. The film is highly robust in repeated stretching and releasing (at least 1000 cycles) since the majority of the film under strain is the bulk rubbery material layer.

The smart windows can also be used in applications such as displays, camouflages, and security, as well as heat/solar gain control.

Our Prototypes

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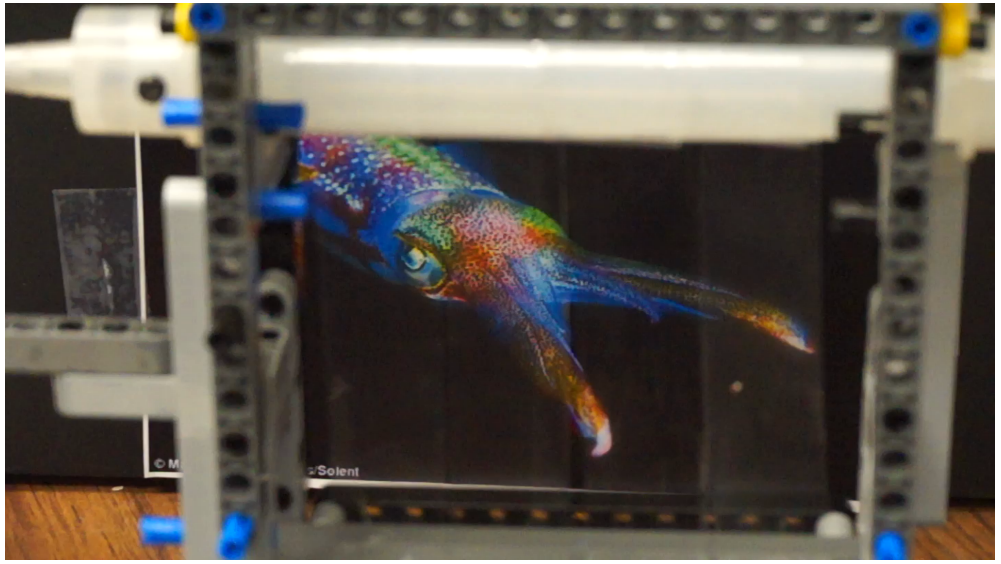
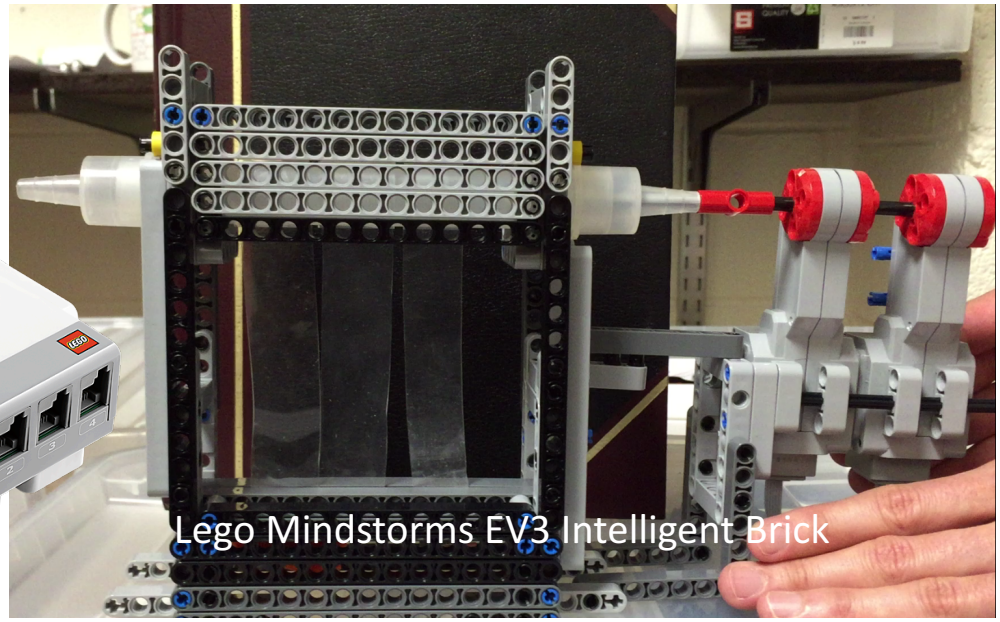


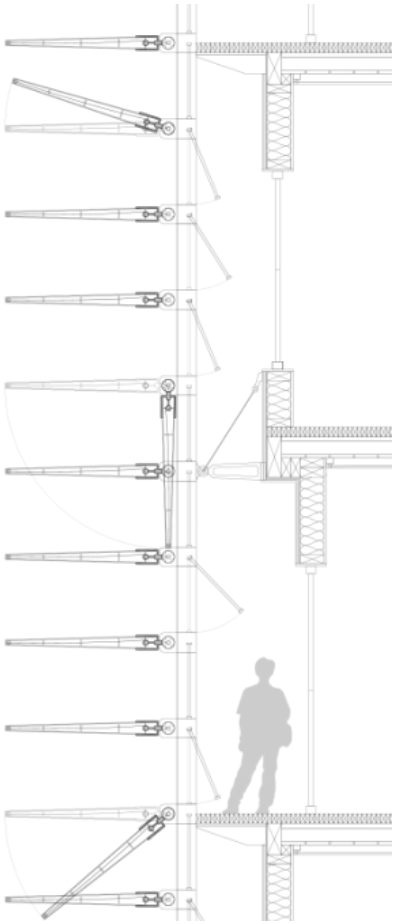


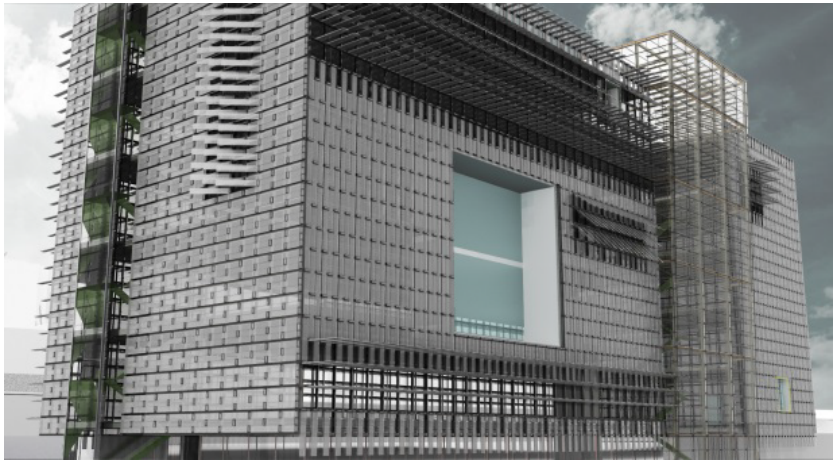
Lego Mindstorms EV3 Intelligent Brick

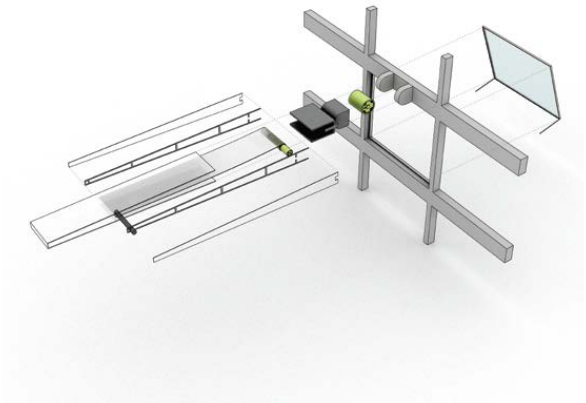
An external blinds shading device

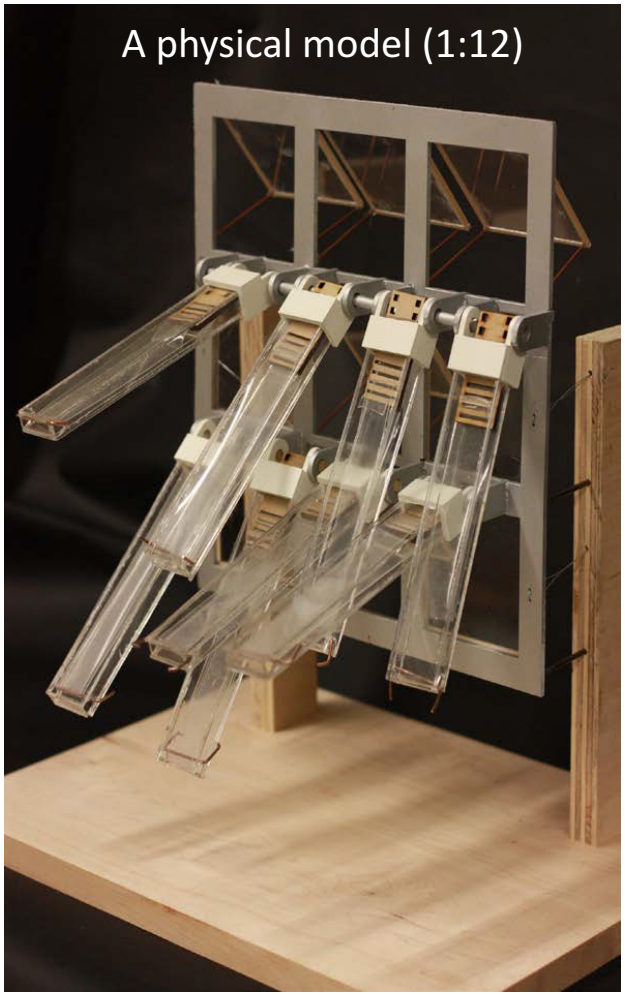
designed by Shai Gerner and Seung Bae Heauk

Movable “Feathers” and the ”Thermal Glazing” windows



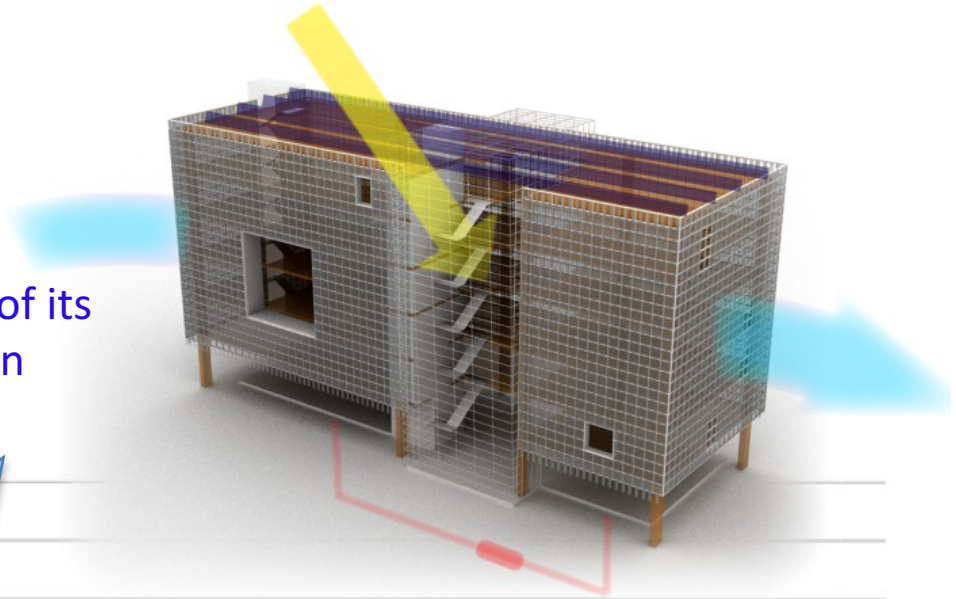




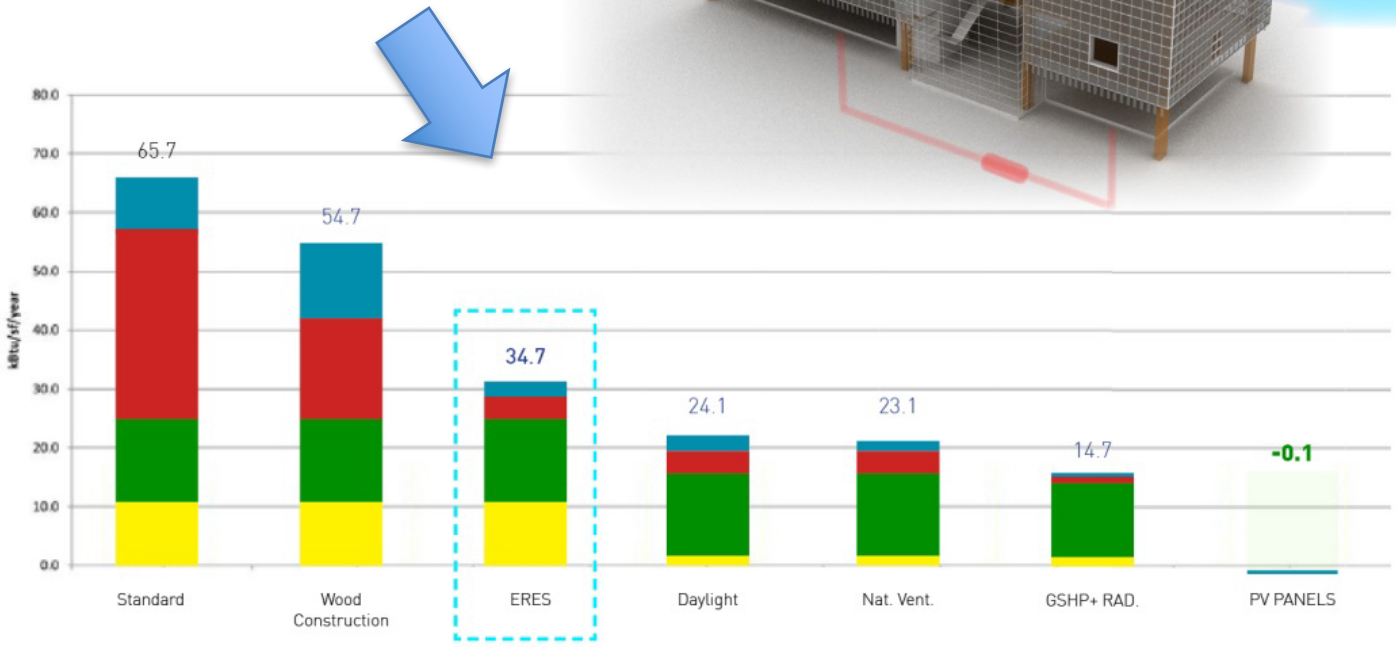


Case Study: Building Energy Efficiency

Test site: 70,000 SQF Net Zero Energy office building in Jamestown, NY



a reduction of 20 kBTu/ft² of its overall energy consumption



By Shai Gerner and Seung Bae Heauk