Invigorating Architecture with Technology

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School of Architecture + Andlinger Center For Energy and Environment

Infuriating Architects with Technology

Beautiful roofs

Collegiate Gothic Architecture

Architecture Infuriating Tour Guides

High performance buildings

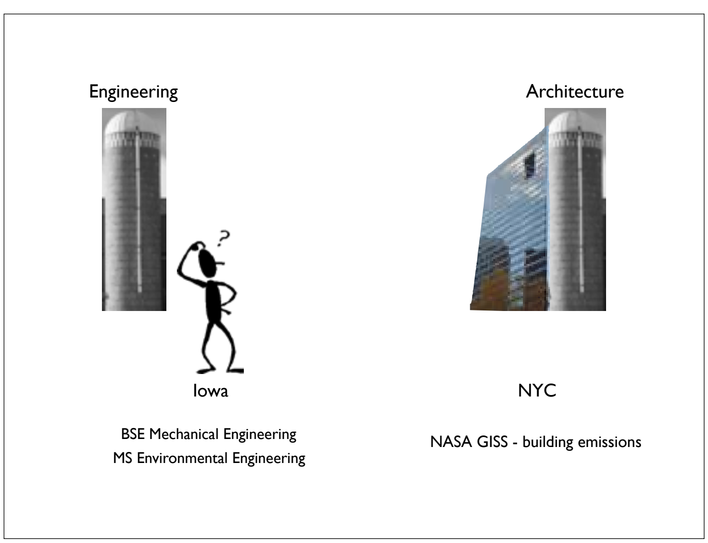
"Green Buildings"

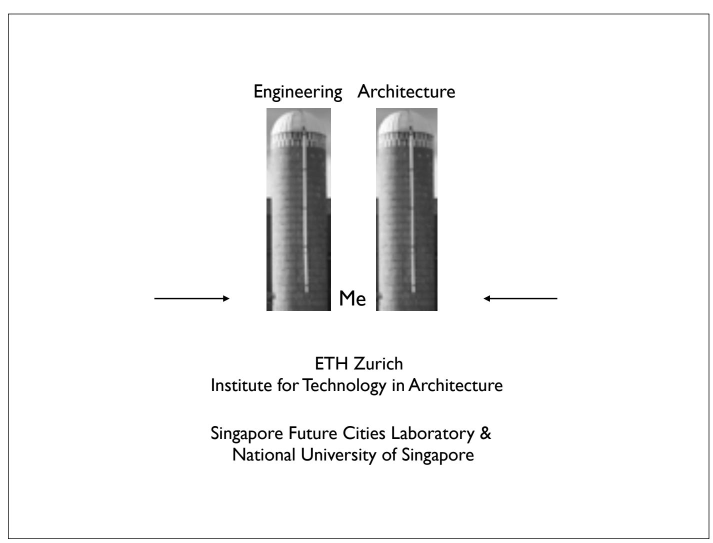

Technology + Architecture
Passive House

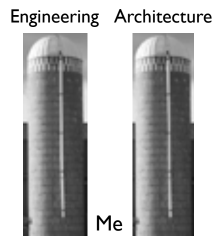

Not add-on


Better?
Bullitt Center
Living Building:
Net Zero Energy
Net Zero Water


Better?
Bullitt Center
Living Building:
Net Zero Energy
Net Zero Water
"UGLY!"
says School of Architecture


Engineering
Architecture
?
Iowa
NYC
BSE Mechanical Engineering
MS Environmental Engineering
NASA GISS - building emissions


Engineering
Architecture
Me
ETH Zurich
Institute for Technology in Architecture
Singapore Future Cities Laboratory &
National University of Singapore



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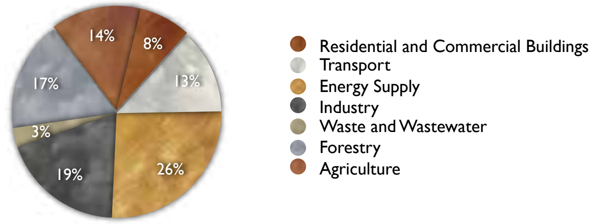
Why Buildings?

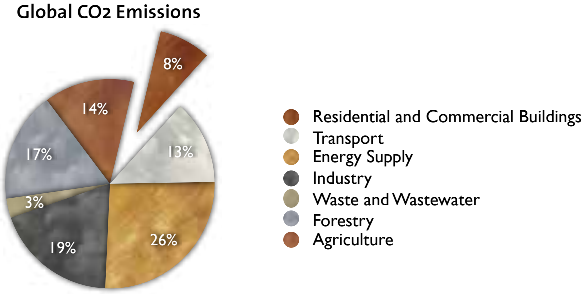
Global CO2 Emissions



IPCC

Why Buildings?

Global CO2 Emissions



Why Buildings?

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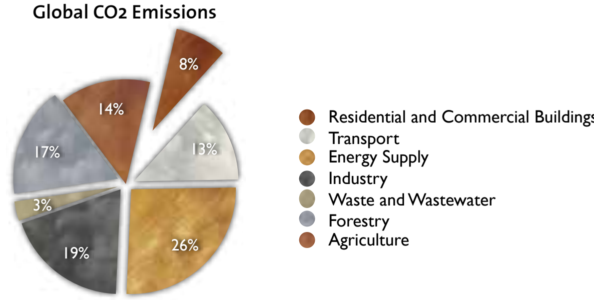

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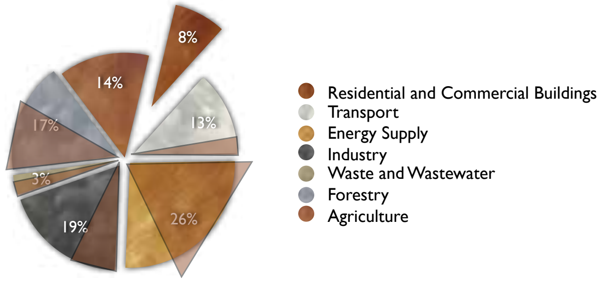

Why Buildings?

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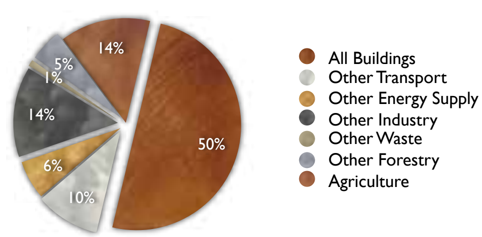

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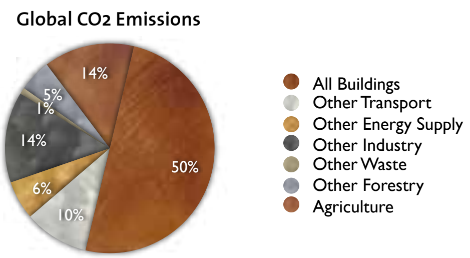
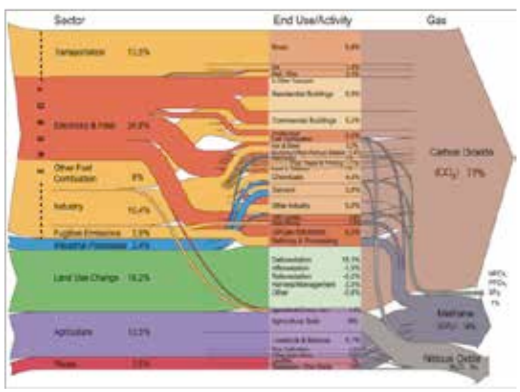


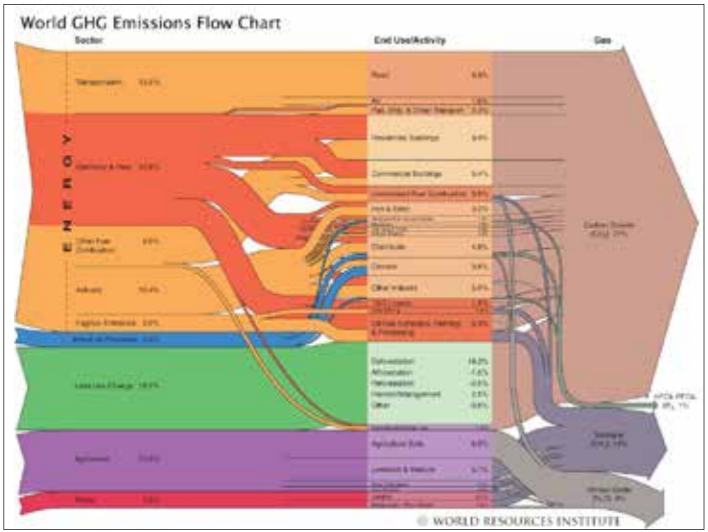
Buildings need improvement

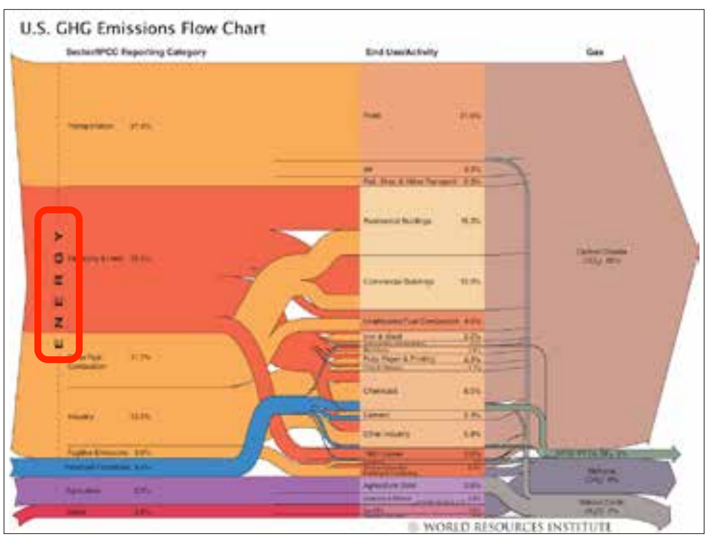
- Most significant single source of emissions
- 2/3 of global electricity consumed by buildings
- 1/3 of global waste produced by buildings
- 40% of USA GHG emissions
- **73% of USA electricity production**
- *Impact: now 2 °C of warming is almost guaranteed*
  - *Mitigation + Adaptation*

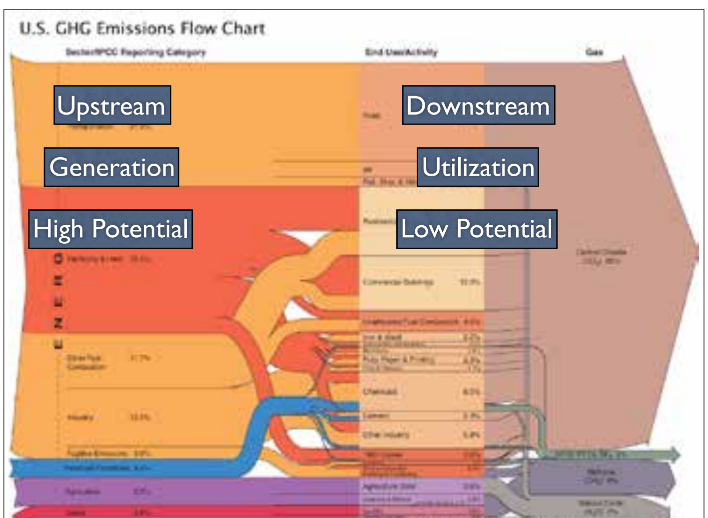
… but it's complicated



World Resources Institute





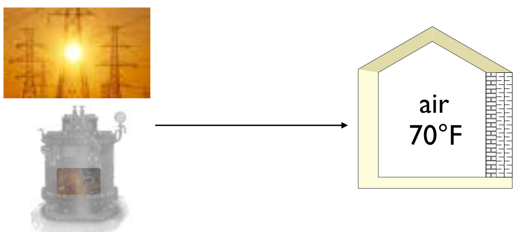


ENERGY

Upstream → Downstream

Generation → Utilization

High Potential → Low Potential



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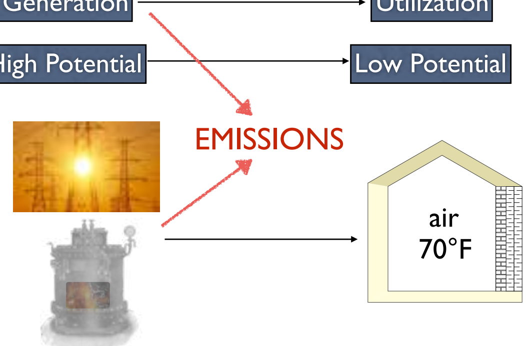
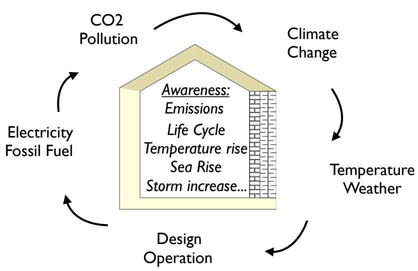
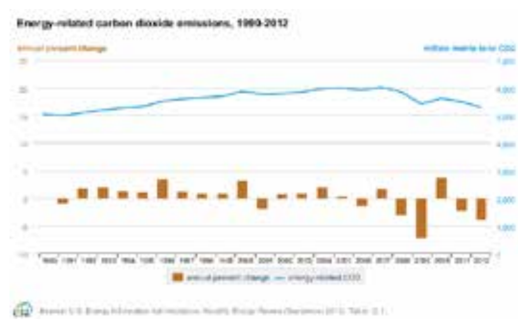


Informing design

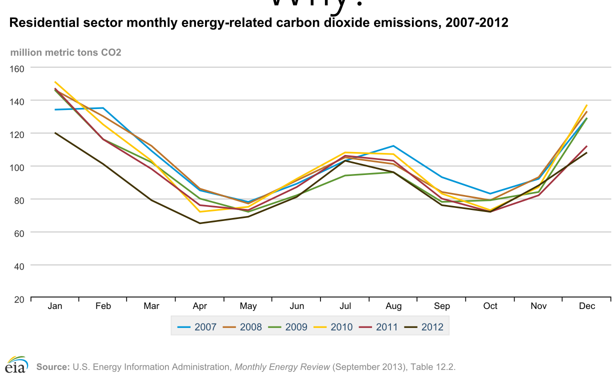


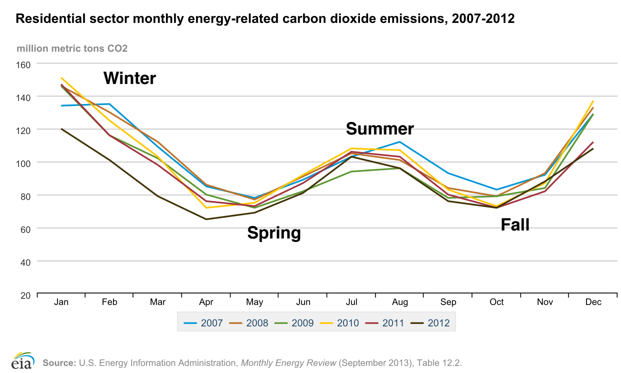
Both Mitigation & Adaptation

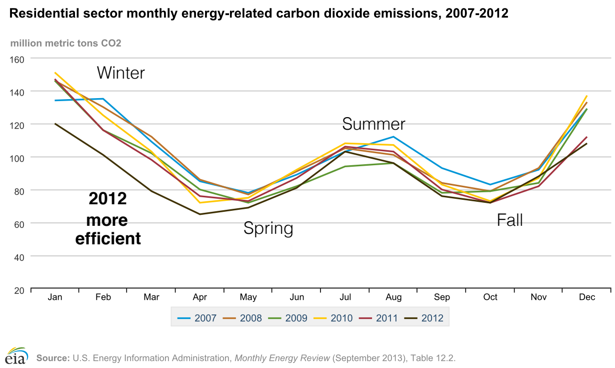
We? are reducing emissions

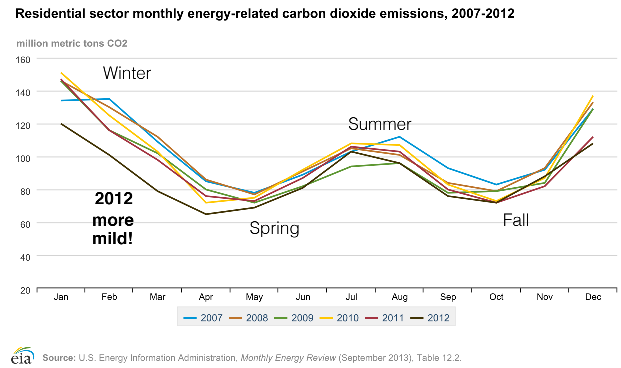


Why?

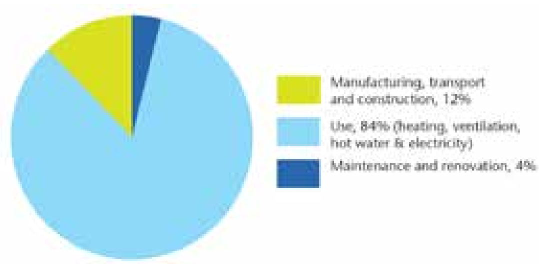








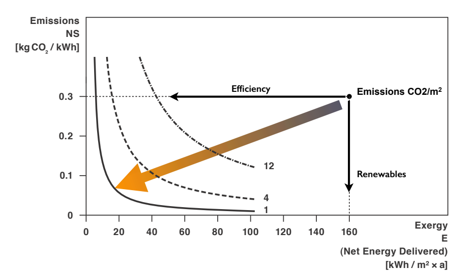
Operation most significant



World Business Council for Sustainable Development WBCSD,
http://www.wbcsd.org/Pages/EDocument/EDocumentDetails.aspx?ID=13559&NoSearchContextKey=true

Mitigation Goal

- Zero Emission Diagram



Todays Lecture:

Energy and buildings (Thermodynamics)
... in 2 parts (Laws)

Energy and buildings (Thermodynamics) ... in 2 parts (Laws)

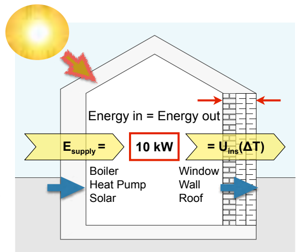
- 1st law and buildings
  - Heat transfer: Conduction - Convection - Radiation
    Walls - Doors - Windows
- 2nd law and buildings
  - Buildings are more than Walls, Doors and Windows

Heating and 1st part (law)

- Energy balance defines building operation

  $E_{out} = E_{in}$

  - Performance defined by envelope
  - Determines energy demand



Heating and 1st Law

- Insulation (Conduction)

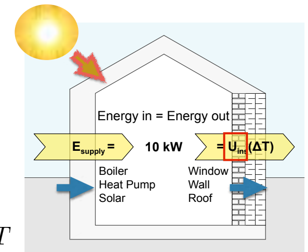
  $Q_{loss} = U * A * \Delta T$

- Ventilation (Convection)

  $Q_{loss} = \dot{m} * c_{p,air} * \Delta T$

- Insolation (Radiation)

  $Q_{gain} = I_{sun} * A * SHT$



Insulation

$Q_{loss} = U * A * \Delta T$

Insuation…
Why Glass!?!

$Q_{loss} = U * A * \Delta T$

$Q = heat$

$U = \frac{1}{R} = insulation$

Jonathan Choe

$A = area$

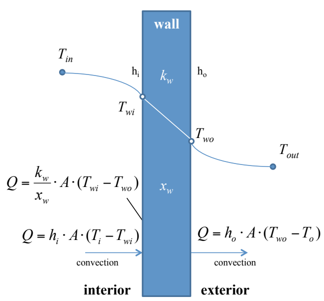
$\Delta T = temperature\ change$

Insulation = R or U-Value

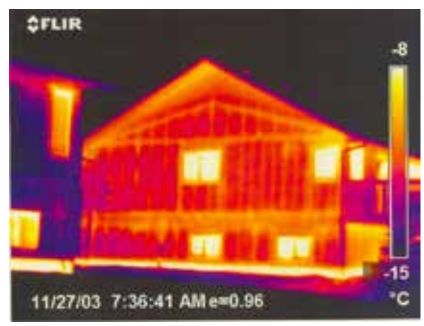
Q_e = heat transfer rate through envelope, Watts
U = overall heat transfer coefficient, W/m²-K
A = wall area, m²
ΔT = temperature difference (in to out), °C or °K
k_w = wall thermal conductivity, W/m-K
h = convection coefficient, W/m²-K
x_w = wall thickness, m

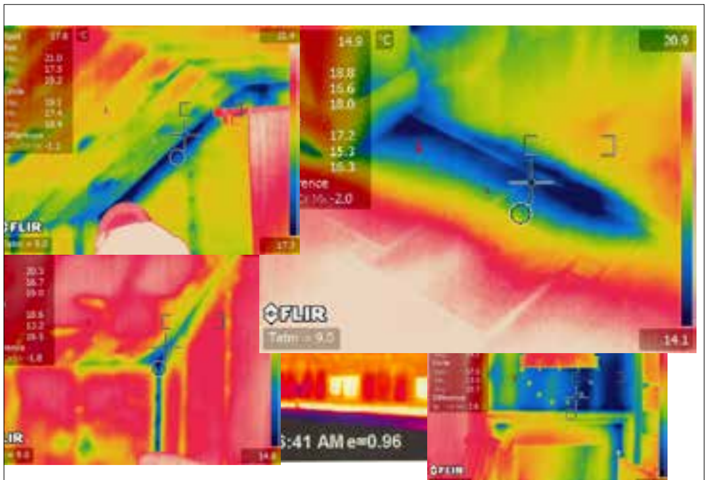
$$Q_e = \frac{A \cdot (T_i - T_o)}{\left(\frac{1}{h_i} + \frac{x_w}{k_w} + \frac{1}{h_o}\right)}$$

$$U = \left(\frac{1}{h_i} + \frac{x_w}{k_w} + \frac{1}{h_o}\right)^{-1}$$



Thermal Bridging

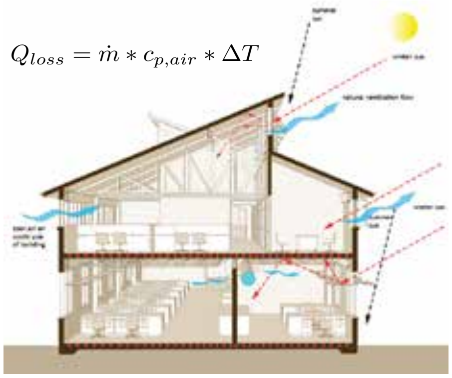




The air and error in Buildings

Building Ventilation

$$Q_{loss} = \dot{m} * c_{p,air} * \Delta T$$



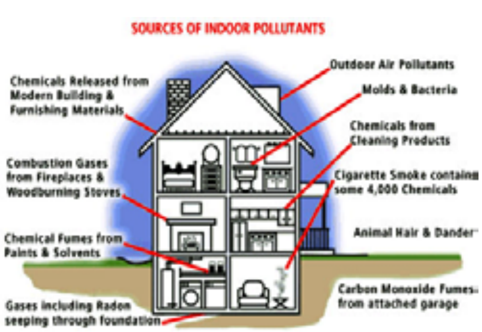
Ventilation energy relationship

- http://afv.com/tale-fireplace-fairy/

Indoor Air Quality

Where does weight go when you lose weight

Indoor Air Quality



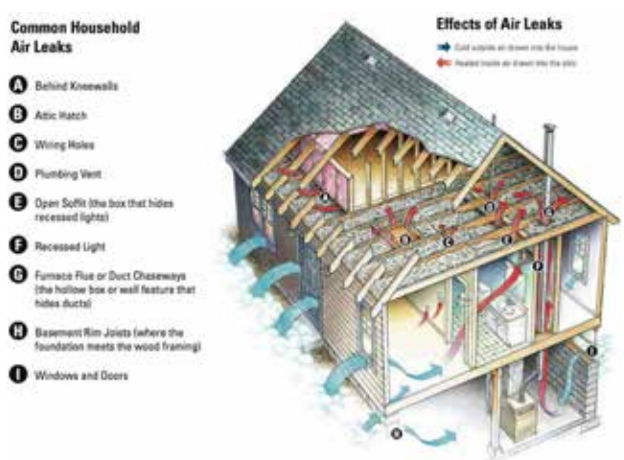
Building Ventilation

- Regulations require
  - 10-30 m3/hr per person or 5-15 cfm per person
  - 1-5 m3/hr or m2 of building
- Quantify ventilation losses also by number of people or area times ventilation rate

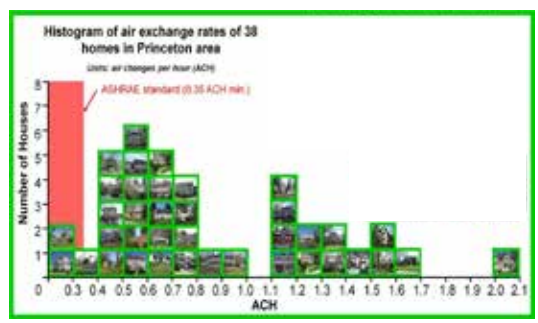
$$Q_{loss} = \dot{m} * c_{p,air} * \Delta T$$

How leaky is this building?

$$Q_{loss} = \dot{m} * c_{p,air} * \Delta T$$



Leaky buildings



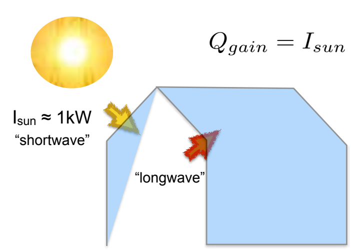
Courtesy of Bob Harris, CEE Department

Understanding error

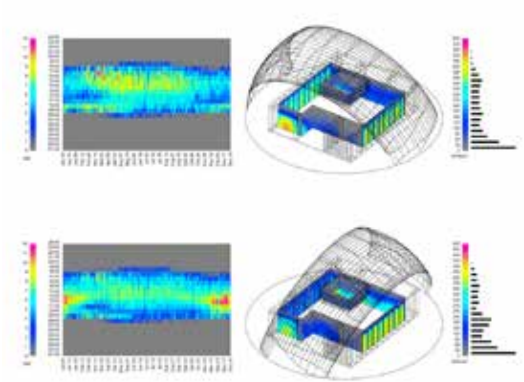
- Air leakiness may change by a factor of 2-3!
- Can you approximate the size of this room?

InSOLation

$$Q_{gain} = I_{sun} * A * SHT$$



Solar



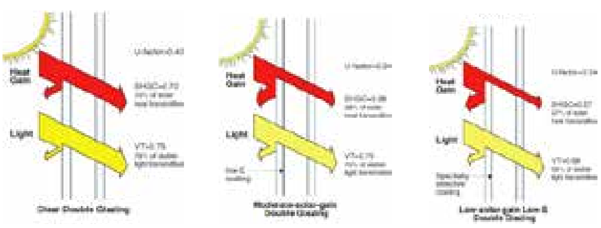
Glass!

Glass performance

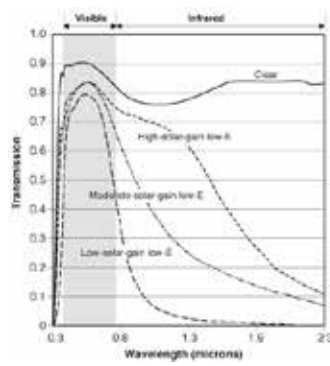
Solar Heat Gain Coefficient (SHGC)

Visual Transmission (VT)

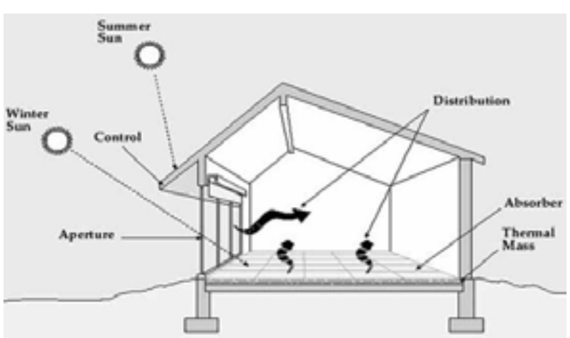
```
range 0-1
```



Low Emissivity Coatings

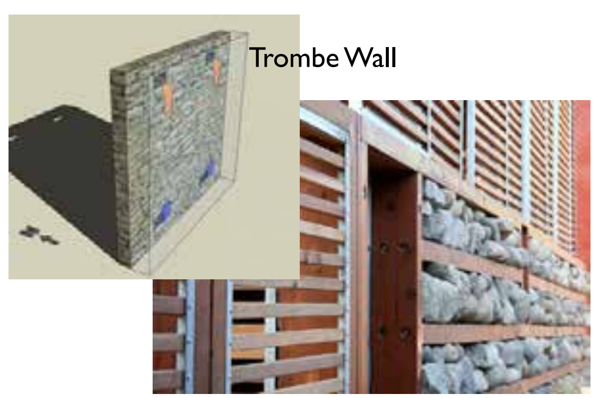


Passive Solar



Thermal Mass

Trombe Wall



Review = Energy Balance

- Insulation (Conduction)
  $Q_{loss} = U * A * \Delta T$
- Ventilation (Convection)
  $Q_{loss} = \dot{m} * c_{p,air} * \Delta T$
- Insolation (Radiation)
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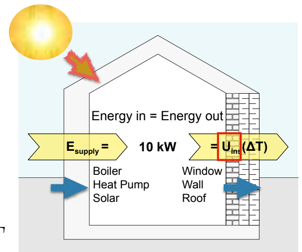
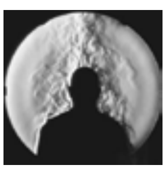
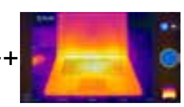


What are we forgetting?

What are we forgetting?

- YOU! … and your stuff

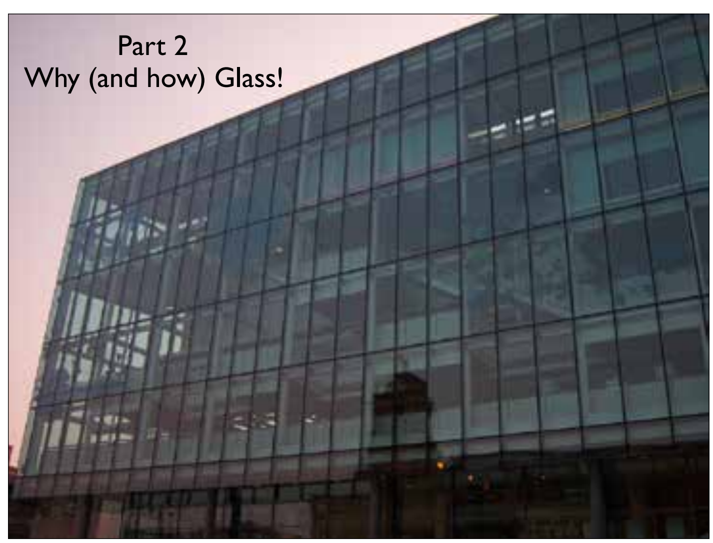
 +  =  = 

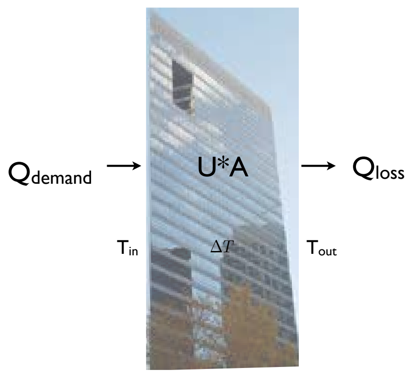
++ 

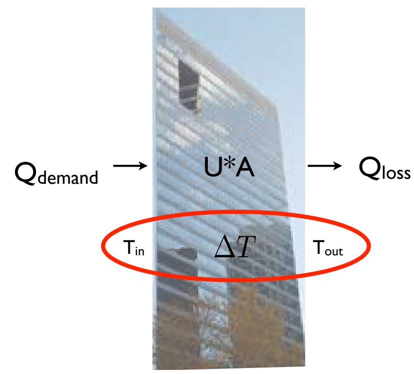
Example

- **Your** room performance…

We need a full view of performance part 2 (2nd Law)







Requires a better understanding of value

It's all about the Benjamins (or Grant? or Ishak?)

50 dollars 50 dollars

Both amount and value matter

50 dollars US ≠ 50 dollars Sing

What about energy?

50 kWh 50 kWh

Must consider amount and value

50 kWh heat ≠ 50 kWh elec

energy systems are designed with the *wrong exchange rate*

... thermodynamics can help

EXERGY

1st law + 2nd law

EXERGY

energy + entropy

for architects?
... and you!

Low Exergy

LowEx

Exergy fundamentals

- Ist and 2nd Laws of Thermodynamics
  - Combination of Energy and Entropy Balances

Energy Out = Energy In

$E_{out} = E_{in}$

Entropy Out = Entropy In + Entropy Generated

$S_{out} = S_{in} + S_{gen}$

Exergy of Electricity

Exergy in an isothermal reversible system has 100% potential

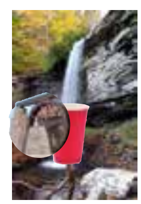
Heat ≠ 100% Exergy

Electricity ~ 100% Exergy

Exergy equation

Exergy = Energy - Anergy OR Energy = Exergy + Anergy

$$Ex = [E - T_0 S]$$
$$Ex = [E - An]$$
$$\underline{E = Ex + An}$$



Exergy of heat

- Constant heat, *Q*, and Temperature, *T*
- Anergy is the required heat dissipation of a cycle

Anergy = Entropy · Reference Temperature, T_0

$$Ex = Q - T_0 S = Q - T_0 \int \frac{\delta Q}{T}$$

$$Ex = Q - T_0 \frac{Q}{T} = Q - Q\frac{T_0}{T} \Big\} Anergy$$

$$Ex = Q\left(1 - \frac{T_0}{T}\right) = Q\boxed{\left(\frac{T - T_0}{T}\right)}$$

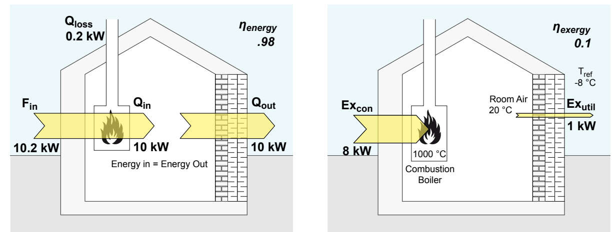
equations are the detailed way of saying <u>temperature matters</u>

No combustion in buildings!

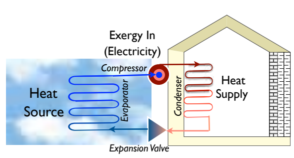
- 1000 °C or higher to heat a 20 °C room
  - 90% exergy loss

Exergy and Buildings

- Exergy reveals the potential of the supply and the real value of the demand



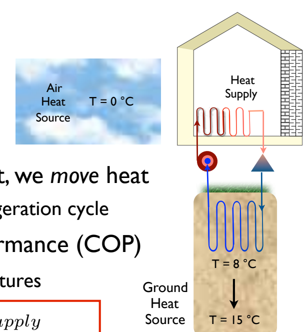
Heat pumps, not fire



- Instead creating heat, we *move* heat
  - thermodynamic refrigeration cycle
- Coefficient of Performance (COP)
  - Ratio of heat output to electricity (Work/Exergy) input

$$COP = \frac{Q_{supply}}{W_{input}}$$

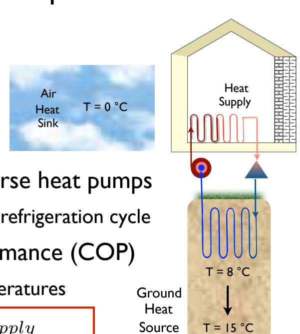
Heat pumps, not fire



- Instead creating heat, we *move* heat
  - thermodynamic refrigeration cycle
- Coefficient of Performance (COP)
  - Depends on temperatures

$$COP = g \cdot \frac{T_{supply}}{T_{supply} - T_{source}}$$

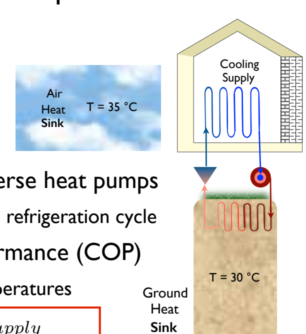
Heat pumps = AC



- Chillers are just reverse heat pumps
  - same thermodynamic refrigeration cycle
- Coefficient of Performance (COP)
  - Still depends on temperatures

$$COP = g \cdot \frac{T_{supply}}{T_{supply} - T_{source}}$$

Heat pumps = AC



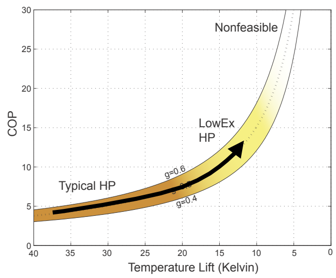
- Chillers are just reverse heat pumps
  - same thermodynamic refrigeration cycle
- Coefficient of Performance (COP)
  - Still depends on temperatures

$$COP = g \cdot \frac{T_{supply}}{T_{supply} - T_{source}}$$

Performance and temp

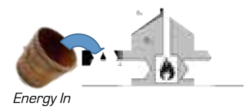
$$COP = \frac{Q_{out}}{W_{in}} = g \cdot \frac{T_{supply}}{T_{supply} - T_{source}}$$

$$COP_{ideal} = \frac{T_h}{T_h - T_c}$$



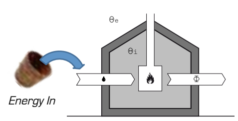
Traditional paradigm

- Increase efficiency by reducing demand



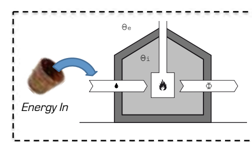
Traditional paradigm

- Better insulation reduces energy demand



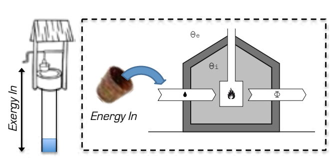
Think outside the box

- Consider the potential of the energy consumed



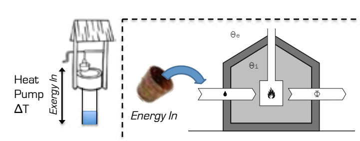
Think outside the box

- The exergy represents that potential



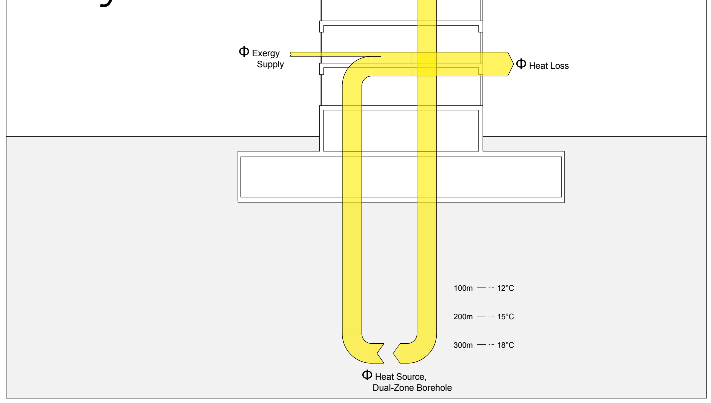
Think outside the box

- Temperature has influences on performance that should not be ignored

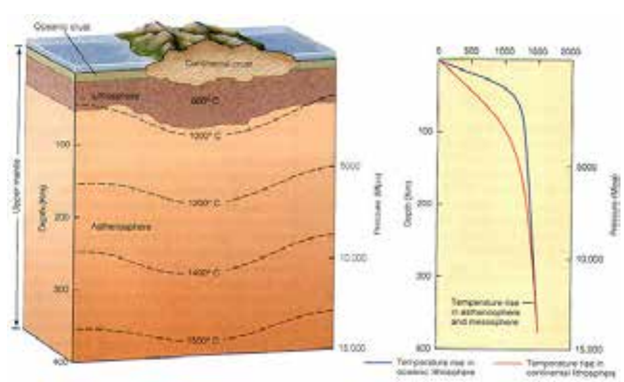


a new paradigm of **appropriate temperatures** will uncover higher potential

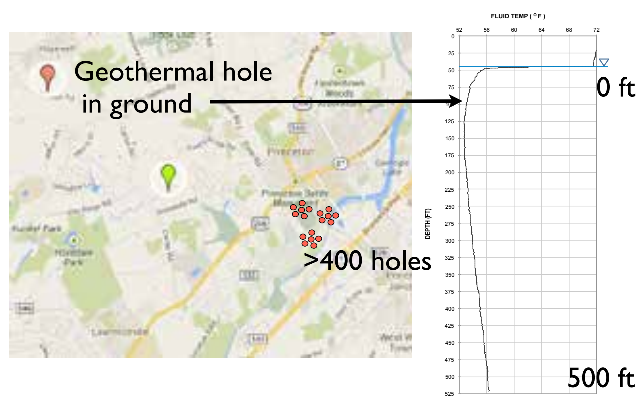
Geothermal Systems



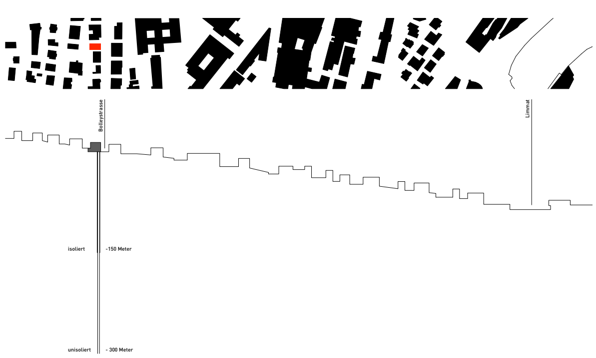
Geothermal gradient



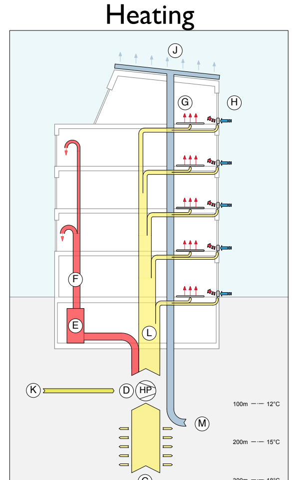
Relevance in Princeton



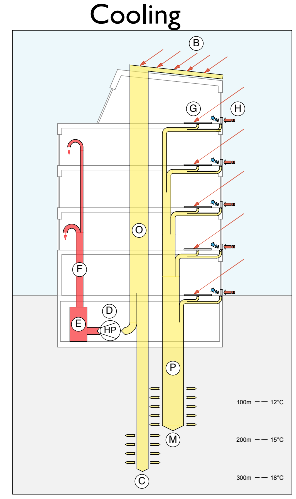
Swiss example deep borehole



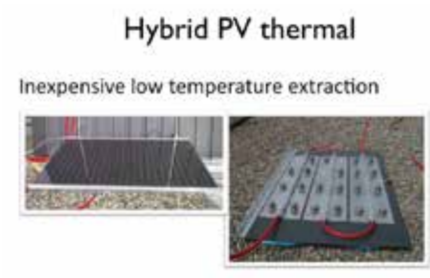
Heating



Cooling

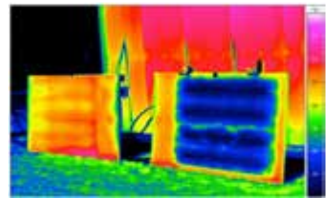


Technology adaption

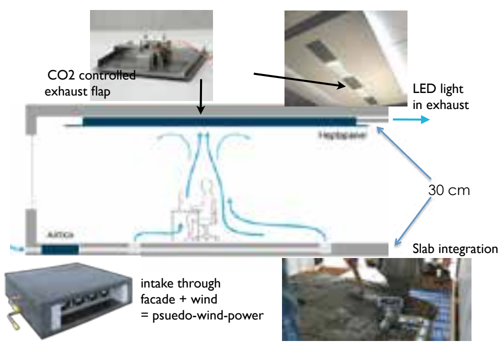


Technology adaption

- Hybrid solar (CHP) experimental validation
  - 12-14% electrical efficiency and 40-50% thermal
  - 30 °C heat valuable for LowEx systems

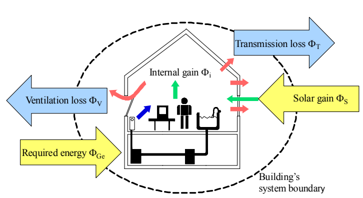


Technology integration

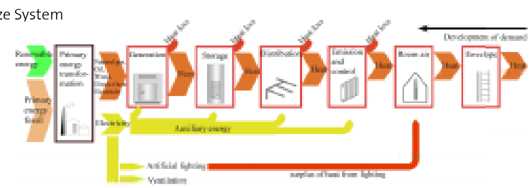


What does this mean for designing buildings?

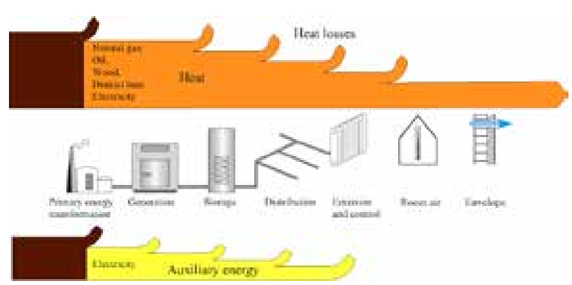
Part 1
determine demand



Part 2
Optimize System



System Losses



What is missing from the chain?

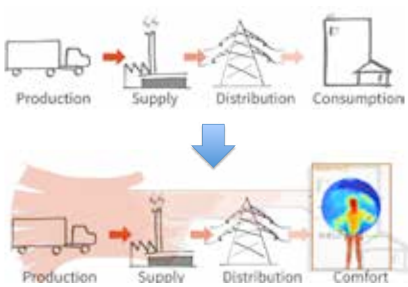
Optimize System

What is missing from the chain?

YOU!! ... again!

Optimize System

Occupant comfort, NOT *room comfort*



Controls need to smarter… better than NEST

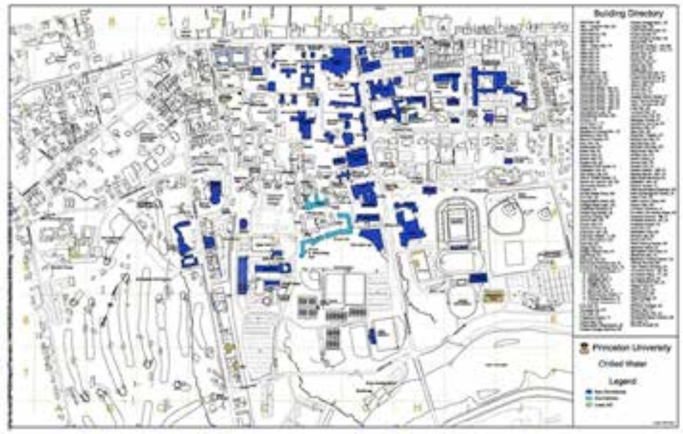
Campus as a Lab!

We have a lot of buildings!

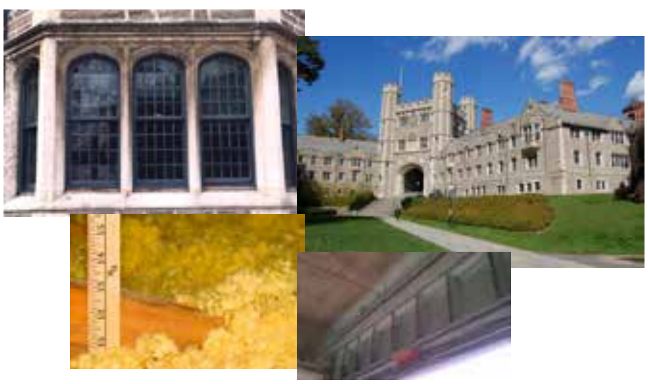
Princeton Energy ~15MW elec

Buildings Heated by CHP Plant

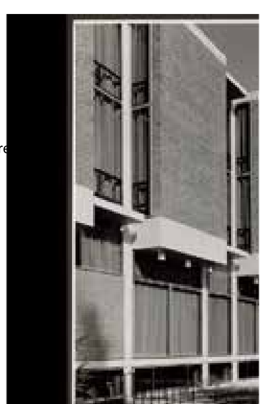
Buildings Cooled with Chilled Water

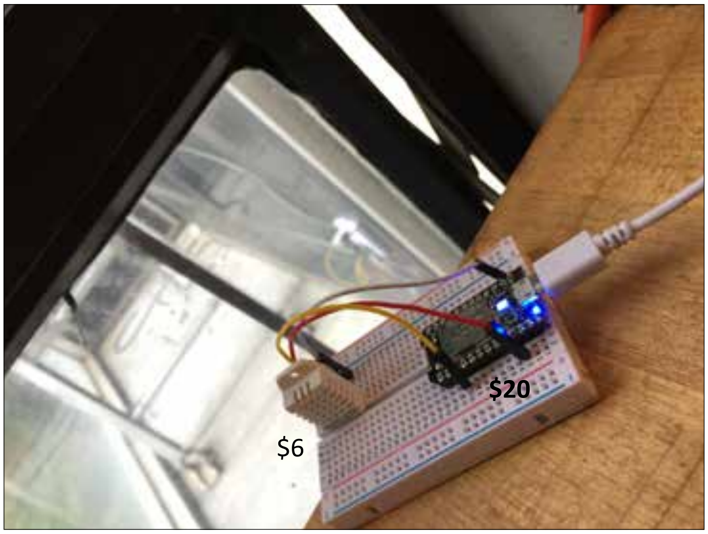


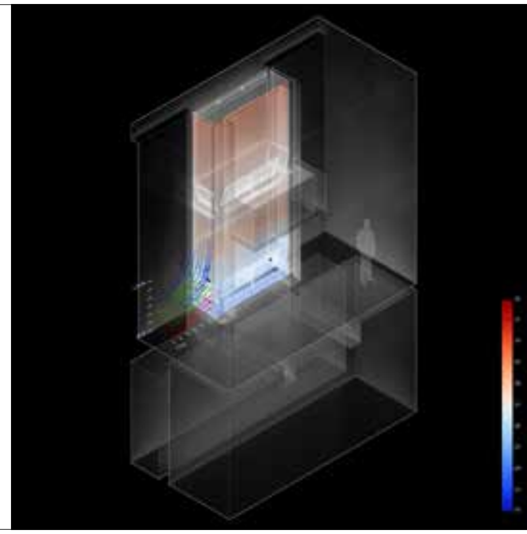
PU Improvements



Princeton
School of Architecture
1950's







Example spaces

Andlinger Buiding acee.princeton.edu

3 for 2 – Singapore
beyondefficiency.blogspot.sg

New Arch Lab at Princeton

Questions

C.H.A.O.S. LAB
Cooling and Heating for Architecturally Optimized Systems

Thanks:
Eric Teitelbaum
Hongshan Guo
Jake Read

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