
ROCKY MOUNTAIN
INSTITUTE

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CEE 173L/273L: Advanced Energy End-Use Efficiency

Public Lectures in Advanced Energy Efficiency:
1. Buildings

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Energy end-use efficiency

- Technologically provides more desired service per unit of delivered energy consumed
- Reduced aggregate energy intensity (primary energy used per dollar of real GDP), mainly through technical improvements, now provides over twice as much service to the U.S. (*vs.* 1975 E/GDP) as does oil
- Fastest-growing U.S. “source” (~2.5–3.5%/y)
- Generally the largest, cheapest, safest, and fastest energy option
- Also the least visible, least understood, and most neglected

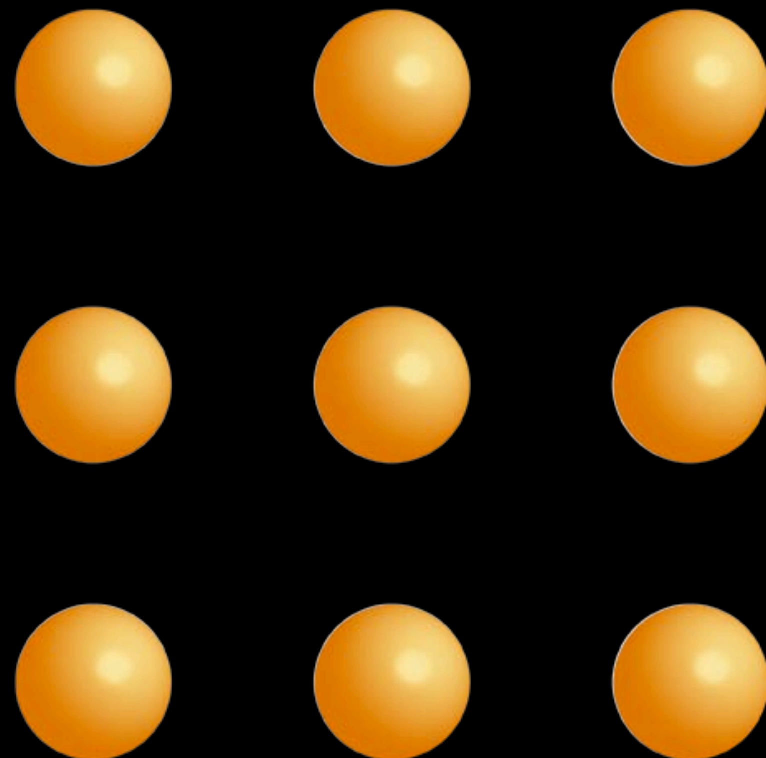
Buildings: dominant end-use

- Buildings (excluding industrial processes inside) use 69% of U.S. electricity, 36% of direct natural gas, 40% of all energy (as of 2005)
- Buildings emit 38% of fossil-fuel CO_2 (60% in UK)
- Buildings have the slowest turnover of any major kind of capital stock—often 50–100 y
- Structures are 85% of U.S. fixed capital assets
- Everyone is familiar with buildings…but in the past century we forgot how to design them optimally
- Buildings are the easiest way to illustrate how whole-system design can make very large energy savings cost less than small or no savings

Edwin Land

"People who seem to have had a new idea have often just stopped having an old idea"

The Nine Dots Problem



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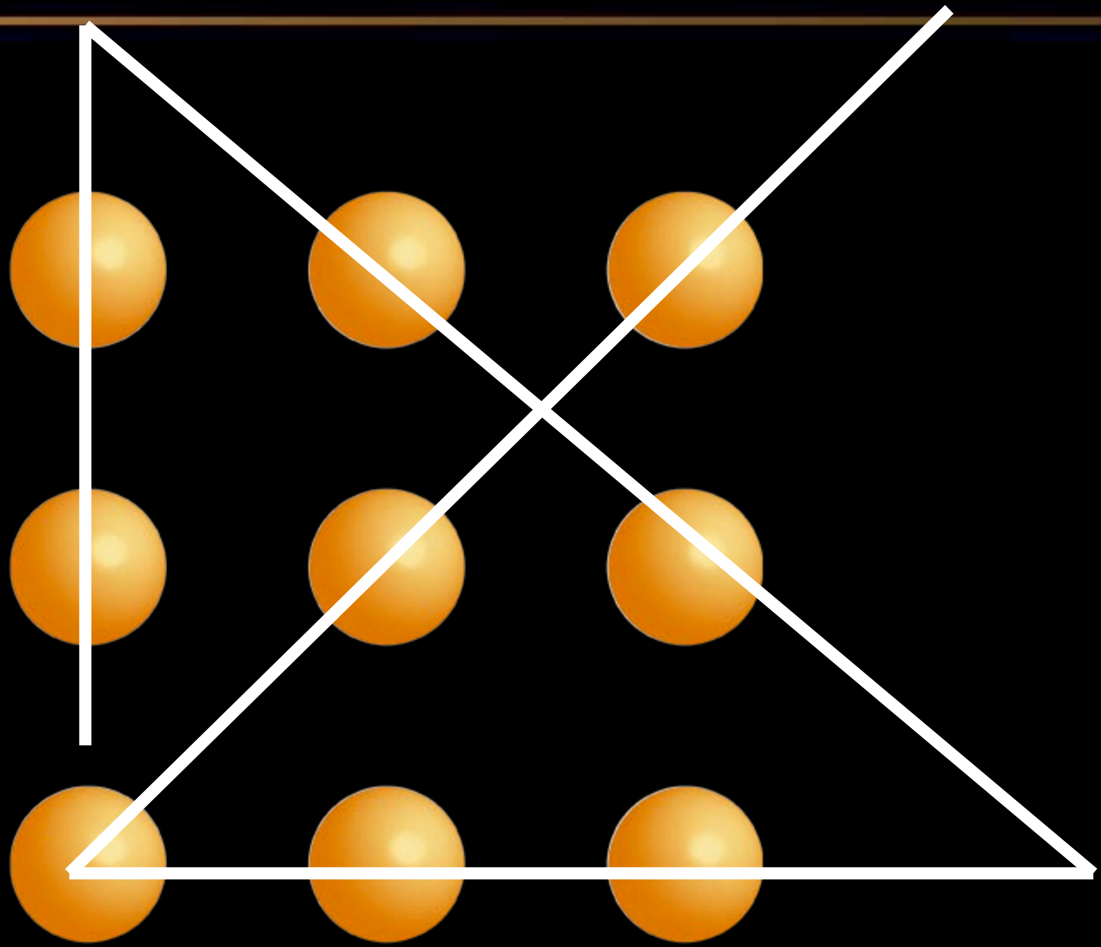

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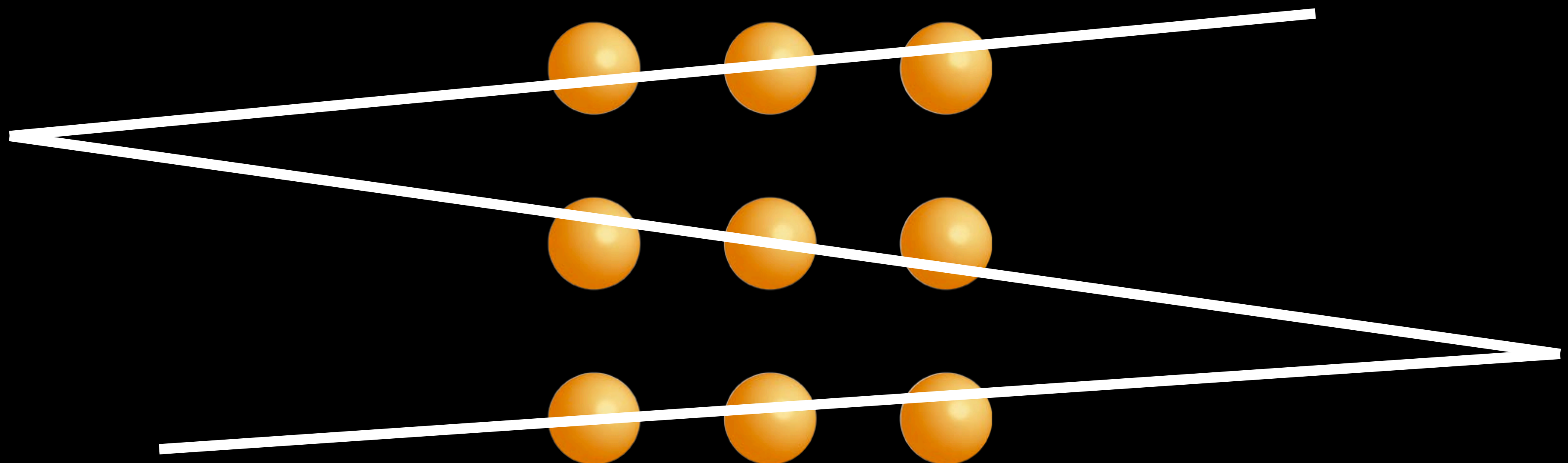
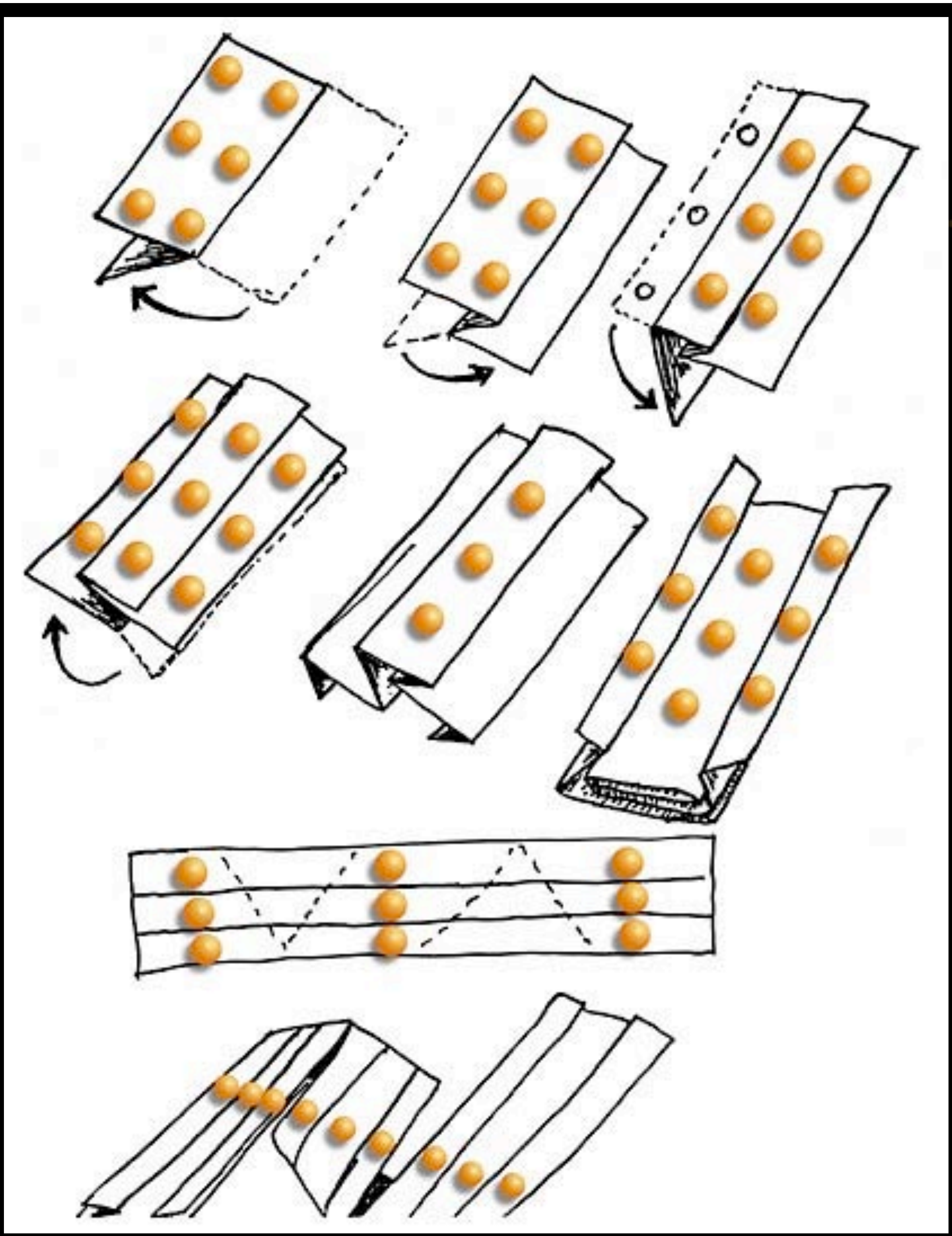
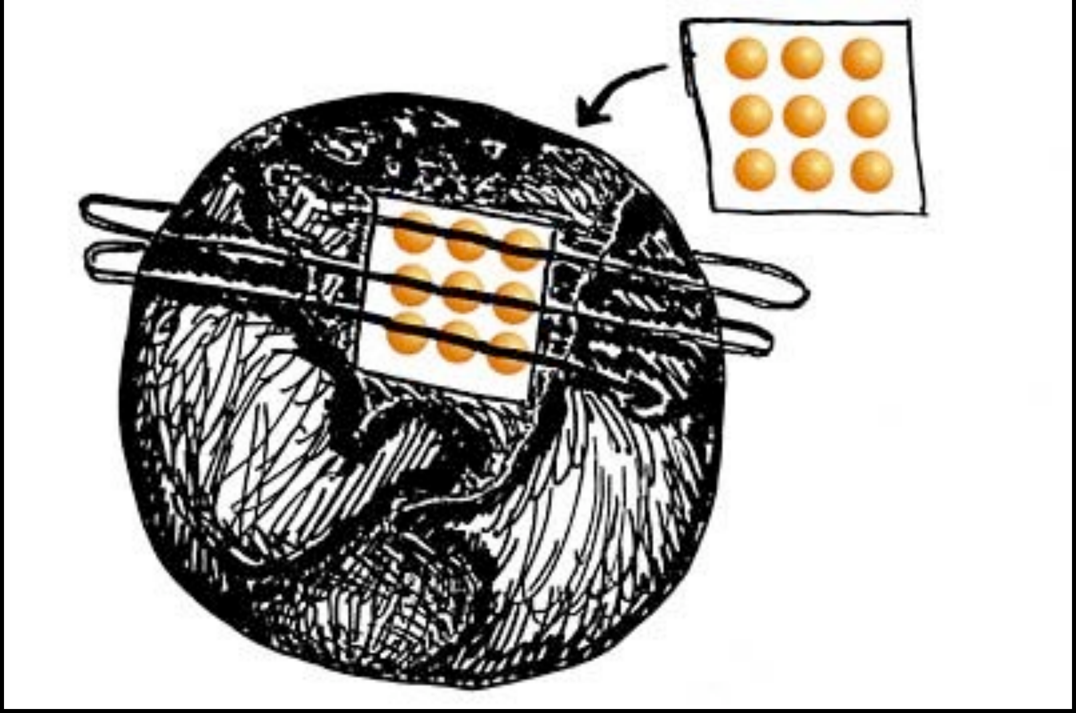


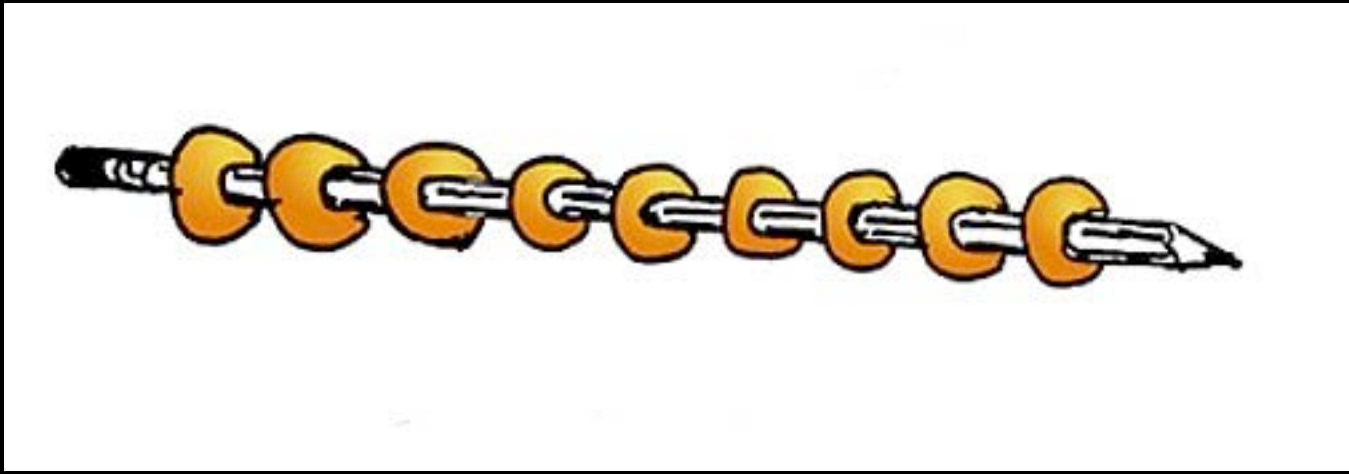


origami solution

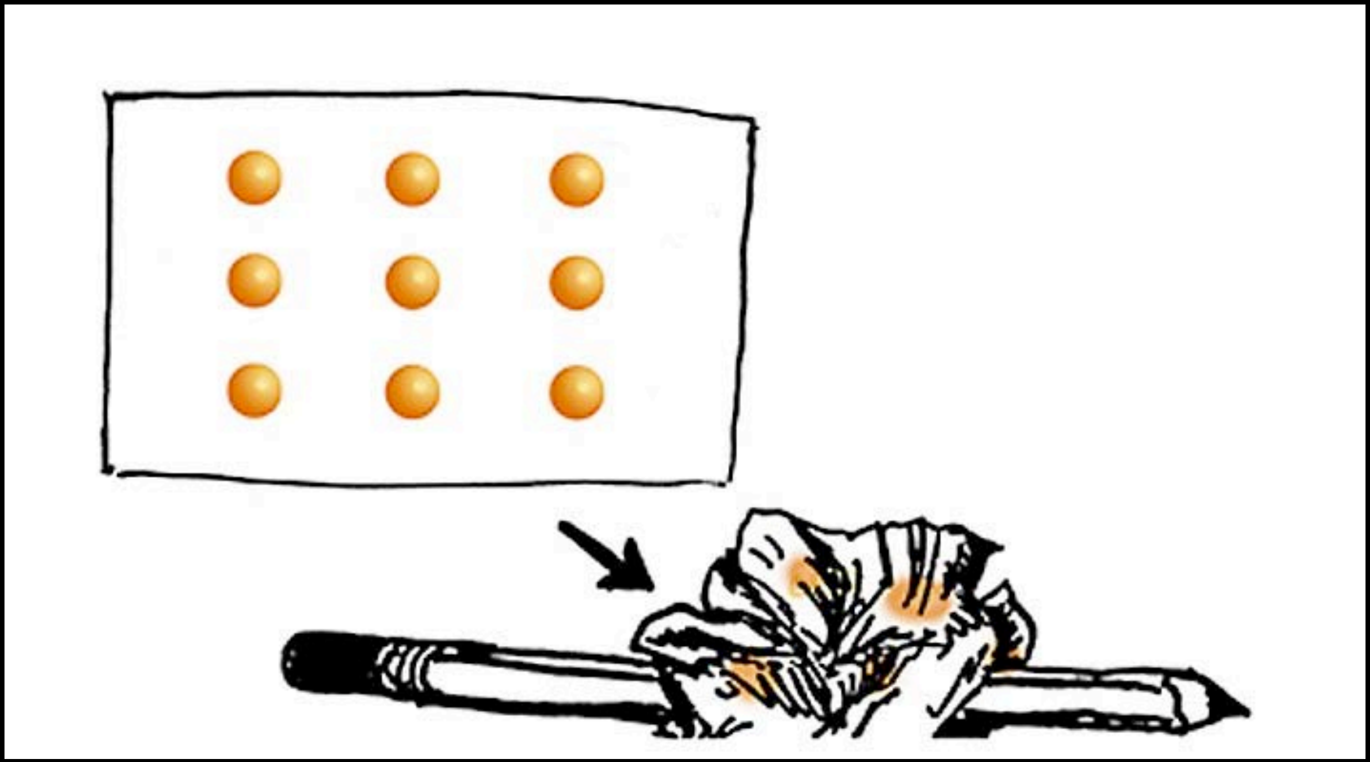
geographer's
solution

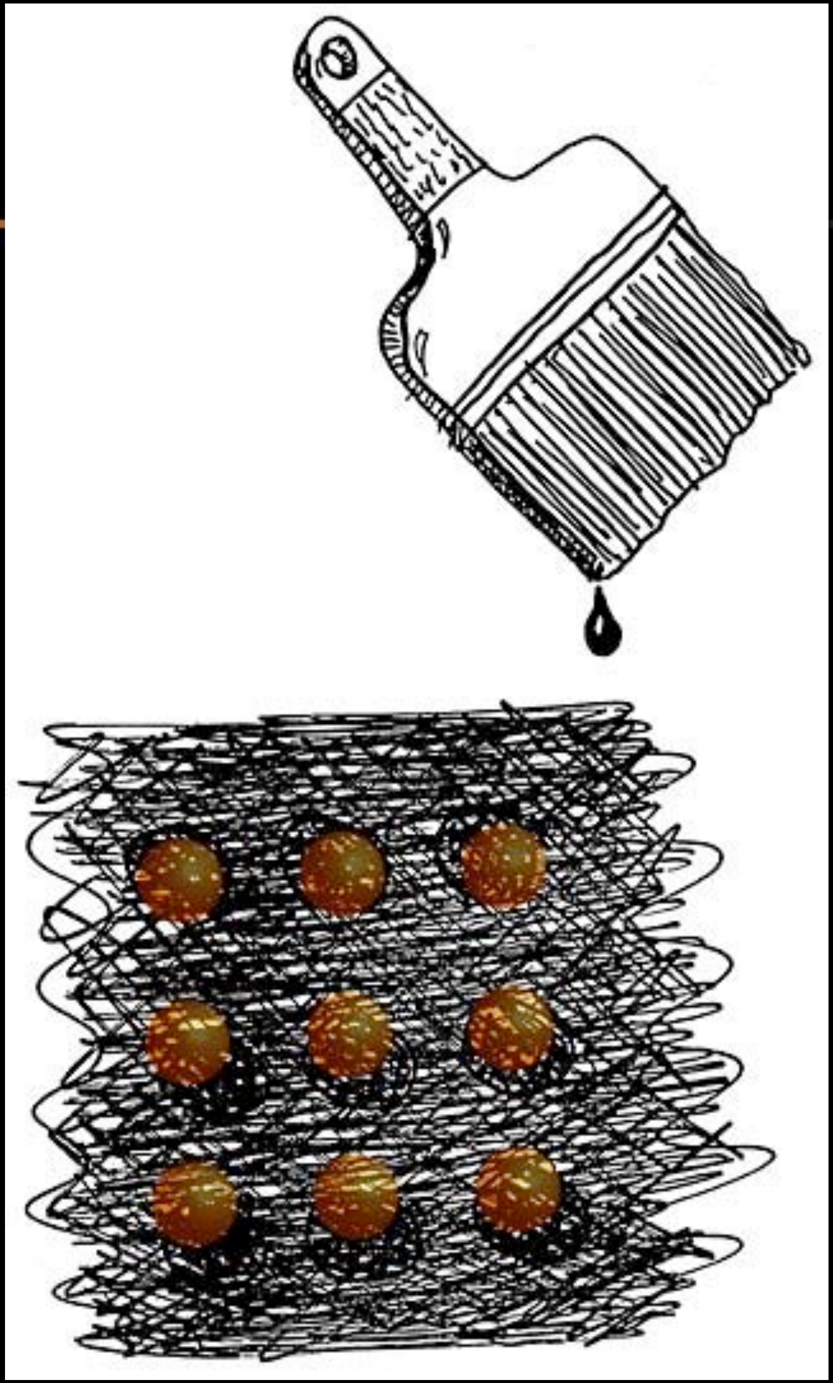


mechanical engineer's solution



statistician's
solution





wide line
solution

−44 to + 46˚C with no heating/cooling equipment, *less* construction cost

2200 m, frost any day, 39 days' continuous midwinter cloud…yet 28 banana crops with no furnace

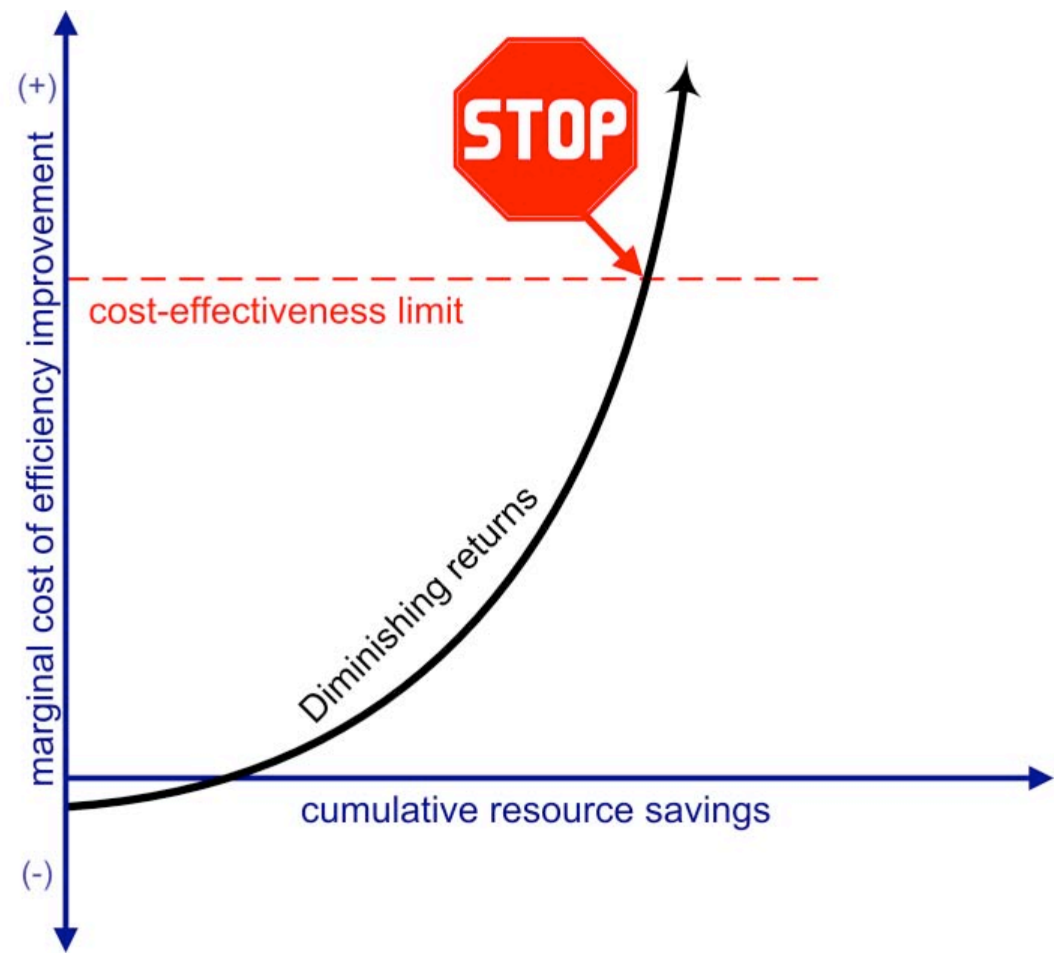
- Lovins house / RMI HQ, Snowmass, Colorado, '84
  - Saves 99% of space & water heating energy, 90% of home el. (372 m^2 use ~120 W_{av} costing US$5/month @ $0.07/kWh)
  - 10-month payback in 1983
- PG&E ACT^{2}*, Davis CA, '94
  - Mature-market cost –$1,800
  - Present-valued maint. –$1,600
  - 82% design saving from 1992 Ca code, ~90% from U.S. norm
- Prof. Soontorn Boonyatikarn house, Bangkok, Thailand, '96
  - 84% less a/c capacity, ~90% less a/c energy, better comfort
  - No extra construction cost

Key: integrative design—multiple benefits from single expenditures

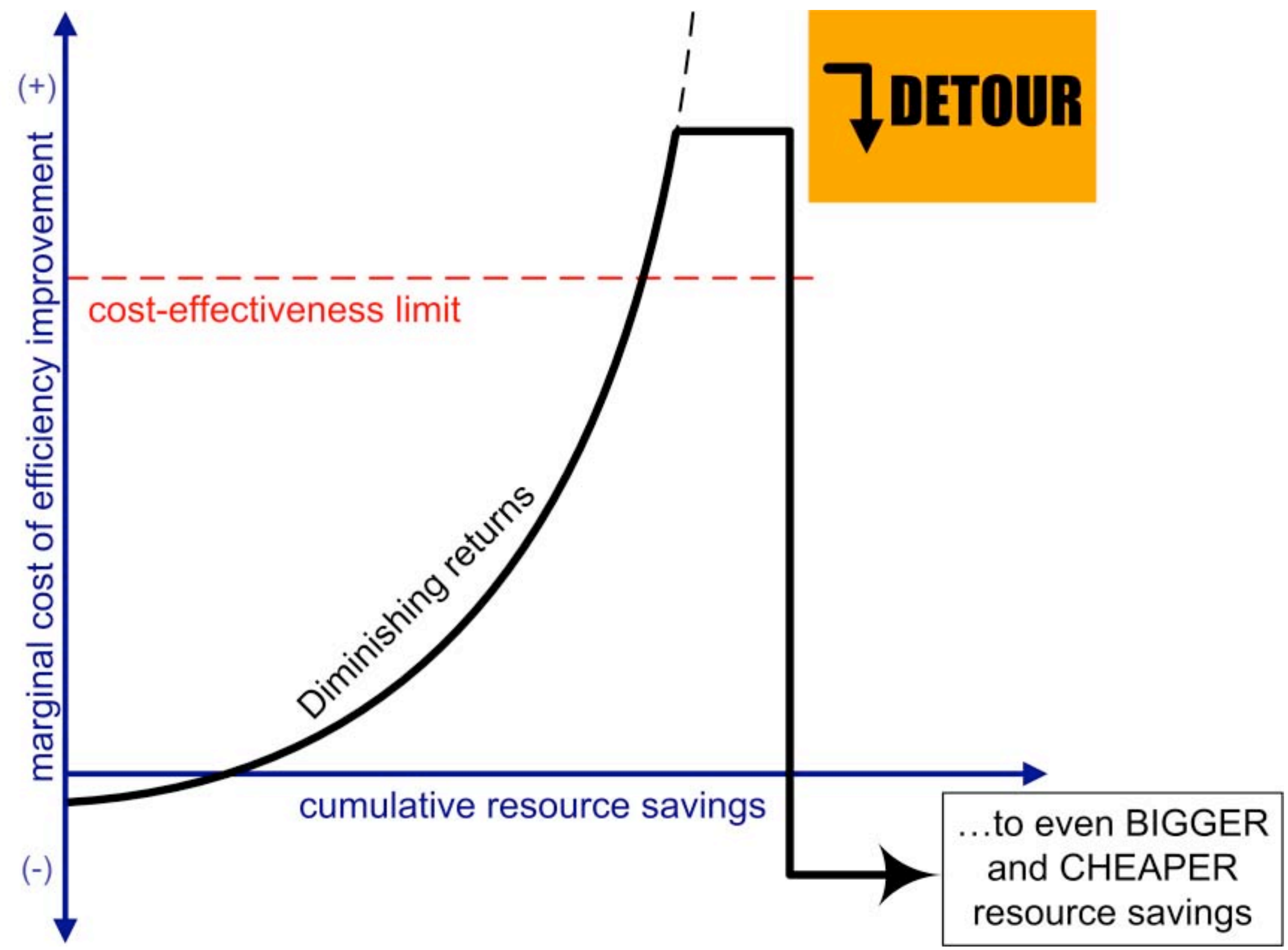
*$18M experiment, 1990–97, 7 old & new bldgs, www.pge.com/003_save_energy/003c_edu_train/pec/info_resource/act2_proj.shtml

Rocky Mountain bananas with no furnace?

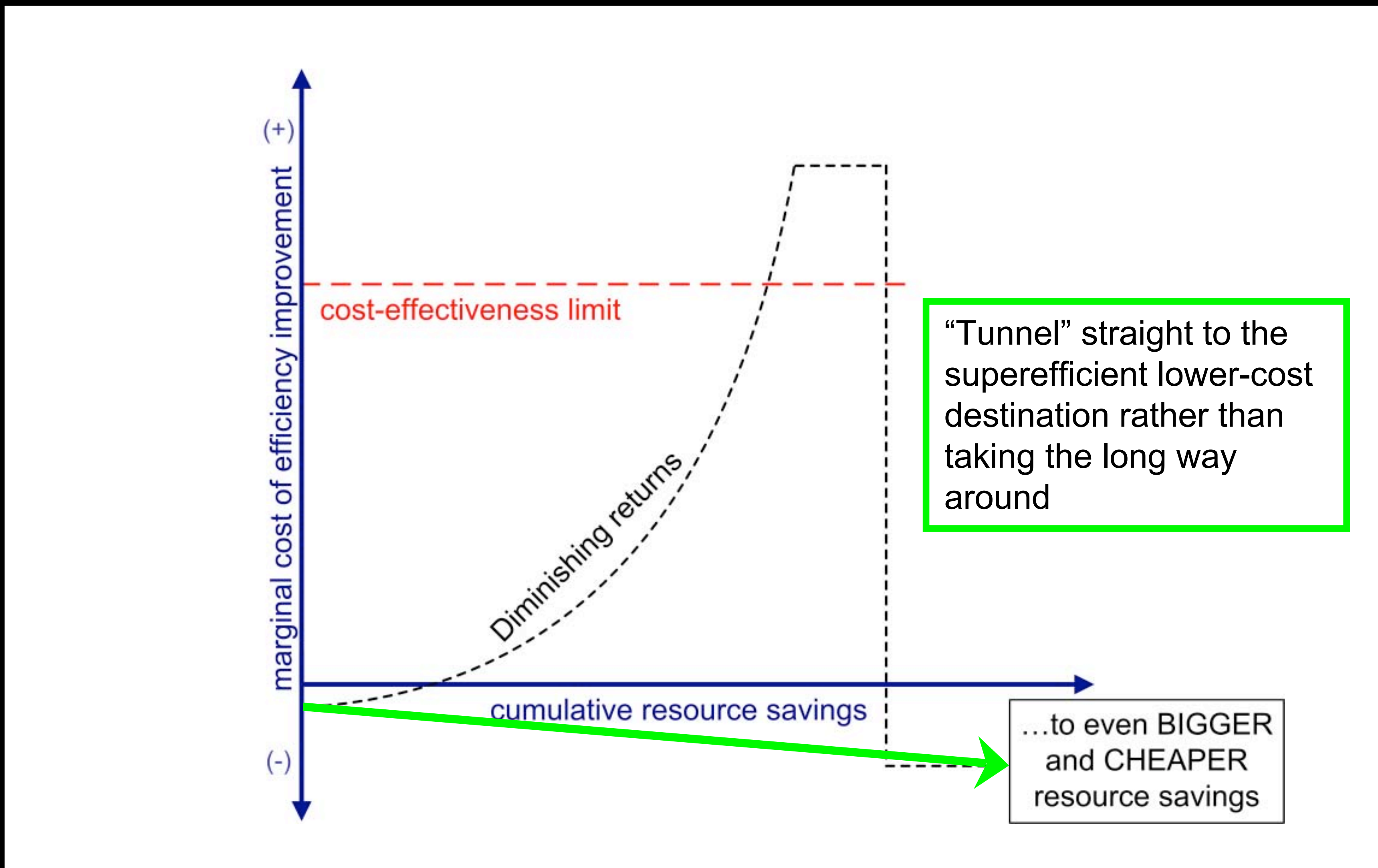
Old design mentality: always diminishing returns...



New design mentality: expanding returns, "tunneling through the cost barrier"



New design mentality: expanding returns, "tunneling through the cost barrier"



Two ways to tunnel through the cost barrier

1. Multiple benefits from single expenditures

- Save energy *and* capital costs…10 benefits from superwindows, 18 from efficient motors & lighting ballasts,…
- Throughout the design: *e.g.*, RMI HQ's arch has 12 functions but just one cost
  - Supports greenhouse glazing, supports roof purlins, distributes varying cantilevered loads, mounts atrium lights, acoustics, esthetics, thermal mass, controls atrium's solar gain seasonally (to prevent north-side overheating), collects hot water and hot air, distributes daylight, vents excess heat
  - Most components of the building do at least three jobs
- A Lotus *Elise* car has a front-end component with seven functions but just one cost
- Designing this way—as nature does—is more fun!

Whole-system design: a 1,208-m² Denver office

Typical analysis

Energy Measure	Incremental Cost	Savings	Payback Period (yrs)
Daylighting	$4,900	$1,560	3.14
Glazing	$5,520	$1,321	4.18
Energy Efficient Lighting	$1,400	$860	1.63
Energy Efficient HVAC	$3,880	$739	5.25
HVAC Controls	$2,900	$506	5.73
Shading	$4,800	$325	14.77
Economizer Cycle	$1,200	$165	7.27
Insulation	$1,600	$101	15.84

Whole-system design:
a 1,208-m² Denver office

Whole-building analysis

- Added construction costs: $26,200
- Capital cost *reductions*: $21,860
- Incremental construction cost: $4,340
- Energy savings (70%): $4,500/year
- Simple payback: about 1 year
- ROI: about 100%

Energy Measure	**Incremental Cost**
Daylighting	$4,900
Glazing	$5,520
Energy Efficient Lighting	$1,400
Energy Efficient HVAC	$3,880
HVAC Controls	$2,900
Shading	$4,800
Economizer Cycle	$1,200
Insulation	$1,600
Fewer E & W Windows	-$4,160
Small & Different HVAC	-$17,700

Greg Franta FAIA, Team Leader,
RMI/ENSAR Built Environment

Tunneling through the cost barrier through integrative design: Grand Forks (ND) office

Incremental costs

Windows	$67,500
Daylighting	$18,000
Insulation	$17,200
Lighting	$21,000
HVAC	-$160,000
Total	-$36,300

Energy savings: $75,000/year

Hotter climate, same story: CSAA Antioch HQ (PG&E ACT², 1994)

- 1,487-m^2 new office in the hot CA Central Valley
- 69% less summer peak load than 1992-Title 24-compliant base case (144→44 kWe_p)
- Saved 63% of 1992 Title 24 total energy, 72% of gas (would have saved more with better HVAC)
- CSAA's cheapest and most pleasant HQ ever
- Simple changes—tuned superwindows, better orientation & shell, good lights & controls (–77%) & daylighting, better (but nowhere near best) HVAC, but no major improvement in office equipment
- Could be better today, at all scales, and saved kW_p could exceed saved kWh/y by even more

A closer look at tunneling: 1. The 372-m² Lovins house design

- Add improvements that save 99% of space heating
  - Superwindows (center-of-glass k ~1.0 W/m²K, later <0.4)
  - Superinsulation (walls effectively k ~0.14, roof ~0.08, later 0.05)
  - Six air-to-air heat exchangers, tight construction (leakage ~75 cm²)
  - High thermal mass, good zone coupling, orientation, passive design
- Thus eliminate the usual heating system, so total construction cost goes *down* by ~$1,100 (1983 $)
- Reinvest that $1,100 plus a further ~$7,100 ($16/m², <1% of total) to save 90% of electricity, 99% of water heating energy, 50% of water: net investment rises by ~$6,000
- Saves $7,100/y at 1983 energy prices; 10-month payback (*NB*: local construction costs 2× U.S. av.)
- Today, could save ~2/3 of remaining el., Δcapex <0

A closer look at tunneling: 2. The 155-m² ACT² Davis house design

- Since Title 24 by law supposedly included all societally cost-effective savings, no more should have been designable, but –82% was!
- Better floor plan (made space more usable but eliminated 11% = 7 m of perimeter), optimized window placement, thermally broken window frames, and a novel engineered wall that saves ~74% of wood, cut costs, & nearly doubled insulation together saved 17% of energy at negative cost (53% of reduced cost is the shortened perimeter wall)
- ~20 further improvements raised design saving to 60%, but raised cost nearly $1,900 despite elimination of $2,050 furnace/ducts/eqt.
  - Most conventional; some surprising: 80% sav. on 1–3%-eff. exh. fans @ same cost
  - Unconventional: dump refrigerator waste heat into domestic hot water (3 benefits)
  - Hydronic radiant slab heater from 94%-eff. water heater provides space-ht. backup
- Designers had reached limit of cost-effectiveness *vs.* saved kWh, but…
  - Still had 1/3 of original 3-ton air conditioner, and could save its *capital* cost, not just its electricity use (@ ~6¢/kWh), so set up a "potential cooling elimination package"
  - Seven measures went into that basket, *e.g.*, better superwindows, core-zone double drywall, ceramic floor tile to help ride through daily heat peaks…$2,600 in all—thus eliminating (w/44% safety margin) the last $1,500 worth of a/c & $800 of maint., earning their way onboard and raising space-cooling savings to 100% (92% w/fans)

So very efficient buildings can cost *less* to construct

(if all other things are equal)

COST	Standard design	Integrated efficient design
		
Capital		~99% × [ ]
Operation		~20% × [ ]

This choice doesn't depend on your time value of money or price of energy—just your integrative design skill

Same logic with NYC apartments

- Chris Benedict RA designs new apartments that save ~85% of NYC-normal energy use for heat and hot water, at no extra cost
- She emphasizes airtightness (air leaks cause half the normal heating and much of the cooling load), innovative ventilation design, and working thermostats in every room (to optimize its gain/loss balance)
  - All these improvements are more than paid for by dramatically downsizing heating equipment
  - *E.g.*, the building on L has only an 8" chimney—smaller than for many single-family houses
  - Insulation *outside* structural concrete traps thermal mass

www.greenhomeguide.com/index.php/service_detail/857/C183

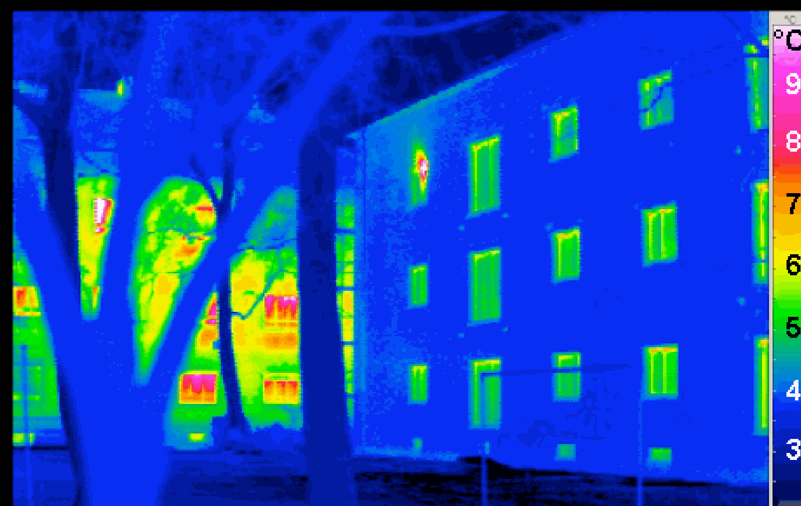
22-unit apartment, 229 E. 3d St., NYC

Henry Gifford, "High Performance Multi-Family Buildings at No Extra Cost with No Extra Funding," pp. 65–67, Lessons *Learned: The Costs & Benefits of High Performance Buildings*," Earth Day New York 2006; www.chrisbenedictra.com (under construction)

And in cold, cloudy climates like Germany (Passivhaus Institut)…

http://en.wikipedia.org/wiki/Passive_house, www.passiv.de

- No central heating system; can add small exhaust-air heat pump or solar panel if desired, but not necessary
- Total primary energy use ≤120 kWh/m^2-y
- ≤15 kWh/m^2-y & <10 W/m^2 heating energy—5–25% of U.S. allowables
- k-0.10–0.15 (k-0.066 roof in Sweden), airtight, high com-fort, loses <0.5 C°/d w/ 0 el.
- >6,000 built in 5 EU nations
- *Zero marginal capital cost* (at least below 60°N lat)



Infrared images of ordinary German apartment (L) and Passivhaus (R)

Multiple benefits from single expenditures

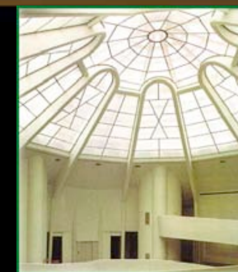
- Our simple examples so far show only two benefits: saved *energy* cost, and reduced *capital* cost
- But the more benefits we create and count, the better bargain we can create
- This is true at the level of the whole building, of its systems, and of their components
- Understanding detailed technical performance at every level helps create greater value for the whole building, as illustrated next with superwindows and dimming ballasts

Example #1: Superwindows' ten hidden benefits

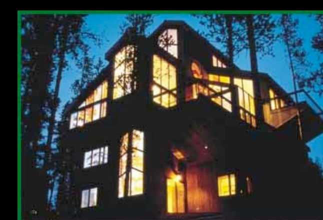
[0. Saved heating energy ($4–7^{+}\times$ double glazing's thermal insulating value)—the only benefit normally counted]

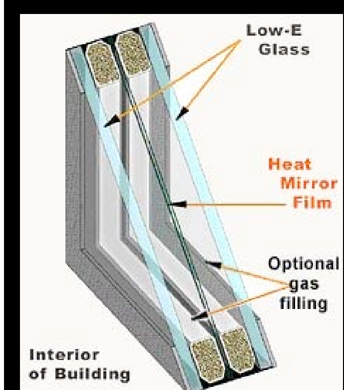
1. Save cooling energy, + fan/pump energy $\propto$ flow^{3}
2. Radiant comfort (half of comfort sensation)
3. Downsize/eliminate space-conditioning capacity
4. Lower construction cost (avoids ducts, etc.)
5. No perimeter zone heating
6. Reduced fading from ~20× less UV <380 nm
7. Reduced noise
8. Less/no condensation and sash rot
9. Improved daylighting
10. Human productivity

All "tuned" to each building elevation (9 flavors of suspended film; many glass types, tints, spacings, fill gases/mixtures)

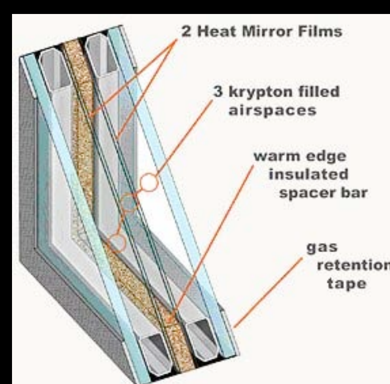









L: ~50-μm Heat Mirror® suspended selective film with argon or krypton fill. R: A two-film k-0.45 (R-12.5) unit. Film can also be coated on both sides for an even higher insulating value. www.southwall.com, www.alpeninc.com




#2: Dimmable electronic lighting ballasts' 18 hidden benefits (beyond ≥4 W/ballast reduced direct losses & better high-freq. lm/W, together saving ≥40%)

1. One cool ballast can control 4–6 lamps, not two, saving capital and installation costs
2. More efficient lamps and ballasts can together nearly optimize lampwall temperature
3. *Ballast can be less sensitive to, or compensate for, lampwall temp. and abnormal supply voltage (reducing by 1/8 the overlighting normally specified as a precaution)
4. Continuous daylight dimming, saving ≥50% in perimeter and other daylit zones
5. *Same feature automatically compensates for lamp age and dirt, saving 14%
6. Less heat reduces convective transport of light-blocking dust
7. *Dimming lamps stretches lamp life and retards lumen depreciation
8. High frequency can further slow lumen depreciation by ~2–5%
9. Dimming permits zonal tuning to tasks done in different zones, saving ~12–20%
10. Dimming optimizes matching to individuals' illuminance preferences, saving ≥20%
11. Modern ballasts facilitate smart occupancy sensors, often saving ~25–50%
12. They also facilitate timers to turn off lights after hours unless overridden
13. Can slightly dim at need during peak-load periods, cutting direct and indirect (via HVAC) utility demand charges w/no material vision loss (eye is logarithmic, $10^{12}\times$)
14. Can shut down lamps, and itself, in certain common failures rather than wasting energy trying to restart failed lamp or energizing a ballast that's providing no light
15. Greatly reduces visual fatigue and lost visual performance from flicker and hum

**Two benefits listed together as one*

Together, saves ~50% of W/lux in central zones, 70–80+% in perimeter zones—*plus* further big lamp, luminaire, and lighting-design savings, for total savings often >90% at very short paybacks

A second way to tunnel through the cost barrier

1. Multiple benefits from single expenditures

- Save energy *and* capital costs…10 benefits from superwindows, 18 from efficient motors & lighting ballasts,…

2. Coordinate with retrofits being done anyway

- A 19,000-m^2 Chicago office could save 3/4 of energy at same cost as normal 20-y renovation —and greatly improve human performance

Renovating a 19,000-m² office

- 20-y-old curtainwall, hot-and-cold climate
- Failing window seals require reglazing
- Superwindows: T_{vis} 0.51 (×5.7), SC 0.25 (× 0.9), k-0.8 W/m²K (÷3.35), noise ÷4, +$8.4/m² glass capex
- With deep daylight, efficient lights (3 W/m²) and plug loads (2 W/m²), cut cooling load at the design hour from 2.64 to 0.61 MW_{th}
- 4× smaller HVAC with COP 1.85→7.04 (× 3.8) costs ~$200,000 less than renovation
- That saving pays for everything else
- Design would save 75% of energy ($285,000 → $80,000/year); peak load 1.25 → 0.30 MW_e; much better comfort; *–5* month payback (+9 months with new curtainwall mounting system)

Air handling: basic physics

$$\text{Fan motor kW} = \frac{\text{cubic meter/s} \times \text{pressure drop (kPa)}}{\text{fan efficiency} \times \text{motor efficiency}}$$

Static or static+dynamic pressure yields static or total fanpower. To obtain fan motor hp from cfm (ft^3/min) and inches w.g., divide by 6,354

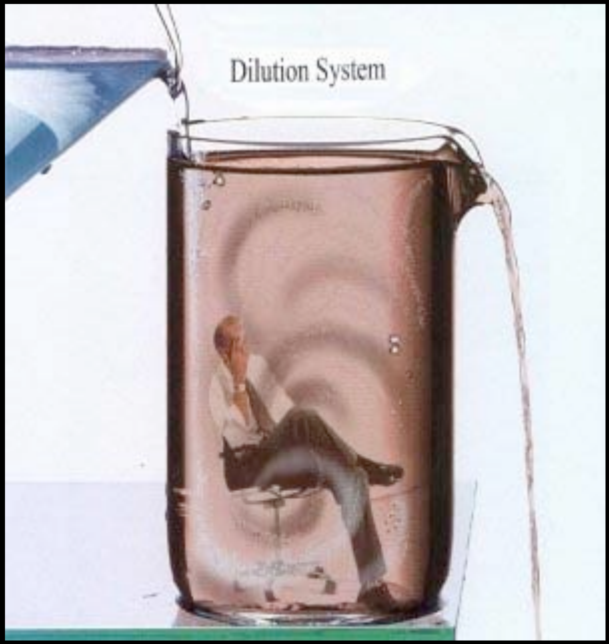
***~2× opportunities:* fan eff.** (≥0.82, usually vane-axial), **motor system eff.** (MotorMaster best, right-sized, high power factor,…—35 improvements), VFDs

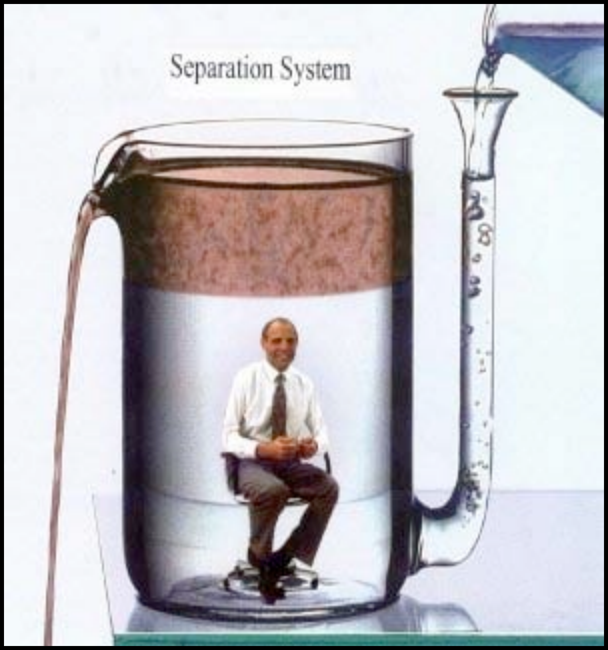
~5–10× (or greater) opportunities:

- **Reduce flow:** air-change rates (base on actual health goals and real-time sensors), displacement
- **Reduce pressure drop:** System design, wring out friction (e.g. duct layout & sizing), low face velocity
  - 60- *vs.* 50-cm duct saves 60% of fanpower ($\Delta P \propto d^{-5.1}$)

COMBINE ALL OF THESE, then downsize chillers

A better *no*-duct solution: displacement ventilation costs less and improves indoor air quality

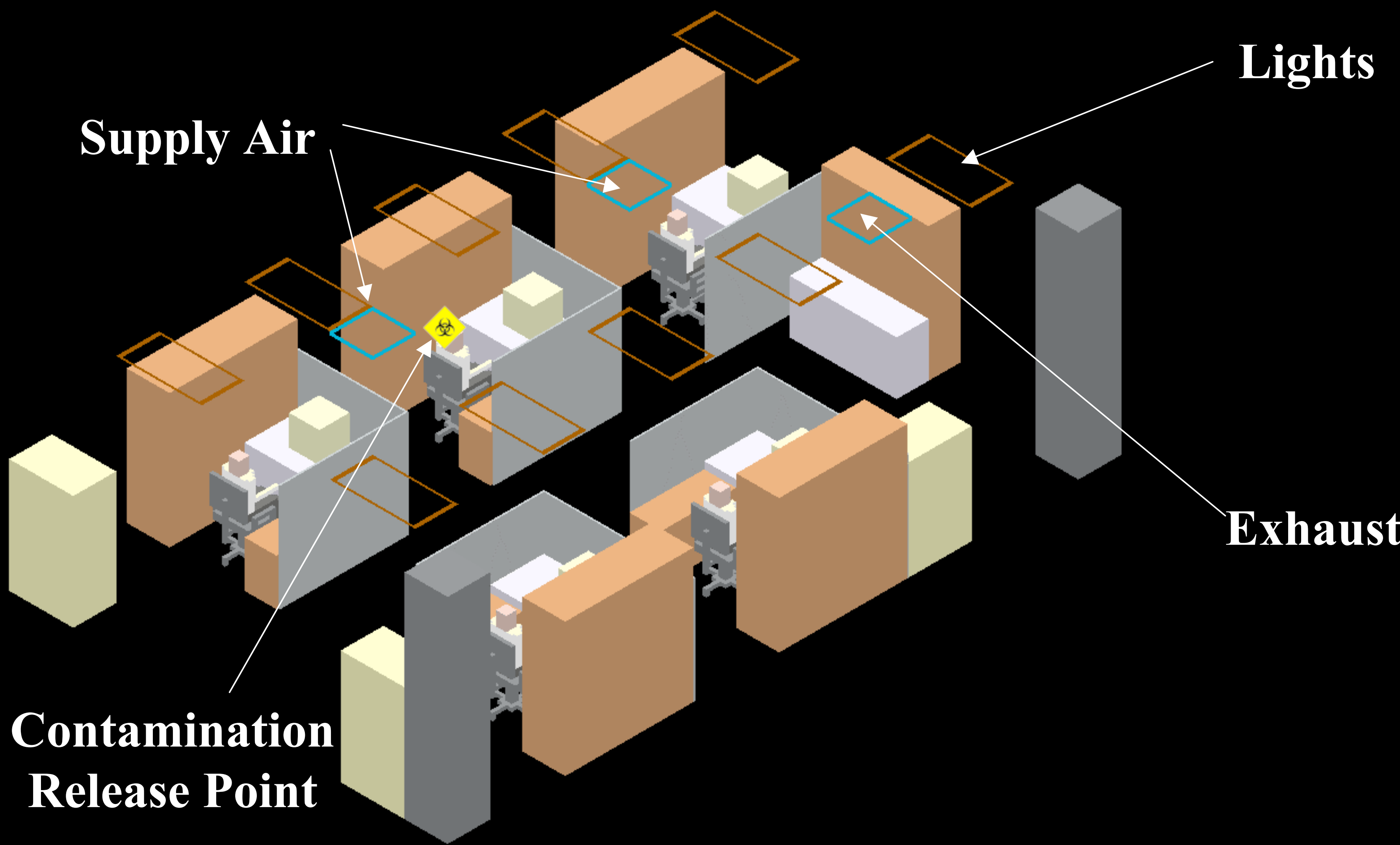




Indoor air quality contamination

One sneeze releases millions of droplets (of 1–4 µm) that may carry virus particles or bacteria

Typical office with 1.52-m partitions: Conventional mixing ventilation



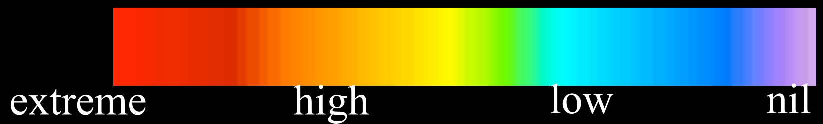
Conventional mixing ventilation

Occupant with cold in cubicle sneezes, or opens contaminated mail

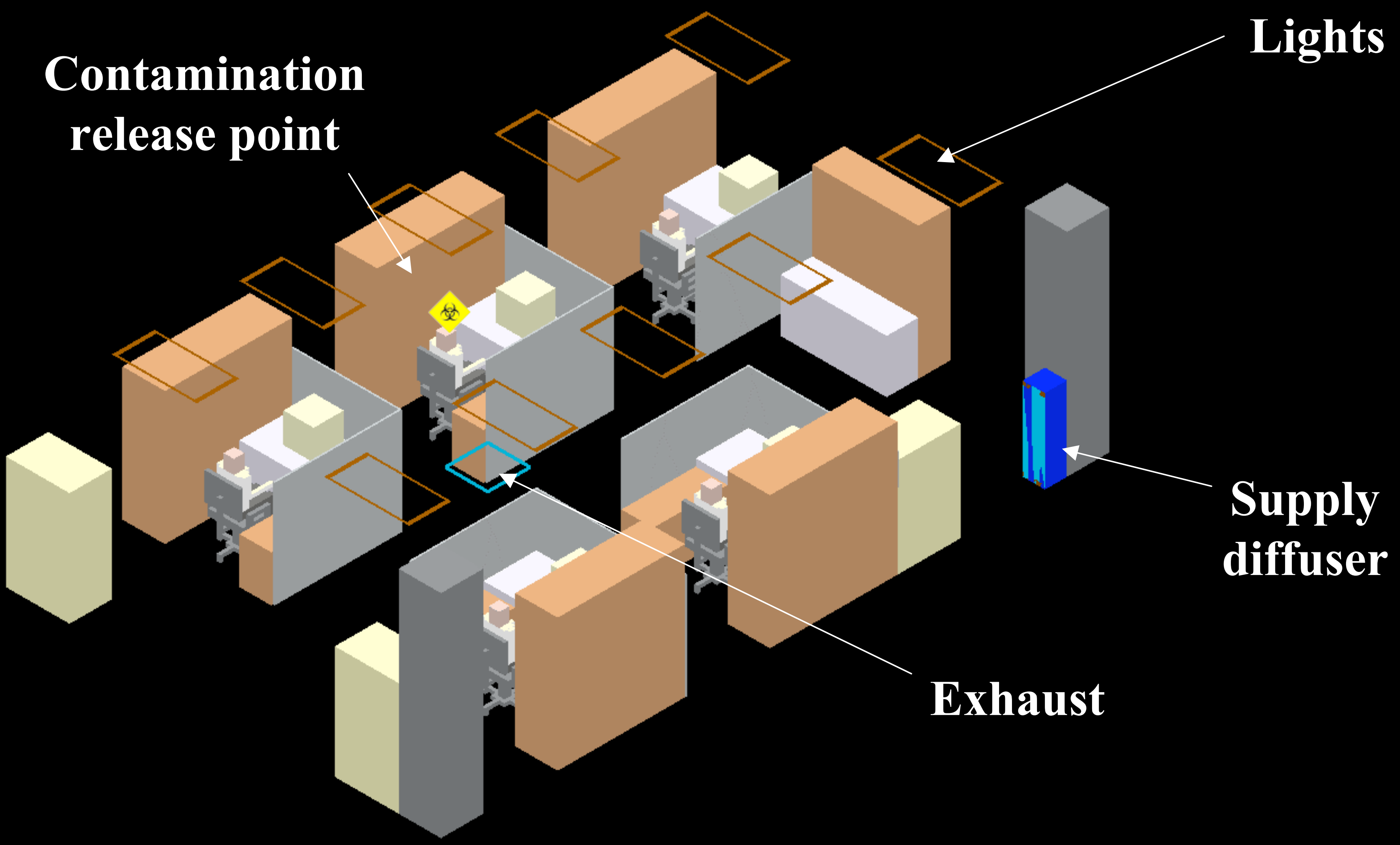
HBI

Animation courtesy of Malcolm Lewis, PE

Germ concentration

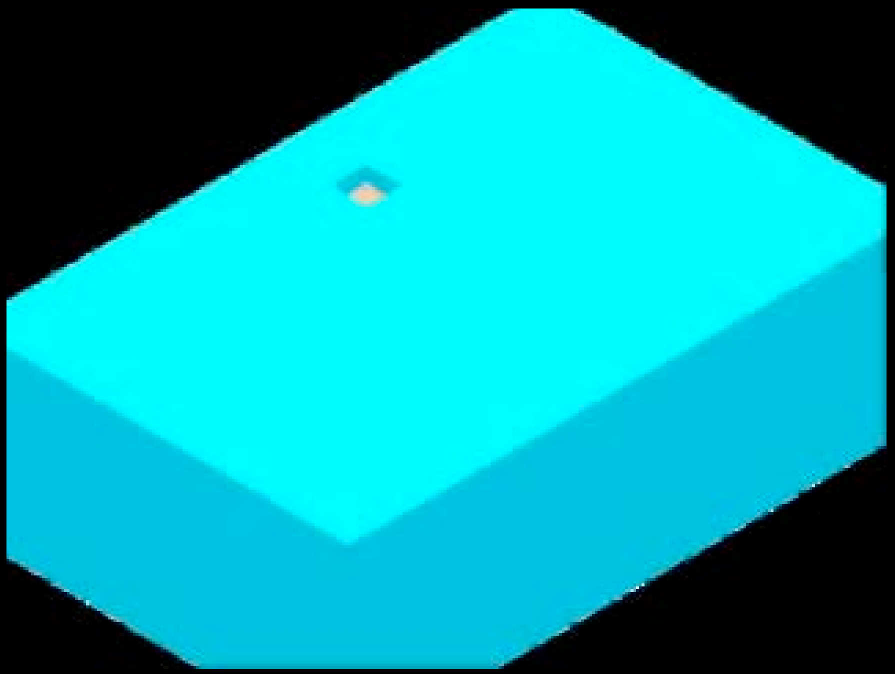


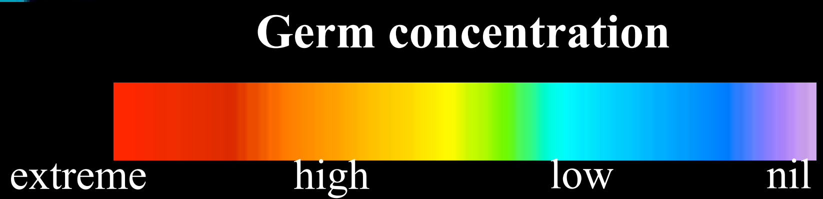
Same office with thermal displacement ventilation



Thermal displacement ventilation

Occupant with cold in cubicle sneezes, or opens contaminated mail





HBI

Animation courtesy of Malcolm Lewis, PE

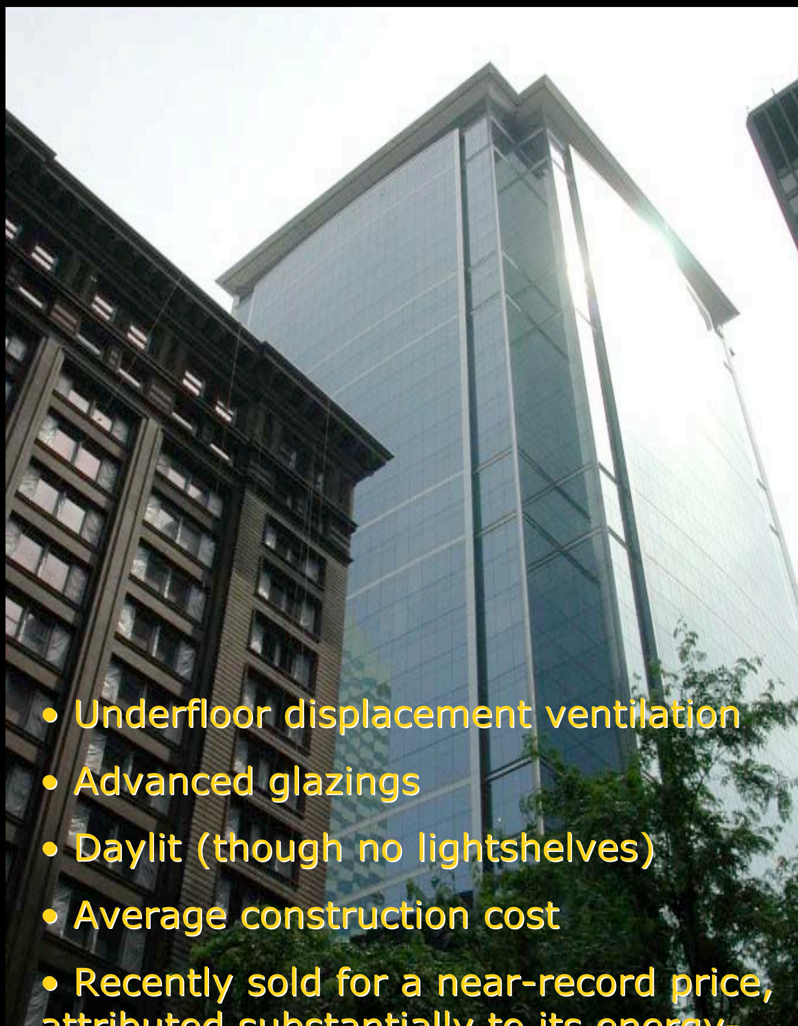
Displacement ventilation

- Once thought to increase capital cost (if built like specialized raised-floor computer centers)
- Now known to have comparable or lower total capital cost in offices (so why not hospitals, etc.?)
    - Can reduce or eliminate ducts
    - Avoids their pressure drop: smaller fans (TSH≤250 pA or 1" wg), smaller chiller to remove fan heat,…; so smaller chillers
    - Less chiller lift because supply air is 18 not 13°C (65 not 55°F)
    - Lower floor-to-floor distance (but higher ceilings)
- Can eliminate fan noise & permit individual control
- Needn't drizzle air up through the floor—can emit fresh air at baseboard level instead
- Should cut airflow, yet improve air quality & health

Banner Bank Building
Boise, ID (LEED Platinum)

- 18,122 m², 11 stories, novel beams
- 65% lighting electricity saving (*without* special daylight), 50% non-plug loads
- 80% water saving from innovative large-area neighborhood capture
- 35%/y ROI, $1.47M asset value, "no discernible extra cost" for LEED Platinum
- Far lower operating costs support rents comparable to buildings 20–30 y older
- Turnover costs reduced by ~$100/m²
- Next project expected to save another 50% of energy use, to ≤25% of baseline
- Developer Gary Christensen: "We don't talk of 'pushing the envelope'—that's so last century. Our motto is 'Stuffing the Envelope—Striving for Nothing.' And then when we get to Nothing, we'll strive to do even less. We like to think of ourselves as the ultimate slackers."

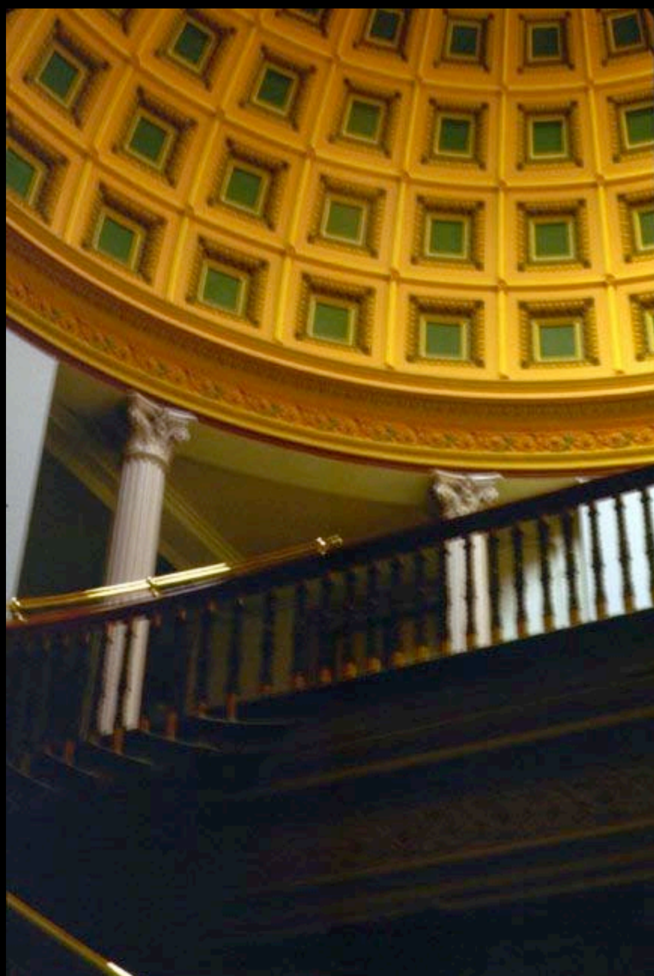
Even a REIT-financed Bank One (now Chase) ~150,000-m^2 Chicago tower



- Underfloor displacement ventilation
- Advanced glazings
- Daylit (though no lightshelves)
- Average construction cost
- Recently sold for a near-record price, attributed substantially to its energy-related design features

Greening the White House
Old Executive Office Building

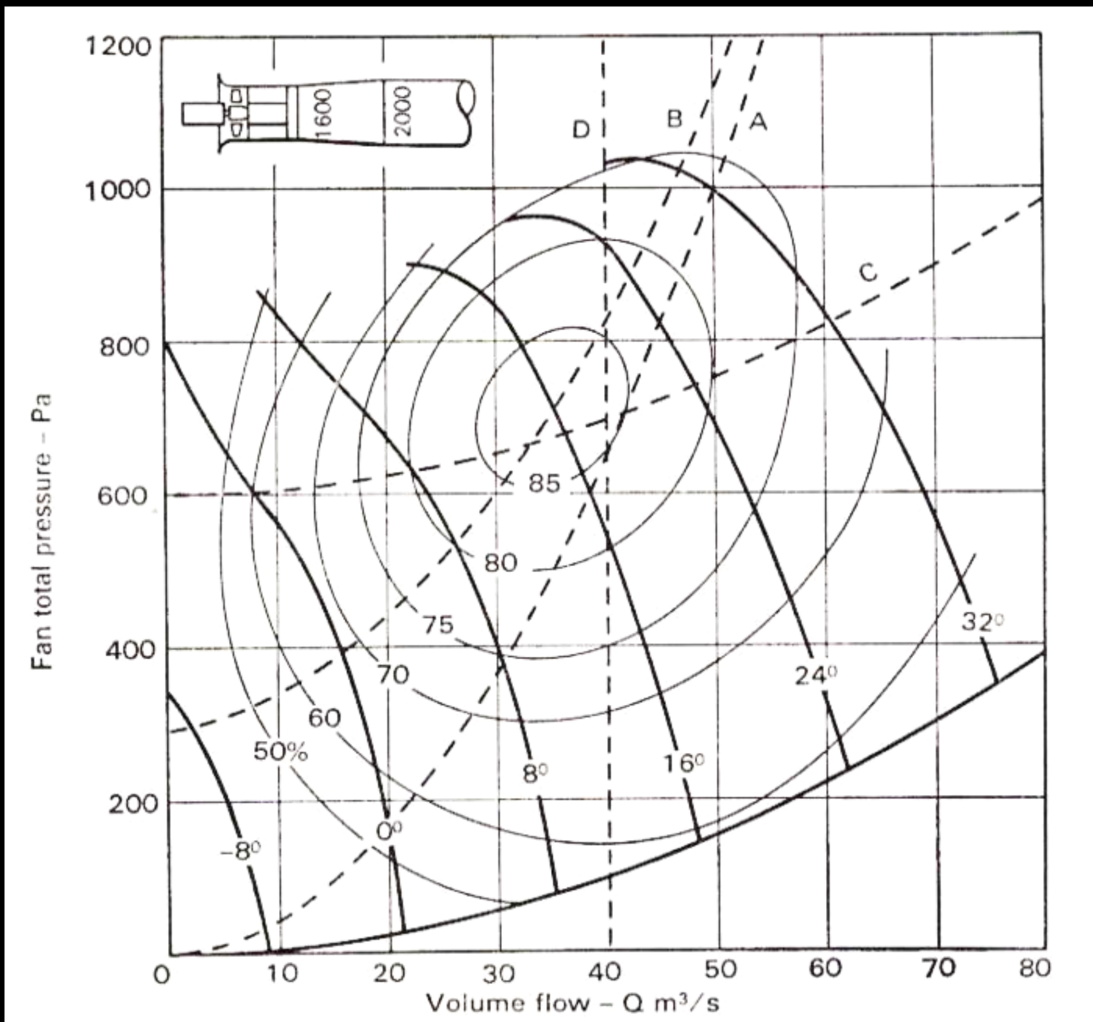
- Built in 1871
- **Passive cooling**
  - Vertical air chimneys in walls
  - Glass domed cupola drew hot air out
- Recent years: 782 window A/C units



Offices for Parliament
London

- Naturally ventilated
- Neo-Victorian style
- Arup design for 200-year lifespan

Not only ingredients but also the cook makes a great cake



The F-1 car to the left (85% efficient fan) will not win the race without Schumacher

—LEE Eng Lock

Whole-system design

Most people think efficient systems are about energy-efficient equipment and expensive gadgets.

This is like saying that using the best ingredients will ensure a tasty dish.

Efficient systems are actually the result of *whole-system design.*

Even the finest and rarest ingredients won’t make our dish tasty unless:

- we use a good recipe,
- combining the right ingredients,
- in the right sequence, manner, and proportions

The right steps in the right order: lighting

1. Improve visual quality of task
2. Improve geometry of space, cavity reflectance
3. Improve lighting quality (cut veiling reflections and discomfort glare)
4. Optimize lighting quantity
5. Harvest and distribute natural light
6. Optimize luminaires
7. Controls, maintenance, training

JohnsonDiversey
Sturtevant, Wisconsin

JohnsonDiversey (LEED-EB Gold)

Sturtevant, Wisconsin

$139/ft² first cost, 10–15% below average

$0.46/ft²-y energy cost *(79% lower than national average—$2.20/ft²-y)*

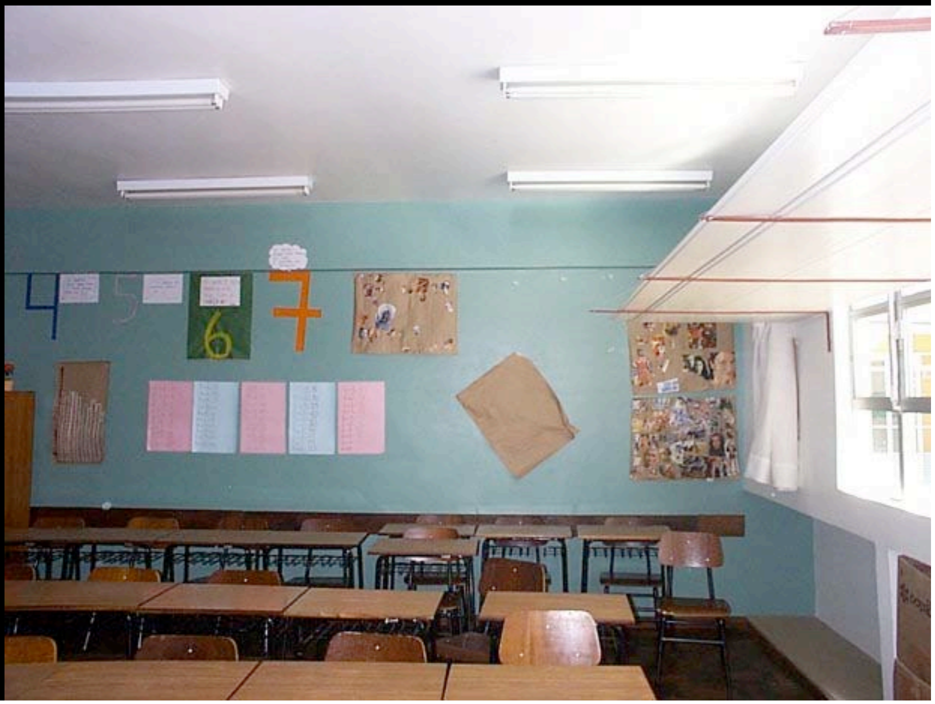
32,530-m² project was ahead of schedule and $4 million under budget

Schools in Curitiba, Brazil

- Of the two classroom window units on the top right, the second has a light shelf inside and outside

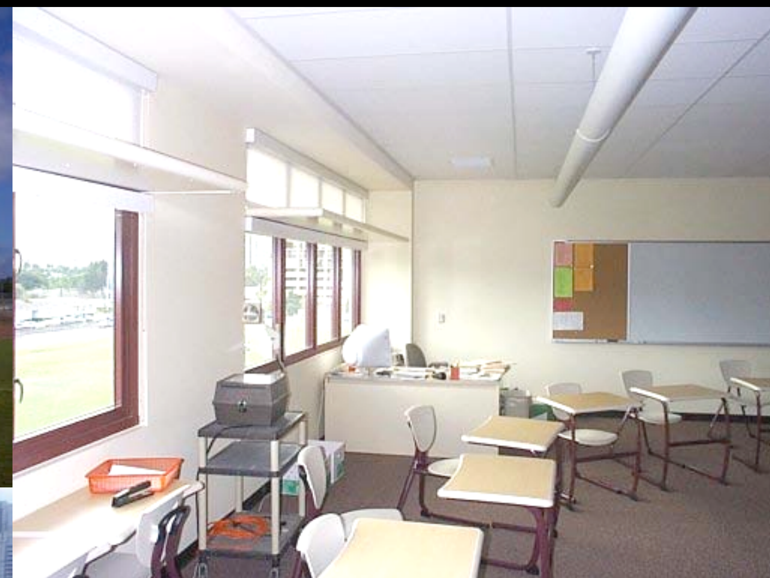
Curitiba Retrofit Experiment

- Top classroom with no lightshelf has high luminance ratios, making the room feel dark compared to the bright window
- Bottom classroom under same condition but with lightshelf appears bright with moderate luminance ratios
- No electric lights are on in either photo
- The lower room saves 75% of electricity, so that class can afford to buy books
- Students also learn ~20–26% faster in well-daylit classrooms
- What's the multiplier from education to national development?



Courtesy of Greg Franta FAIA, RMI/ENSAR Built Environment, Boulder, Colorado

‘Iolani School, O‘ahu, Hawai‘i



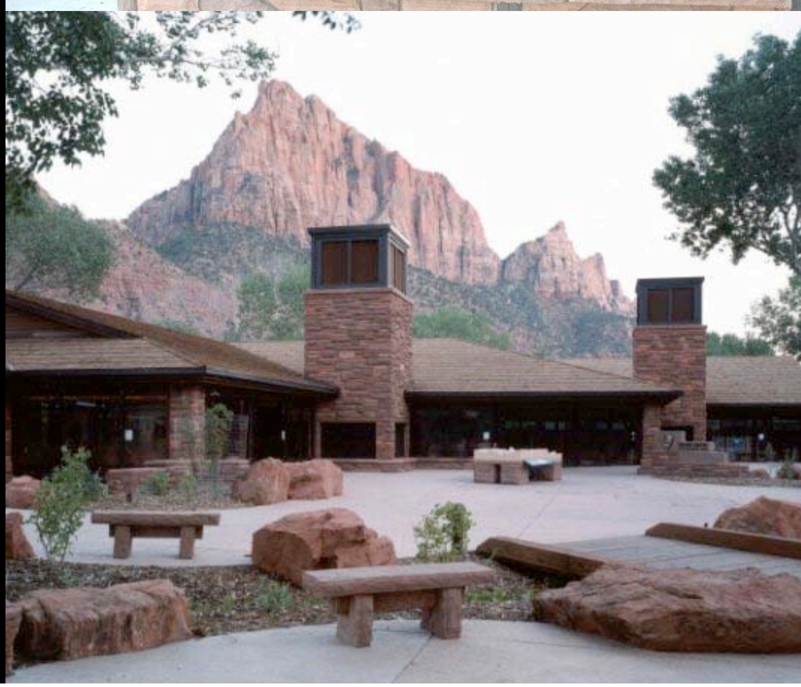
Interior & exterior lightshelves give exceptional daylight quality

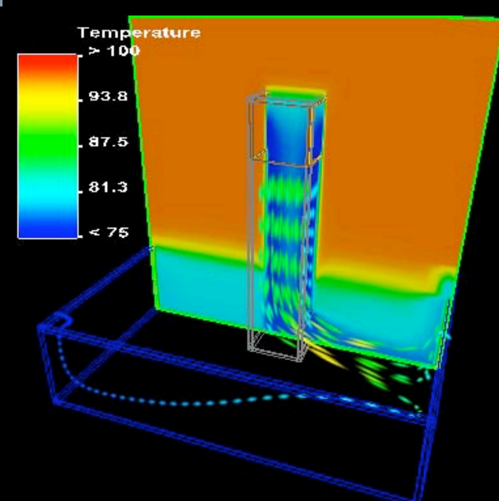
The right steps in the right order: space cooling

0. Cool the people, not the building
1. Expand comfort envelope (check assumptions!)
2. Minimize unwanted heat gains
3. Passive cooling
   - Ventilative, radiative, ground-/H_2O-coupling, icepond
4. Active nonrefrigerative cooling
   - Evap, desiccant (CDQ), absorp., hybrids: COP >100
   - Direct/indirect evap + VFD recip in CA: COP 25
5. ~~Superefficient refrigerative cooling: COP 6.8 (Singapore water-cooled centrifugal *system* @ design)~~
6. Coolth storage and controls
7. Cumulative energy saving: ~90–100%, better comfort, lower capital cost, better uptime

A worthy goal: extirpate hot-dry-climate refrigerative air conditioning, including big commercial (e.g., use NightSky, integrated with passive lighting & PVs)

Zion National Park visitor center (Springdale, Utah, 706 m^2), –30% capex

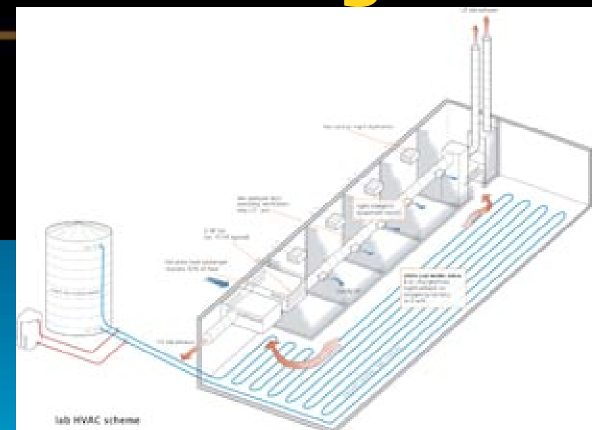


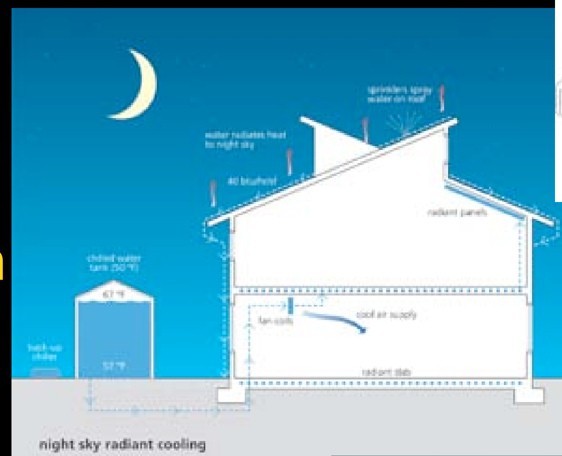


Persian draft towers for natural cooling, Trombe walls, & PVs save 30% of el. (~10 kW$_p$, ~$14k/y)

Stanford's Carnegie Institute for Global Ecology wet-lab building

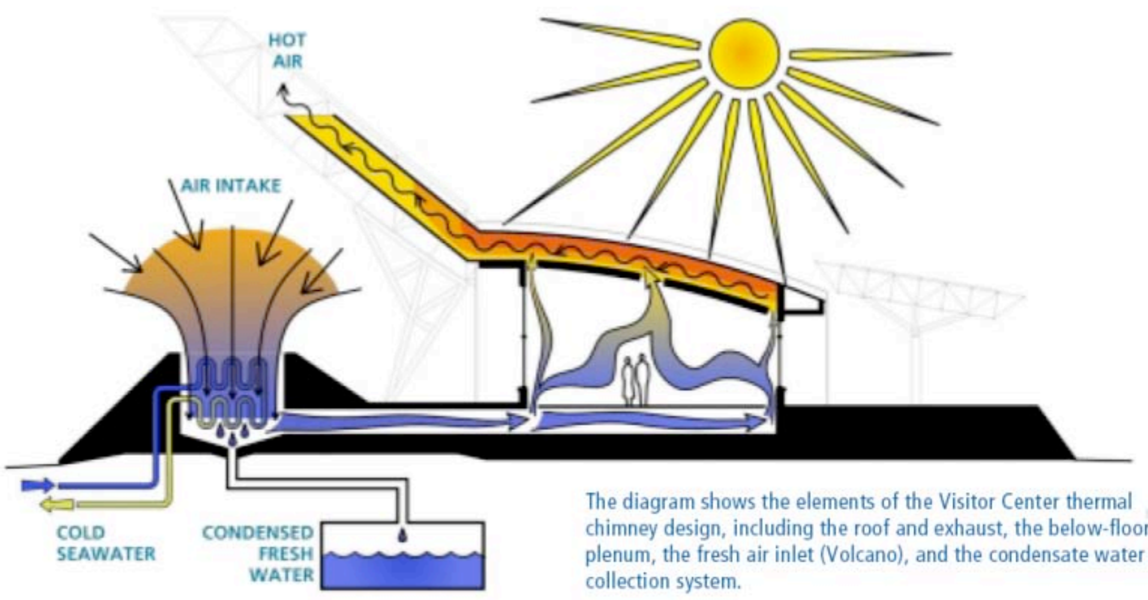
- NightSky (radiant roof spray), draft-tower, and air-economizer cooling, COP ≥50 (≤0.07 kW/t); wd improve with optimized pumping-system design
- Efficient shell, daylit, high occupant satisfaction
- Normal capital cost
- ~1/5 normal energy use, despite peculiar safety rules requiring high-rate ventilation of empty, dark labs
- This usage excludes server farm, whose efficiency is the next logical target





1,012 m^2, \$4,002/m^2 in 2004—normal cost; energy data posted at http://globalecology.stanford.edu/DGE/CIWDGE/CIWDGE.HTML

Natural Energy Laboratory of Hawai‘i, Kailua-Kona (LEED Platinum)



The diagram shows the elements of the Visitor Center thermal chimney design, including the roof and exhaust, the below-floor plenum, the fresh air inlet (Volcano), and the condensate water collection system.

- 335-m^2 visitor center, 2× net energy producer from 25-kW PV + fuel cell
- 8,600 site BTU/sf-y (very low, saves $25k/y)
- Deep seawater for space cooling, condensation irrigation, and sewage conveyance
- Solar chimney drives passive (fan-free) ventilation
- Water –73% in-/–100% outside

Not rocket science

Davis Energy Group, www.davisenergy.com

- Davis Star Mart (362-m^2 convenience store), Davis CA, installed an evaporative precooler coupled to 232 m of underfloor plastic tubing and a chip control
- Measured 50% energy saving worth $3,000/y
- Rooftop compressor unit downsized 33% to 10 t
- Net of that downsizing, a 0.9-y simple payback on $2,600 marginal cost

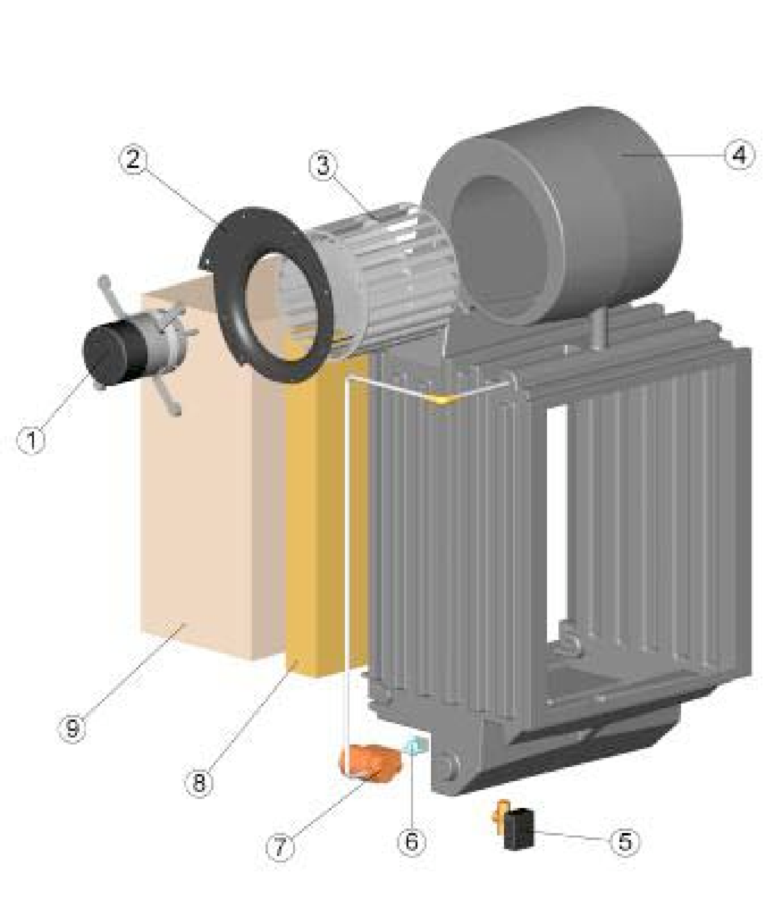
"…[A]ir conditioning can be eliminated in nearly half of California's climate zones and significantly down-sized in others, providing substantial energy and demand savings."

—Davis Energy Group *Outlook*, Winter 2004

80–90% California cooling energy and demand savings without active dehumidification (2003)

- EER-40–135 (COP 12–40) steady-state, depending on airflow
- 0.5-max-kW indirect-direct evaporative cooler replaces 2–3-ton refrigerative system
- 100% outside air
- CEC-funded Davis Energy Group development made by Speakman CRS

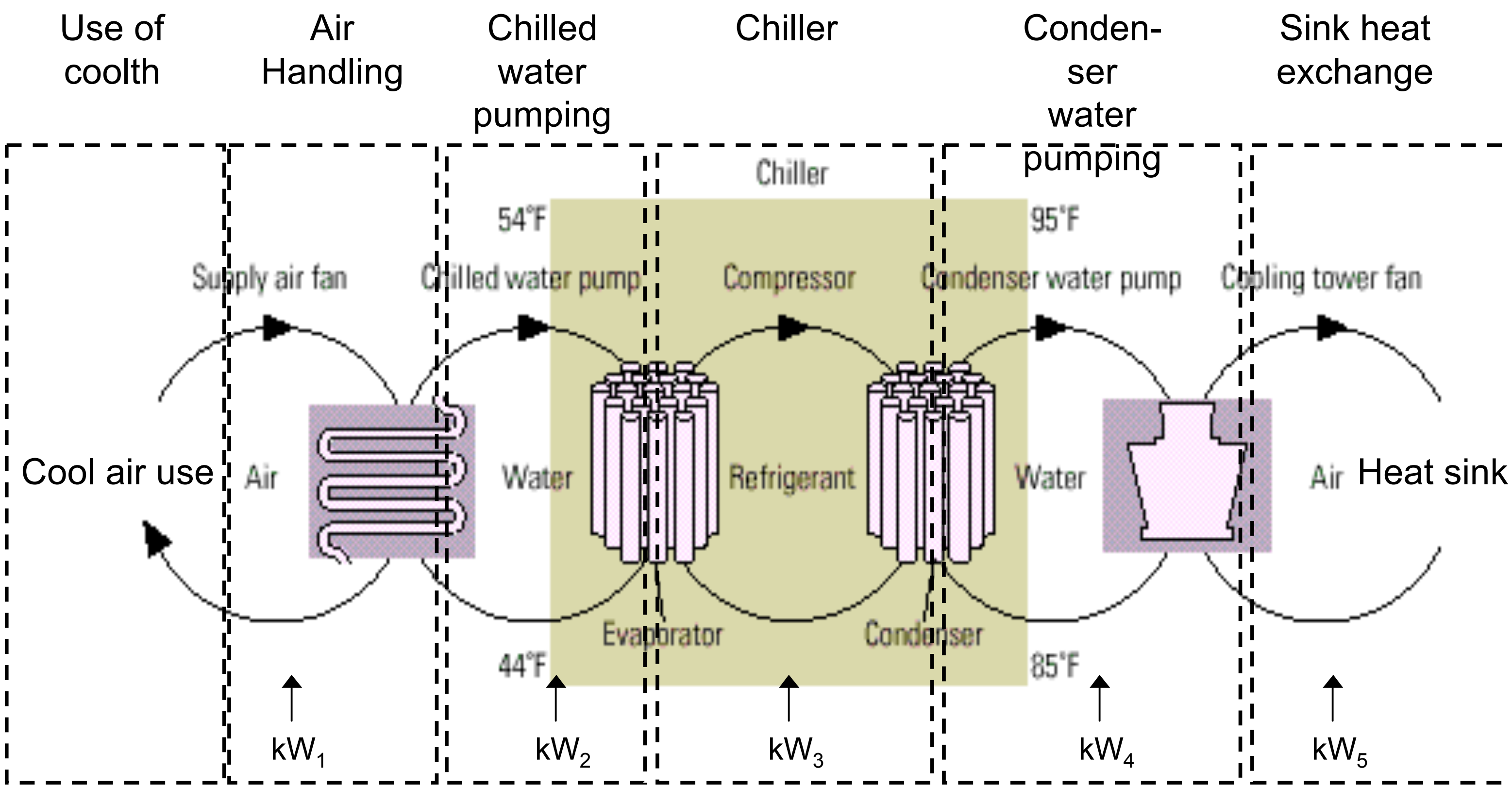
www.davisenergy.com, www.speakmancrs.com



1: 3/4-hp GE ECM2.3 variable-speed motor. 2. Venturi mounting plate. 3: Morrison 11–11 squirrel-cage blower. 4: polyethylene cabinet. 5: Drain valve. 6: Fill valve. 7: Taco 003 water circulator pump. 8: Munter's CELdek® direct cooling stage. 9: Speakman indirect cooling stage.

Overview of a large refrigerative chiller *system*

Efficiency basics: minimize friction and losses, operate very efficient components at variable speed, minimize the approach temperatures in all four heat exchangers so the chiller need do less work to produce the desired cooling effect



Cooling system kW/Ton $= \dfrac{kW_1 + kW_2 + kW_3 + kW_4 + kW_5}{Ton}$

Parasitic load to chiller $= kW_1 + kW_2 \approx 10\%$

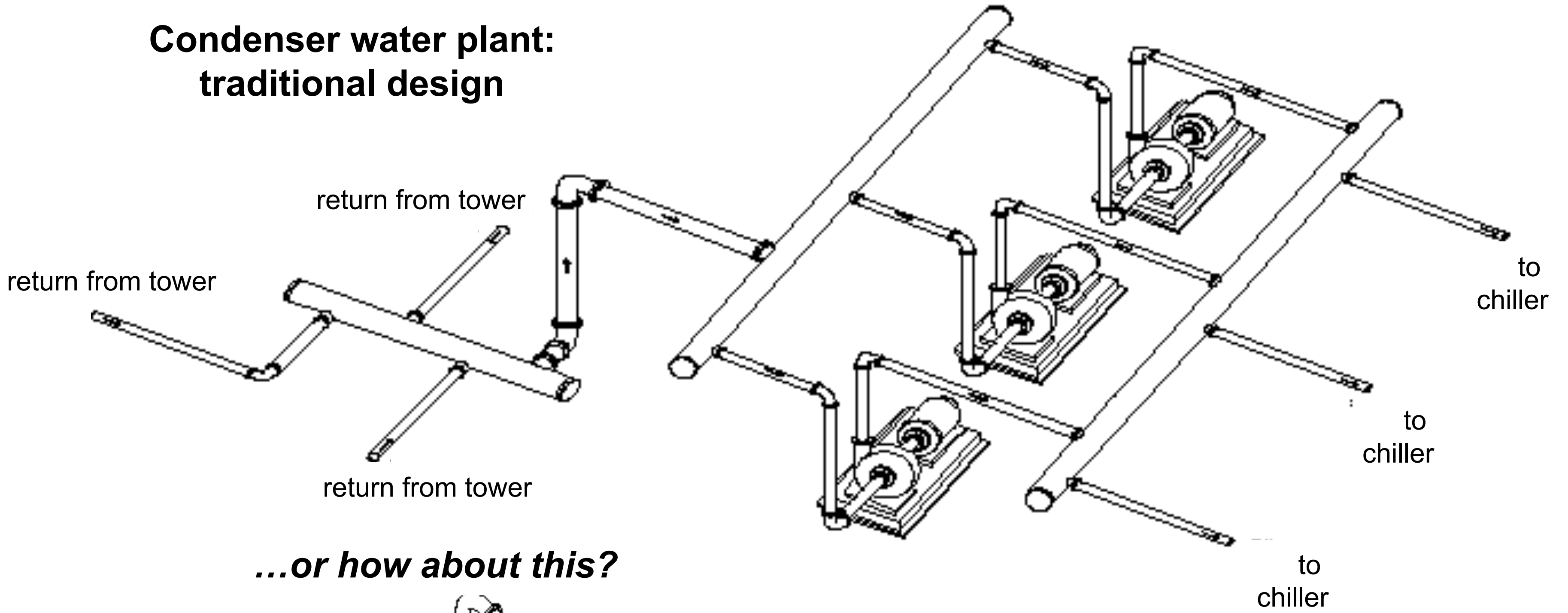
Superefficient big refrigerative HVAC too

(10^5+ m^2 water-cooled centrifugal, Singapore, turbulent induction air delivery — but underfloor displacement could save even more energy)

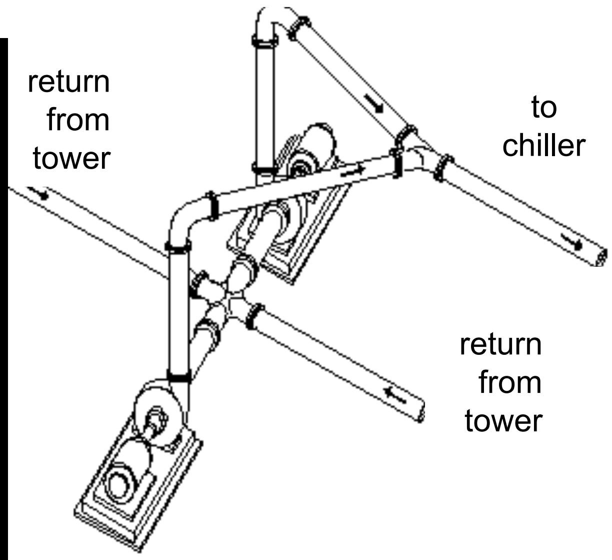
Element	Std kW/t (COP)	**Best kW/t (COP)**	**How to do it**
Supply fan	0.60	0.061	Best vaneaxial, ~0.2–0.7 kPa TSH (less w/UFDV), VAV
ChWP	0.16	0.018	120–150 kPa head, efficient pump/motor, no pri/sec
Chiller	0.75	0.481	0.6–1 Cº approaches, optimal impeller speed
CWP	0.14	0.018	90 kPa head, efficient pump/motor
CT 	0.10	0.010	Big fill area, big slow fan at variable speed
TOTAL	*1.75 (COP 2.01)*	*0.588 COP 5.98, 3× better)*	*Better comfort, lower capital cost*

(Best Singapore practice w/dual ChW temp.: **0.52 total kW/t** including 0.41 chiller, **COP 6.8**)

Which of these layouts has less capex & energy use?



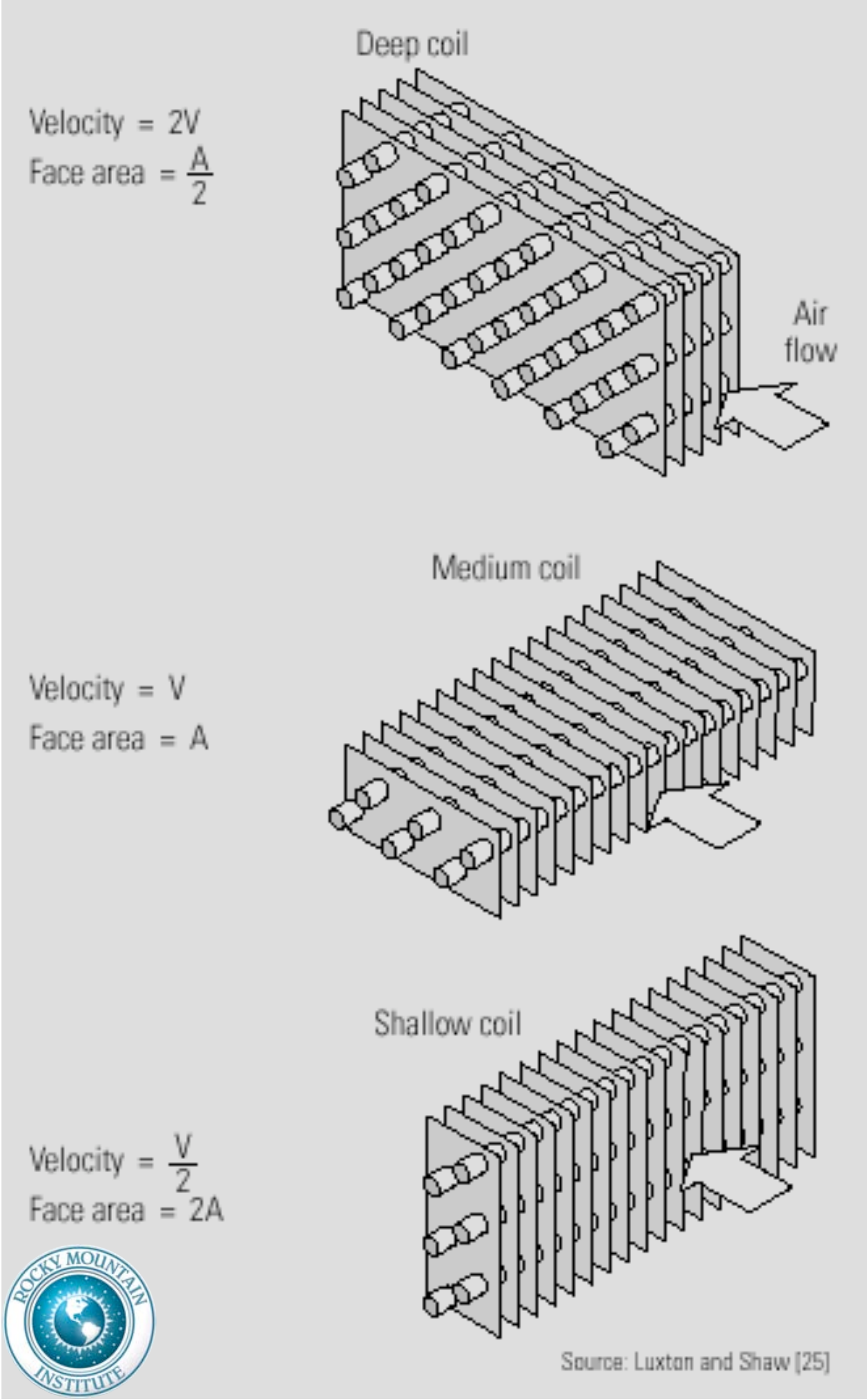
…or how about this?



- Less space, weight, friction, energy
- Fewer parts, smaller pumps and motors, less installation labor
- Less O&M, higher uptime

ROCKY MOUNTAIN INSTITUTE

RUMSEY ENGINEERS INC

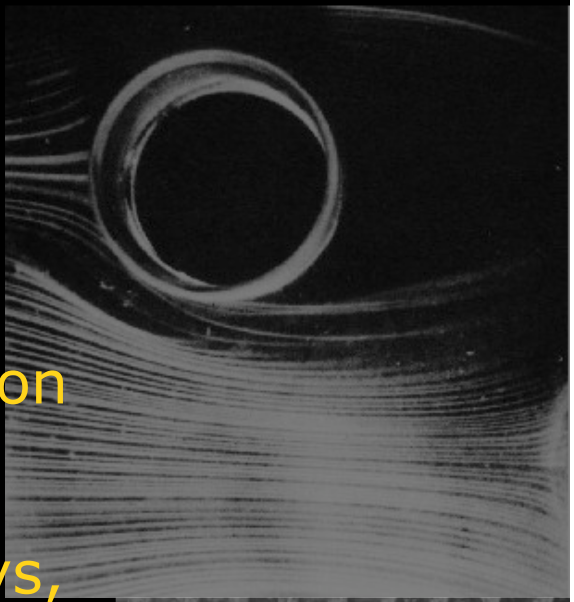


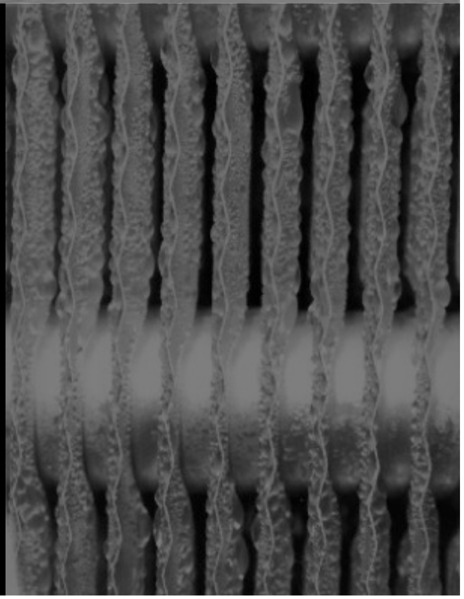
Source: Luxton and Shaw [25]

Low-face-velocity, high-coolant-velocity coils…

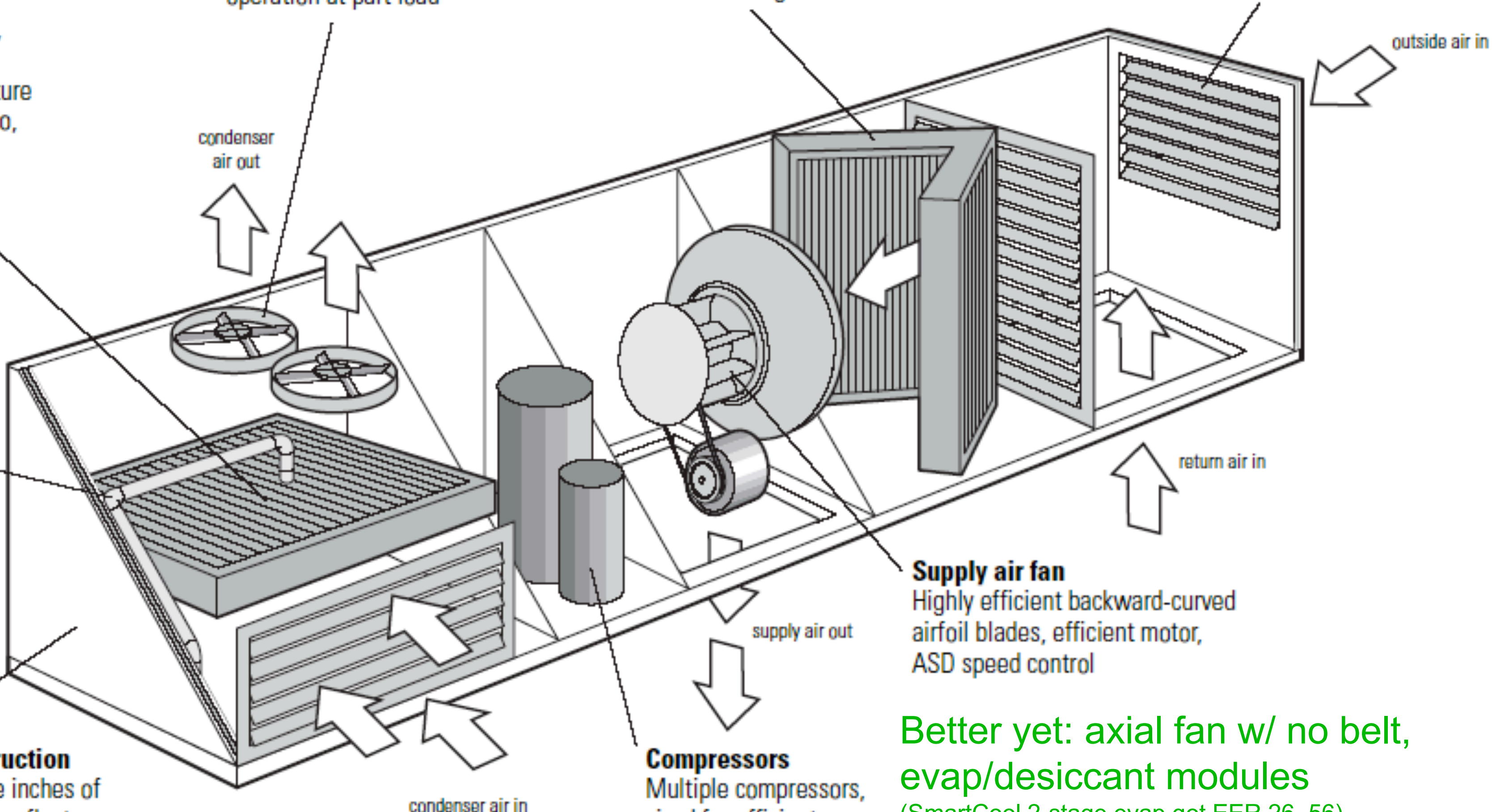
Correct a 1921 mistake about how coils work

Flow is laminar and condensation is dropwise, so turn the coil around sideways, run at <1 m/s (<200 fpm); 29% better dehumidification, airside ΔP –95%; smaller chiller, fan, and parasitic loads; lower total capex





Simple rooftop DX changes for seasonal EER 12.9 (COP 3.78), IPLV 17.7 (CIEE/USEPA prototype 1997)



Better yet: axial fan w/ no belt, evap/desiccant modules
(SmartCool 2-stage evap got EER 26–56)

E SOURCE *Space Cooling Technology Atlas*

Integrated office design

- RMI led design for Hines and Gensler
- Tightly integrated state-of-the-shelf choices
  - Deep daylighting, superefficient direct/indirect lighting, very efficient plug loads and HVAC
  - Underfloor displacement ventilation
  - No or almost no dropped ceiling
  - Tuned superwindows, careful shading/mass
  - Optimized structural bays
  - Optimized surface optics to reject solar heat

Integrated office design results

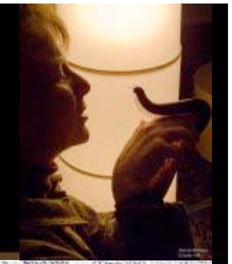
- Energy –50% without, or –75⁺% with, influence over tenant loads (approx.)
- 6 stories in 23 m lowrise limit, ceiling +15 cm
- Superlative lighting, thermal, & air quality
- Silent; individual worker air/thermal control
- Reconfiguration costs almost eliminated
- Same or slightly lower capital cost
- Simpler construction, 6 months faster

Benchmarking a new office

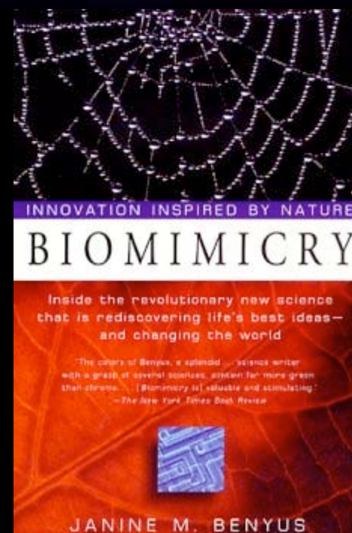
(~10,000+ m², semitropical climate)

	standard US	better	best practice
site MJ/m²-y	1,100	450–680	100–230
el. kWh/m²-y	270	160	20–40
lighting W/m²	16–24	10	1–3
plug W/m²	50–90	10–20	2
glazing W/m²K	2.9	1.4	<0.5
glazing T_{vis}/SC	1.0	1.2	>2.0
perimeter heating	extensive	medium	none
roof α, ε	0.8, 0.2	0.4, 0.4	0.08, 0.97
m²/kW_{th} cooling	7–9	13–16	26–32+
cooling syst. COP	1.85	2.3	6–25+
relative cap. cost	1.0	1.03	0.95–0.97
relative space eff.	1.0	1.01	1.05–1.06

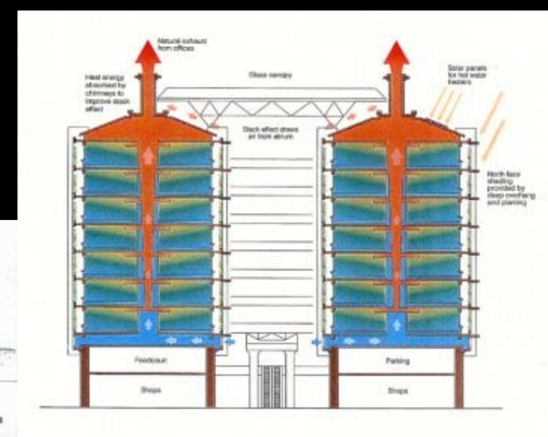
Climate-adaptive, not climate-excluding, building design

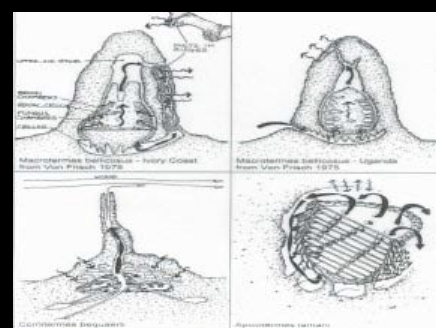


- Millennia of vernacular architecture have provided comfort in harsh climates all over the world, at low resource cost, benignly
- Now nature's 3.8 billion years of design genius can reveal ways to get our comfort, air, water, and light for free
- As always, the secret is integrative design—multiple coevolved functions for each element, harmoniously self-regulating



Sto Lotusan® paint sheds dirt just as lotus petals clean themselves





Eastgate (biggest commercial building in Harare, Zimbabwe), 13,600 m^2, passive office cooling/ventilation saving ~90%, halved total energy, same or better comfort, normal capex, 20% lower rents

10 m high, maintains 31±1˚C in 3–42˚C for termites' fungus-farming

K. Butti & J. Perlin, *A Golden Thread: 2500 Years of Solar Architecture & Technology*, Cheshire (Palo Alto) / Van Nostrand Reinhold (NY), 1980

www.biomimicry.net (The Biomimicry Institute)

Wider benefits at larger scale

- Light-colored roofs and pavements, plus shade trees and vegetation, to bounce solar heat away (1 urban tree ≈ 9 window air conditioners), could cool Los Angeles by ~6 F° (~4 C°)
- This would cut the city's cooling loads by ~20% (in addition to improved efficiency in the buildings and their cooling systems)
- It would also cut smog by ~12%, improving health
- Total indirect savings: ~$0.5 billion per year just in Los Angeles

Global drivers of building green

Materials: The building industry uses 3 billion tons/y of raw materials—**40%** of total global use

Energy: 40% of the world's energy is dedicated to construction and operation of buildings

Water: The building industry uses **16%** of global fresh water annually

People: The "built environment" is humanity's largest artifact…and North Americans spend over **90%** of their time indoors

"We shape our buildings and afterwards our buildings shape our lives."

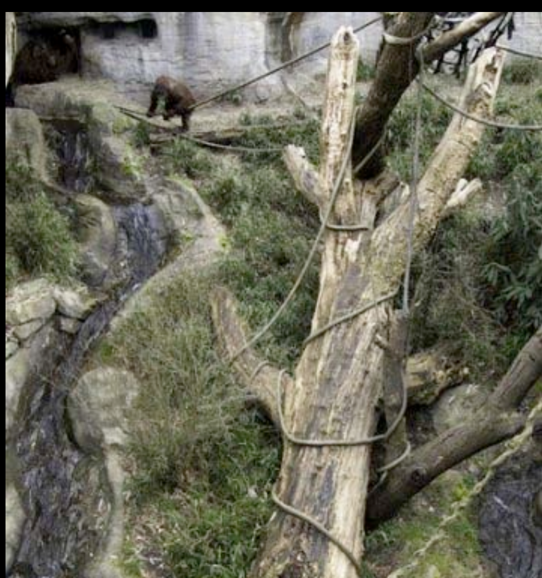
—Churchill

Shouldn’t our buildings…

- Make people healthier, happier, and higher-performing?
- Create delight when entered, well-being when occupied, regret when departed?
- Be designed for their last day of occupancy as much as their first day?
- Take nothing, waste nothing, and do no harm?
- Be net producers of energy, clean water, beauty, perhaps food, and right pedagogy?
- Cost less to build and operate?
- Be more flexible for unknowable future needs?

Zoos and offices, Victorian and now

(concept by Dr. Judith Heerwagen)



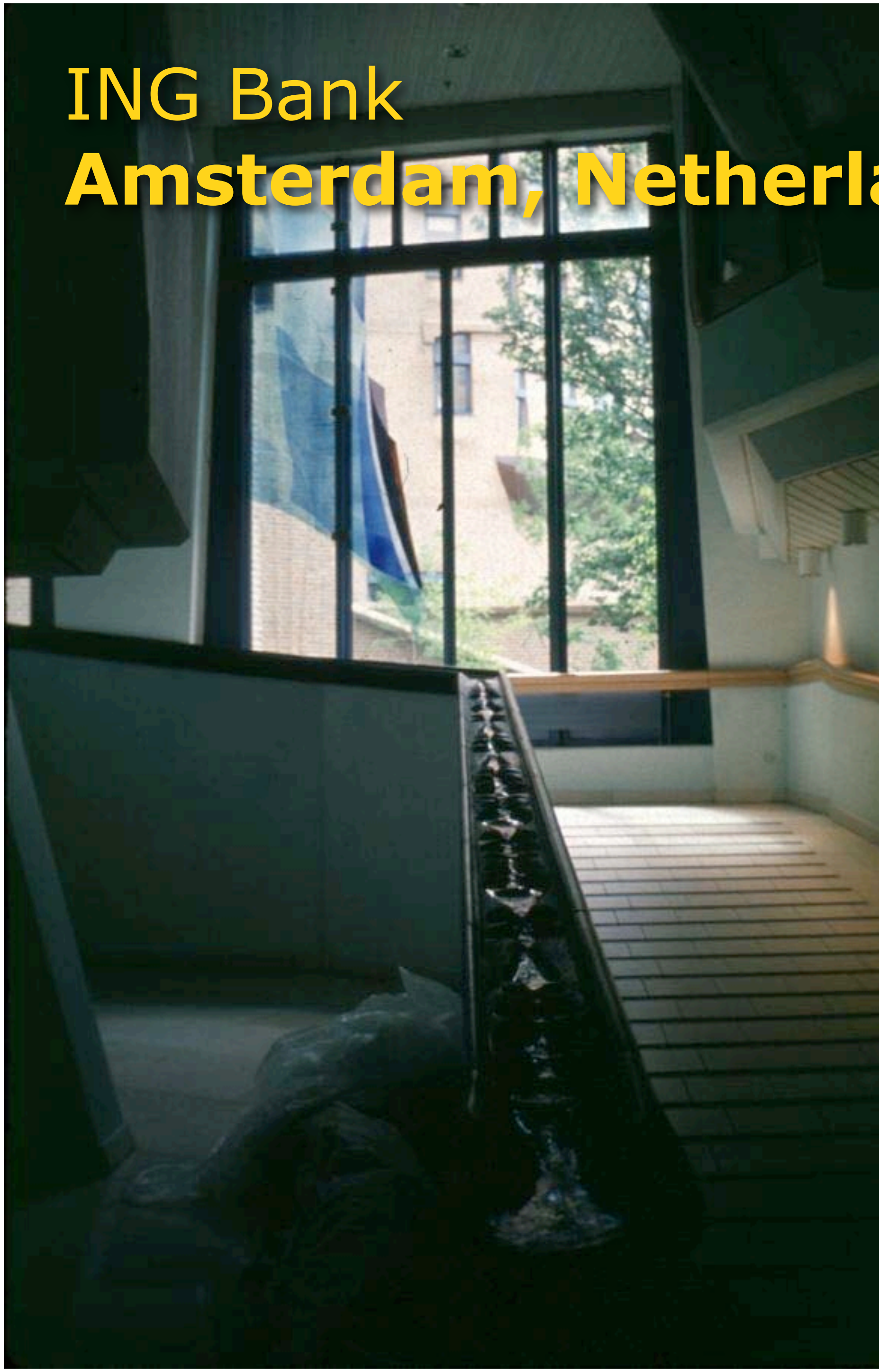
ING Bank

Amsterdam

- 50,200 m² in 10 meandering towers
- Sits on parking
- Harvests rainwater
- Active & passive solar collectors
- Operable windows
- Passive cooling; backup absorption chillers
- >90% energy saving
- 3-month payback
- ~15% higher productiv-ity & lower absenteeism

ING Bank
Amsterdam, Netherlands

ING Bank
Amsterdam, Netherlands



Biophilia

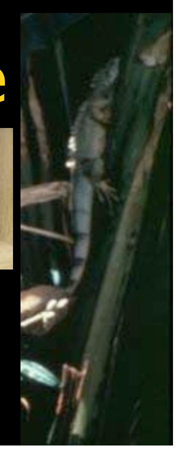
"The biophilia hypothesis boldly asserts the existence of a biologically based, inherent human need to affiliate with life and lifelike processes."

—*The Biophilia Hypothesis*, Stephen R. Kellert and Edward O. Wilson

Strong evidence is now emerging that human health, happiness, and productivity are much improved by biophilic design—including faster healing in biophilic health-care facilities

Why is my passive-solar banana farm so pleasant to be in?

- Natural light
- Curves (do you have corners?)
- α-tuned waterfall, no mechanical noise
- Good indoor air quality (construction + cleaning)
- High radiant / low air temperature, optimal humidity
- Moderately varying (not static) climate conditions
- Sight, smell, O_2, ions, & (optionally) taste of plants
- Ever-changing jungle scenery, interesting wildlife
- ?Very low 60-Hz electromagnetic fields
- Maybe other attributes we don’t yet know about



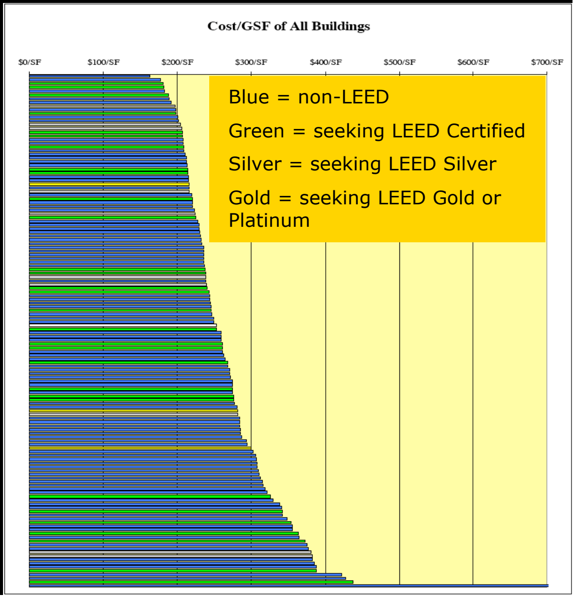
Do certified green buildings cost more?

G. Kats, *The Costs and Benefits of Green Buildings: A Report to California's Sustainable Building Task Force, Oct. 2003,* www.cap-e.com/ewebeditpro/items/O59F3259.pdf

- 33 diverse CA LEED buildings put up in past 10 y, averaged 1.84% extra capex (0 for five)
- Average benefits were 12–16× greater, yielding ROIs 25–40%/y (3-y average simple payback)
- Average 30% energy & 30–50% water savings—not yet tunneling through the cost barrier

L.F. Matthiessen & P. Morris, "Costing Green: A Comprehensive Cost Database and Budgeting Methodology," Davis Langdon, July 2004, graphed below:
www.usgbc.org/Docs/Resources/Cost_of_Green_Full.pdf#search=%27Costing%20Green:%20Davis%20Langdon

- Contrasted 45 LEED-seeking with 93 comparable non-LEED buildings, all normalized for time and location
- Found no statistically significant correlation between LEED status and construction cost (which varied widely for both), even for specific types—classrooms, labs, and libraries



My personal suspicion: LEED documentation does cost a bit, but evolving analysis will probably show that project capex correlates far less with green/non-green than with the experience of the design team

What about green schools?

100%-daylit corridor, North Clackamas High School (exterior shown top right), Oregon, 24,163 m^2, Heinz Rudolf FAIA, BOORA Architects (Portland OR)

G. Kats, *Greening America's Schools: Costs and Benefits*, *Oct. 2006*, *www.cap-e.com/ewebeditpro/items/O59F9819.pdf*

- 30 green schools built 2001–06 in 10 states
- Capex rose 1.7% (~\$3/ft^2); zero increase for 4 schools
- Net financial benefits are \$74/ft^2, of which \$12/ft^2 flow directly to the school district: \$9 energy, \$1 water/waste-water, plus teacher retention and reduced health costs
- Other benefits flow to society, including totals of \$8 health improvements* and \$49 increased earnings

**E.g.*, 17 studies, not specific to schools, have found 14–87% (av. 41%) health gains from better indoor air quality

Opportunities for Stanford to lead

- Green design and construction
  - Works better, builds cheaper, lasts longer
  - Higher return at lower risk than even the endowment portfolio
  - Happier, healthier, more productive people
- Green operations, purchasing,…
- Avoid regulatory/community hassle (air/water/…)
- Stretch local resources (electricity, water, roads)
- Boost local economy via richer linkages
- Speed national move to climate-neutral
- Building as pedagogy (*all* buildings teach; what lessons will be learned here?
- Student and staff engagement, outreach, emulation
- Moral obligation

What does it take?

- Clear, strong leaders who get it
- Vision across boundaries
- Be careful, prudent, persistent, fearless
- Strong transdisciplinary design team
  - Hire the right people, especially the MEs
- Inclusive charrette process
- Specify component & system performance
- Measure to make sure you achieve goals
- Meticulous, unflagging attention to detail
- Performance-based design fees
  - Keep “value engineers” at bay

Performance-based design fees

- Corrects *one* of the roughly two dozen perverse incentives that have made the U.S. misallocate $1 *trillion* of capital just to air-conditioning
- Get paid for what you save, not what you spend
- Five successful experiments, simple protocol*
- Use models (Energy10, DOE-2,…) to back out changes in weather, occupancy, etc.
- Balanced rewards/penalties for over/under-performance *vs.* preset target (code or better)
- Distinguishes the best designers in the market
- Maybe "wellness doctor" relationship afterwards?

*www.rmi.org/sitepages/pid174.php#D04-23 or www.archenergy.com/library/general//perfcntr.doc

Extraordinary growth in green building adoption

- 5,562 projects totaling 867 million square feet are registered for the LEED certification process as of March 2007
- U.S. Green Building Council's organizational members numbered 10 in 1995, 570 in 2000, 6,500 in 2005, 7,500 in 2006…
- In some markets like Seattle, it's reportedly hard to get a construction loan for a new office that's not at least LEED Silver—because lenders perceive too much risk it won't rent

The secret of great design integration:

No Compromise!

- Design is *not* the art of compromise and tradeoff—how not to get what you want
- J. Baldwin: "Nature doesn't compromise; nature optimizes. A pelican is *not* a compromise between a seagull and a crow." It is the best possible pelican (so far)—and after 90 million years, that's a pretty good one

The need for compromise is generally a symptom of misstated design intent

Helpful design hints

- You can only get to simplicity through complexity. — Anon.
- I wouldn't give a nickel for the simplicity on this side of complexity, but I'd give my life for the simplicity on the *other* side of complexity. — Einstein
- Everything should be made as simple as possible…but not simpler. — Einstein
- Perfect simplicity is not when there's nothing left to add, but when there's nothing left to take away. — St.-Exupéry
- How did I sculpt *David*? I just chiseled away everything that wasn't *David*. — Michaelangelo
- Seek the pattern that connects. — Bateson
- You know you're on the right track when your solution for one problem accidentally solves several others. — Corbet
- Avoiding problems is even better than solving them. — Lovins
- All the really important design errors are made on the first day. — Design proverb

Green design: let's try it, measure it, make it better, and learn quickly

Spring Term project course #CEE 273R will offer 21 select students from this course the opportunity to apply these concepts to all Stanford buildings

www.rmi.org

Thanks to my farflung design and development colleagues—especially the RMI/ENSAR Built Environment Team led by Greg Franta FAIA, gfranta@rmi.org