Physics and Energy

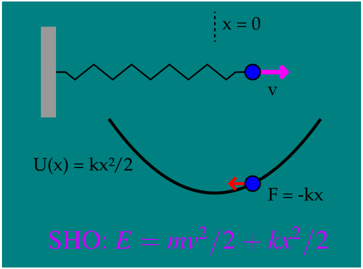
KITP colloquium

November 6, 2019

Washington Taylor

MIT

Energy is a central concept in physics



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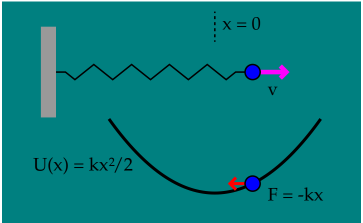
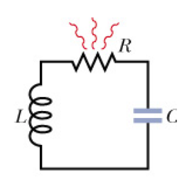


SHO: $E = mv^2/2 + kx^2/2$

[http://www.phys.ufl.edu/courses/phy2049/f07/lectures/2049_ch31A.pdf]



$$\frac{d}{dt}(LI^2/2 + Q^2/2C) = -I^2R$$

Follow energy flow → understand system

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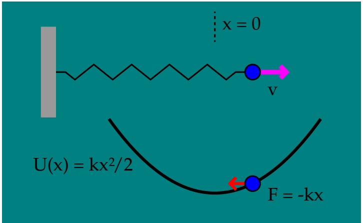

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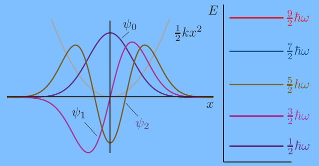

Quantum SHO: $E_n = (n + 1/2)\hbar\omega$

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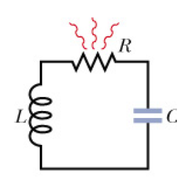

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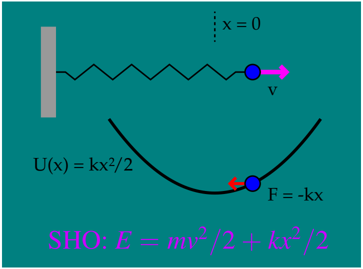

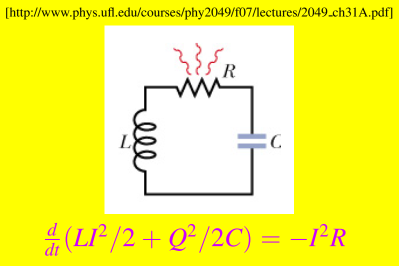

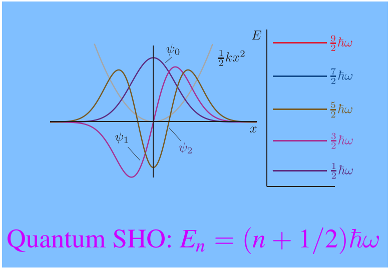

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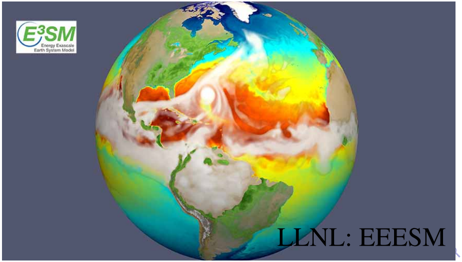
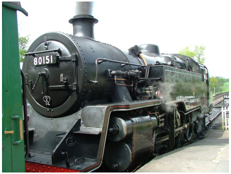


Energy science/technology have enabled development of modern civilization



[images: publicdomainpictures.net]

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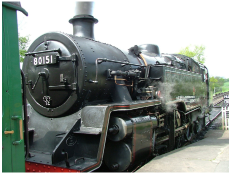

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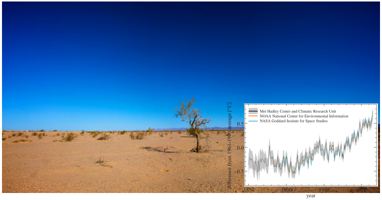
Human energy use → a central challenge of the 21st century



Rising temperatures

[publicdomainpictures.net]

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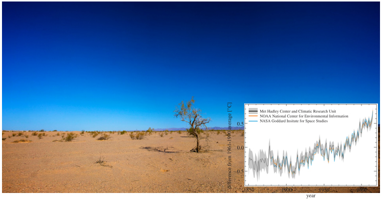

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Rising seas

[USA Today]

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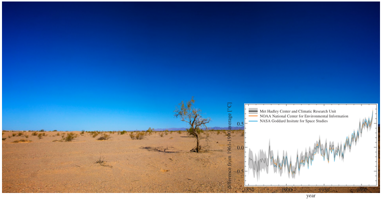

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More extreme weather events

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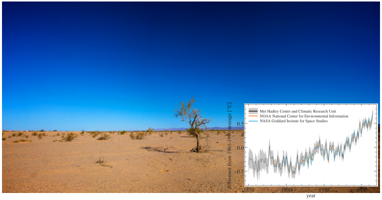

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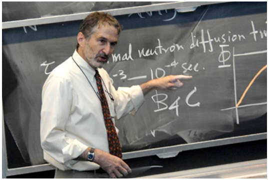
Ocean acidification

[API.com]

10 years ago … Robert Jaffe and I started teaching a course to MIT undergraduates on “The Physics of Energy”



Goals:

1) Introduce students with freshmen physics background to the basic scientific principles of energy systems: sources, conversions, storage, uses, and effects like radiation and climate change

2) Use energy as a theme to introduce and unify modern physics

Target audience: MIT undergrads in all majors

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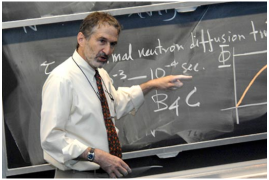

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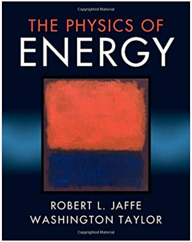
Last year: Published textbook evolved from course notes



Neither Bob Jaffe nor I specialize in research related to practical energy systems.

But we believe that energy is an important topic and should be included in relevant ways in physics curricula

Primary messages of this colloquium

1. Physical science lies at the core of real-world energy systems and problems

2. As physical scientists we should understand energy systems
   Most of the physics needed is fairly simple!

3. We should educate others about energy science

Solving the world's energy and climate issues is primarily at this point a political, economic and social challenge.

But the right decisions and directions must be informed by sound science, and we as physicists are in the best position to explain and educate people about this science.

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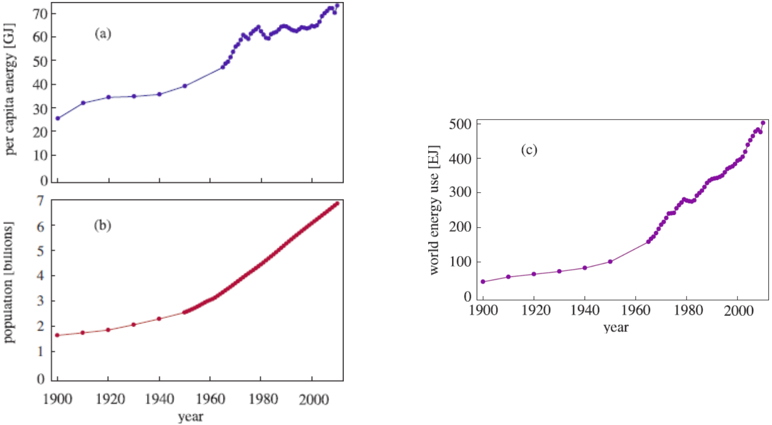
Outline

1. Energy and climate

Human energy “use” has tripled in the last 50 years



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Per cap. U.S.: $\sim$ 1 GJ/day (global $\sim$ 0.2); Human food energy: $\sim$ 10 MJ/day

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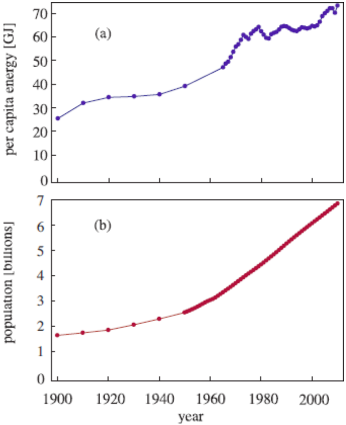

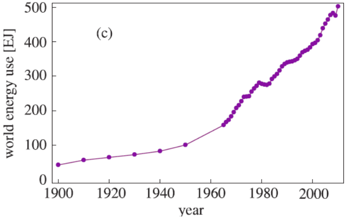

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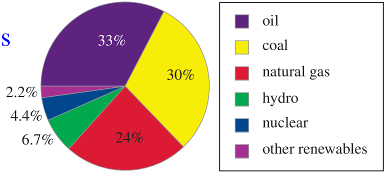
Roughly 85% of energy from fossil fuels

2014 world primary E consumption:



- Fossil fuels abundant, compact source of energy
- Enough resources for ∼ 200 years at current use rate
  (with interconversions, tar sands, oil shale, etc.)
- Big infrastructure built up, economically efficient
- Some pollution issues (car exhaust, mercury, mine tailings etc.)
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- Biggest issue: greenhouse gas (CO_2, methane) emissions and climate

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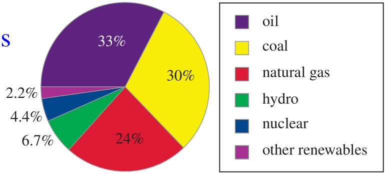

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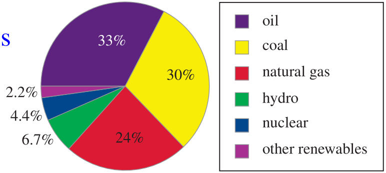

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Climate: mean Earth surface temperature is a good proxy

Regulated by a nice piece of physics: Radiative balance $P_{\text{out}} = P_{\text{in}}$.

Total solar power on Earth: $P_{\text{total}} = \pi R_{\oplus}^2 I_{\odot} \cong 173\,000$ TW ($I_{\odot} \cong 1\,366$ W/m^2)
Roughly 16% is reflected by Earth's surface (surface albedo $a = 0.16$)

Assume: Only O_2, N_2 in atmosphere, homogeneous temperature,
Earth radiates as a blackbody (perfect emission), $a = 0.16$

Earth radiates at a temperature T where (Stefan Boltzmann law)
$P_{\text{out}} = \sigma T^4 A = P_{\text{in}} = (1-a) I_{\odot} \times A/4$, where $\sigma \cong 5.67 \times 10^{-8}$W/m^{2}K^4
$\Rightarrow T \cong 267$ K $\cong -6\,^\circ$C

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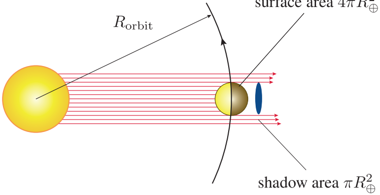

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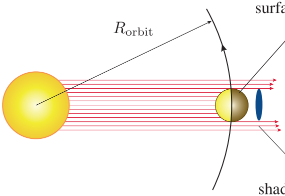

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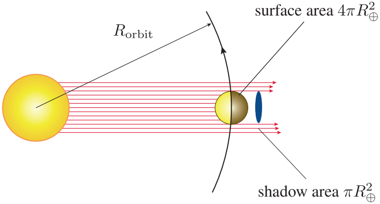

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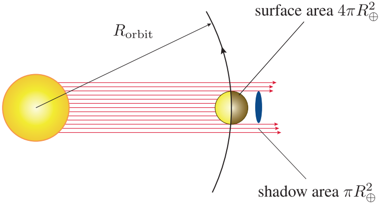

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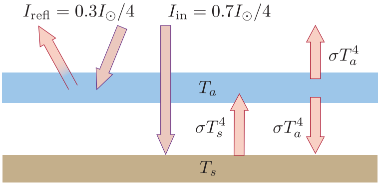
Greenhouse effect: raises surface temperature

Water, CO_2, … in atmosphere absorb and re-radiate outgoing thermal radiation



Simplified model: single-layer atmosphere
atmosphere absorbs outgoing IR radiation
total albedo $a = 0.3$ (actual w/ atm.)

Gives $T_s \cong 30\,^\circ\mathrm{C}$

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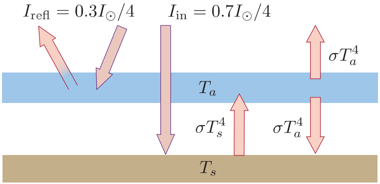

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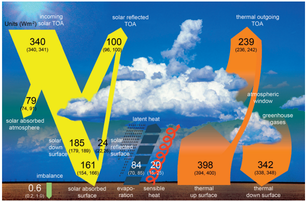


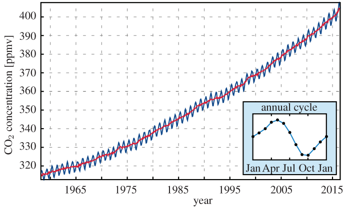
Actual radiative balance numbers

Only some frequencies absorbed;

Single-layer imperfect approximation

$T_s \cong 14\,^\circ\text{C}$

Changing CO_2 levels



How does this affect radiative balance?

CO_2 absorption spectrum well understood (wavelength dependent)

Simple calculation: given current atmospheric configuration,
Doubling $CO_2 \rightarrow \Delta F_{2\times} \cong 3.7\ \mathrm{W/m^2}$ (radiative forcing: $\downarrow$ flux at tropopause)

Direct effect (uniform temperature response) $\Delta T_{2\times}^{(\mathrm{direct})} \cong 1.2\,°\mathrm{C}$
(shifts σT^4 to match forcing)

This basic effect has been understood for $\sim$ 100 years (e.g. Arrhenius)

No question: CO_2 is going up, Earth's temperature will increase.

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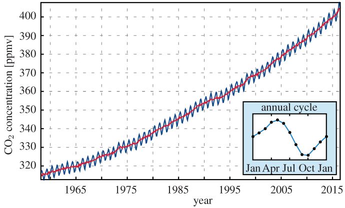

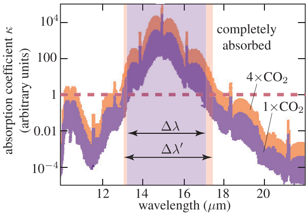

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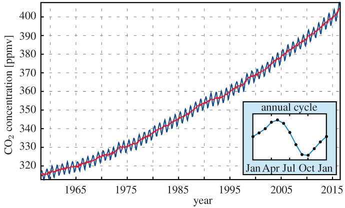

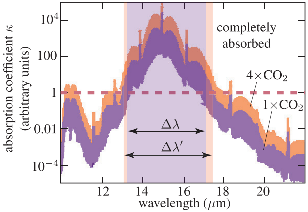

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No question: CO_2 is going up, Earth's temperature will increase.

Big question: how much warming will actually happen?

Feedbacks: devil is in the details.

e.g. Ice albedo: higher temperature $\rightarrow$ melting ice $\rightarrow$ more forcing

Climate is a complicated, nonlinear system

Linear feedback analysis: $F \rightarrow \Delta T_0, \quad \Delta F_1 = \lambda \Delta T_0, \ldots$

Geometric series: $\Delta T = \Delta T_0 + \Delta T_1 + \cdots = -\frac{1}{\lambda_0 + \lambda} F$

Planck feedback parameter $\lambda_0 \cong -3.2 \pm 0.1$ W/m^2 °C ($\leftrightarrow$ uniform T response)

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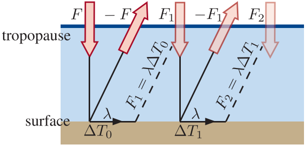

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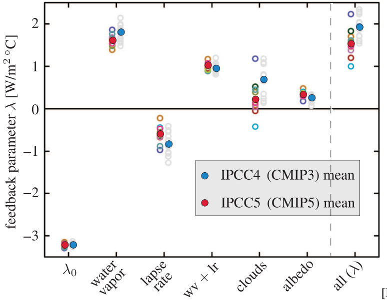
Feedback estimates from general circulation models ($\sim$ 20 GCM's)



[IPCC]

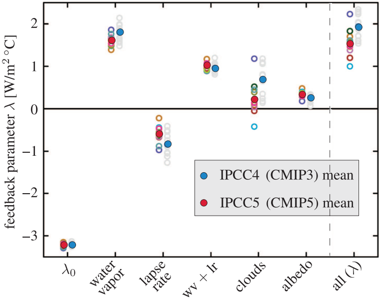
Upshot: estimate total $\lambda \cong 1.6$ W/m$^{2\circ}$

So equilibrium climate sensitivity $\sigma = \Delta T_{2\times}/F_{2\times}$ is approximately $\sigma^{\text{linear}} = -\frac{1}{\lambda+\lambda_0} \approx 0.6\,^\circ$C/(W/m^2), in linearized approximation

IPCC estimates $\Delta T_{2x} \cong \sigma F_{2x} \cong 3.2\,^\circ\text{C} \pm 1.3\,^\circ\text{C}$

($\sigma \approx 0.9 \pm 0.5\,^\circ$C/(W/m^2)) including nonlinear effects)

Feedback estimates from general circulation models ($\sim$ 20 GCM's)



[IPCC]

Upshot: estimate total $\lambda \cong 1.6$ W/m$^{2\circ}$

So equilibrium climate sensitivity $\sigma = \Delta T_{2\times}/F_{2\times}$ is approximately $\sigma^{\text{linear}} = -\frac{1}{\lambda+\lambda_0} \approx 0.6\,°$C/(W/m^2), in linearized approximation

IPCC estimates $\Delta T_{2x} \cong \sigma F_{2x} \cong 3.2\,°\text{C} \pm 1.3\,°\text{C}$

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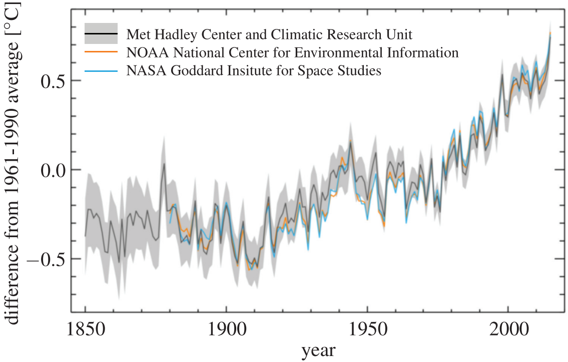
Data on temperature



Estimated average global surface temperature anomalies from three sources.

- Some controversy but pretty solid numbers.
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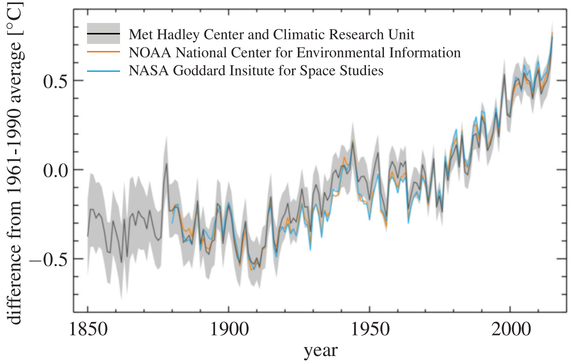

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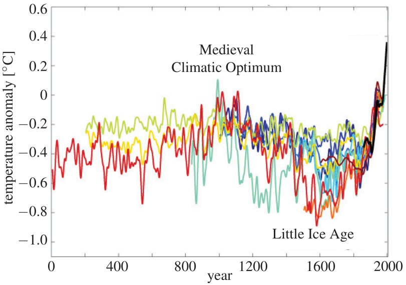

[wikimedia]

Temperature exceeds last 2000+ years

- Change to ∼1950: recovery from Little Ice Age (?)

Anthropogenic effects responsible for 0.5–1.0 °C rise

Current CO_2 levels ∼ 410 ppm →∼ 1.6 ± 0.6 °C (using IPCC σ)
But long time frame for full impact ($\mathcal{O}$ (100 y)).

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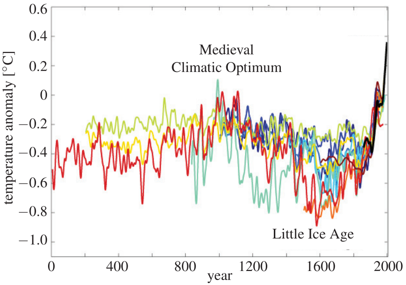

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Some statements made by physicists and others regarding warming/climate

Freeman Dyson (+ many others):

Radiative forcing grows logarithmically with CO_2 levels

True (for direct effects)

If $2 \times CO_2 \rightarrow 3.7$ W/m^2

then $4 \times CO_2 \rightarrow 7.4$ W/m^2,

(Implicit in notation $F_{2\times}$)

From exponential form of "wings" on CO_2 absorption band

In linear feedback regime, $\Delta T \approx \Delta T_{2\times} \log_2(M_{CO_2}/M^*)$

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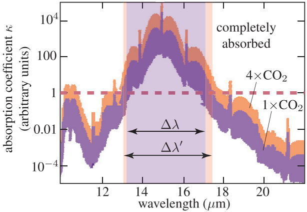

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- Paleoclimate data:

Suggest that 55 m years ago CO_2 was 5–10 × higher
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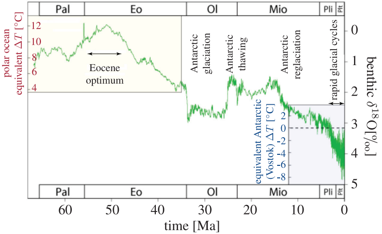

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True in some senses, but not relevant to current situation

+ More $CO_2 \Rightarrow$ enhances plant growth in some areas
$\sim$ 2.5 Gt (out of 10) of carbon emissions are absorbed in terrestrial biomass

+ Warmer climate $\Rightarrow$ additional arable land

If we could gradually increase CO_2, T over 100,000's (or millions) of years, might be a net positive.

Wrong time scale!

Anthropic warming will occur over the coming $\sim$ 200 years,
CO_2 pulse absorbed in 100's or 1000's of years

– Ecosystems (already pressed) will not be able to adapt, increased extinction

– Millions (billions?) of people will be displaced/affected by sea level rise, extreme weather, drought, etc.

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Some physics on two issues:

Sea level rise

Over half (so far) from thermal expansion
$\Delta V = \alpha_V V \Delta T$, $\alpha_V \approx 213 \times 10^{-6}\ \mathrm{K}^{-1}$

Warming mixed layer (200 m) by 1 °C:
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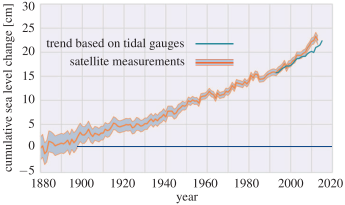

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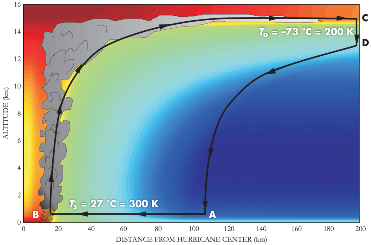
Hurricanes as Carnot engines (K. Emanuel)

[BBC (Hurricane Florence)]



[Physics Today (K. Emanuel)]

A → B: Isothermal expansion (air rushes in over sea surface)

B → C: Adiabatic expansion (air ascends)

C → D: (Approximate) isothermal compression

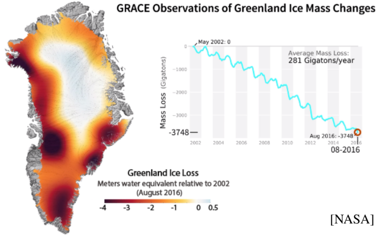
D → A: Adiabatic compression

Powered by disequilibrium between ocean surface and atmosphere

Higher temperatures, more energy → stronger hurricanes: $v^2 \propto \frac{T_s - T_0}{T_0} E$

Many uncertainties beyond simple temperature range

Ice melt



[NASA]

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Weather intensity

Predictions for increased drought + weather intensity, increased variability
e.g. 2018 UCLA study: drought + flooding both likely to increase in CA

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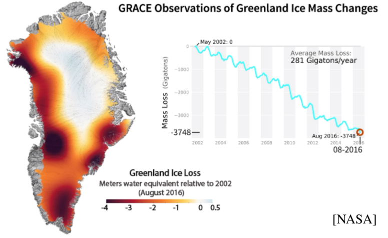

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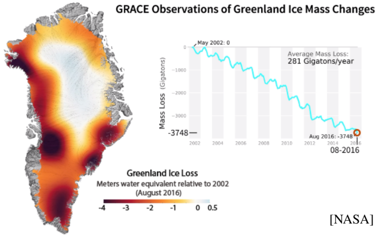

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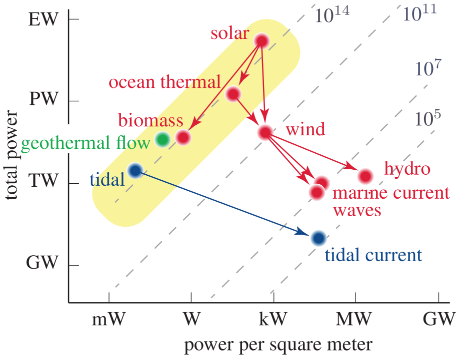
2. Energy systems: sources, uses, conversions

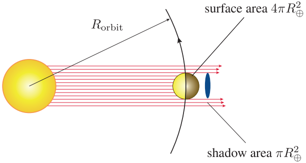
Where else can we get energy? Organize renewable sources by flow, scale



Sources to the right are dense → economically desirable

Sources near the top are abundant → viable FF replacements

Solar energy: scale of resource



Solar power on Earth: $P_{\text{total}} = \pi R_\oplus^2 I_\odot \cong 173\,000$ TW

So 0.01% of incident solar energy could provide all our needs!

There is no shortage of energy.

Existing solar thermal, PV technology deployed on 1-2% of global desert area $\rightarrow$ 4 TW; all current electric power + land transport needs

Main challenge: storage (days w/ STE); transmission OK ($\sim$ 7% over 2000 km)
But main obstacles to transformation are political, economic, social

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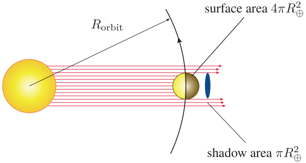

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Physics and materials constraints limit energy density (no Moore's law!)

Mechanics: pumped hydro

$E = mgh$

At $h = 300$ m, need $m \cong 3 \times 10^{10}$

Volume 3×10^7 m^3 of water

EM: capacitors: high power but E density limited by breakdown voltage
(air: 40 J/m^3– supercapacitor 100 MJ/m^3 $\rightarrow \geq 3 \times 10^7$ m^3)

Chemical energy/batteries: limited by binding energy/mass ratio of constituents
e.g. lithium-ion ≤ 1 MJ/kg, hydrogen $\sim$140 MJ/kg
9×10^{13} J $\rightarrow \sim$ 900,000 car batteries w/ 100 MJ, or 600,000 kg of hydrogen

Some viable scenarios but all require large-scale systems
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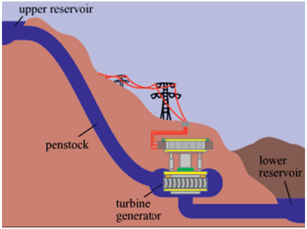

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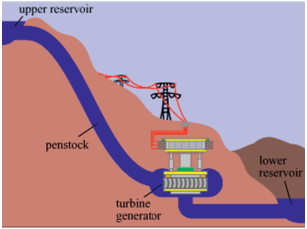

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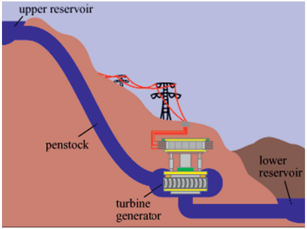

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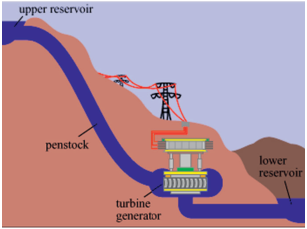

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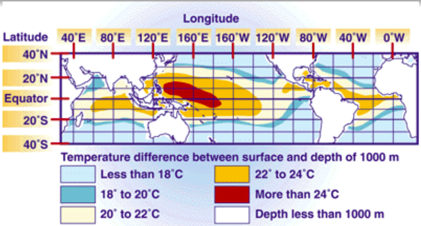
Ocean Thermal Energy?



[NREL]

In tropics, top 200 m at 22-27°C, below 1000 m at $\sim$ 5°C.

Energy content: 200 m $\times$ 70 Mkm^2 $\times$ 20°C $\times$ 4 MJ/m^{3}K $\cong$ 1100 ZJ
(density 16 GJ/m^2 — absorb. rate $\sim$ 0.15$\times$ 200 W/m^2 $\cong$ 30 W/m^2)

Absorbed in equatorial 40%: [Stewart]
$\sim$ 0.15$\times$ 200 W/m^2 $\times$ 140 Mkm^2
$\cong$ 4000 TW

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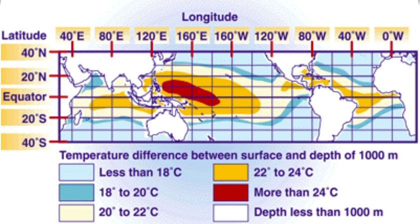

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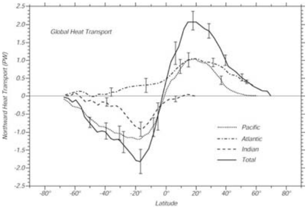

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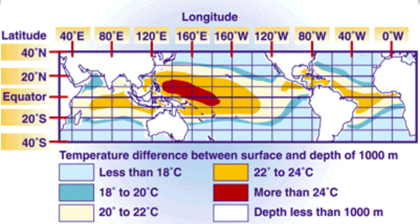

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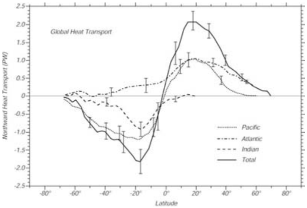

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"Using" energy, the second law and exergy

Second law of thermodynamics: entropy (randomness) cannot decrease

- Shannon information entropy $S = \sum_i -p_i \log_2 p_i$
  - — Number of bits needed to transmit info about sample from distribution p
  - — Physical entropy: rescaled by $k_B \ln 2$
  - — Characterizes distribution of micro states, e.g. gas in a box at fixed T, p
  - — Second law intuitive from reversibility of physical laws

Example: free expansion of gas from $V \to 2V$: $\Delta S = N\, k_B \ln 2$

$\to \quad \to$

Leads to distinction: high-quality energy has minimal entropy (e.g. kinetic E) vs. low-quality energy with lots of entropy (e.g. low T thermal energy)

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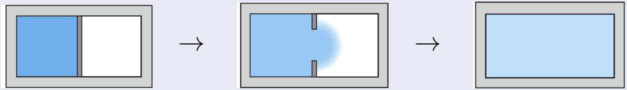
Example: free expansion of gas from $V \to 2V$: $\Delta S = N\, k_B \ln 2$



Leads to distinction: high-quality energy has minimal entropy (e.g. kinetic E) vs. low-quality energy with lots of entropy (e.g. low T thermal energy)

"Using" energy, the second law and exergy

Second law of thermodynamics: entropy (randomness) cannot decrease

- Shannon information entropy $S = \sum_i -p_i \log_2 p_i$
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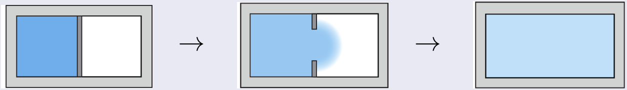

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- Second law explains how "conserved quantity" can be "used up" (changed from high-quality → low-quality)
- Explains necessity of lost energy from car engines ($\eta \sim 25\%$), power plants (n. gas $\eta \sim 65\%$, coal $\eta \sim 35\%$)

Useful concept: Exergy B (not a state function)
Exergy = maximum amount of usable work that can be provided by a system/material when brought into equilibrium with environment
e.g. $B = U - U_0 + p(V - V_0) - T_0(S - S_0)$ for gas at p, V w/ env. at p_0, V_0

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  — e.g. waste heat, mine tailings, . . . : not malfeasance, just thermodynamics
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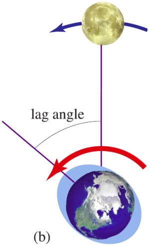
Some other possible energy sources

Tidal power:

Earth loses angular momentum to moon, tidal friction

Apollo reflectors: $\delta r \sim 38$ mm/y
$\rightarrow\sim 3.7$ TW

Mostly non-recoverable (deep ocean)
High density but cannot replace $\sim$18 TW



Wind power:

Estimates range from 1-100 TW recoverable energy

Issue: not really a 2D resource

But high quality energy, economically viable, useful role in renewable energy production

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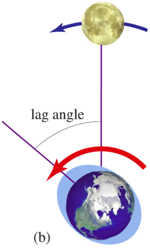

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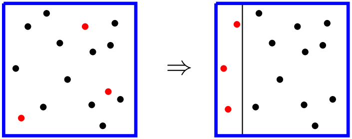
Why not just remove carbon?
Carbon capture costs energy

Energy of separation
from entropy of mixing

Mix • at concentration $c \ll 1$



$$\Delta S \cong -Nk_B \ln 1/c$$

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[Gibbs free energy: $G = H - TS$]

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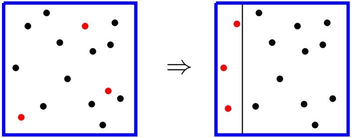

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Energy needed for capture/storage

Capture 1 kg of (atm.) CO_2:

$$N \cong 1\ \text{kg}/44\text{u} \cong 1.4 \times 10^{25}$$

$$T\Delta S \cong (300\text{K})Nk_B \ln 10^6/387$$

$$\Delta E = T\Delta S \cong 460\ \text{kJ}$$

Store at 100 atm., $+Nk_BT\log 100$

$$\Delta E_{cs} = 730\ \text{kJ}$$

Coal plant (η =30%):
10 $\text{MJ/kg}_\text{C} \cong 2.7\ \text{MJ/kg}_{\text{CO}_2}$

E to capture and store 37 Gt CO_2:

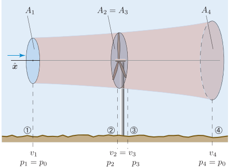
27 EJ

(> 40% of electricity production)

Beyond the 2nd law: Physics imposes other limits on energy conversion

- Betz limit (power extraction from wind across disk area A):

$$P \leq \frac{16}{27}\left(\frac{1}{2}\rho v^3 A\right)$$



- Shockley-Queisser limit (single-junction PV efficiency):

$$\eta \leq \text{ff} \times \frac{eV_{\text{oc}}}{E_{\text{gap}}} \times \eta^{\text{max}}_{\text{collection}} \leq 0.34$$

- Rabl bound (on concentrator with acceptance angle θ_a)

$$C \leq 1/\sin^2\theta_a \qquad \text{(solar: } C_{\text{max}} \cong 40\,000\text{)}$$

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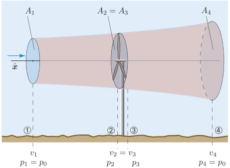

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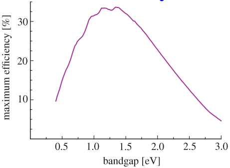

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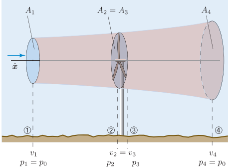

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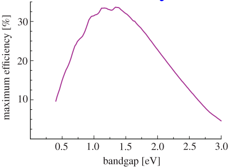

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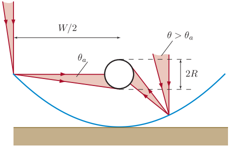

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4. Energy in the physics curriculum

What is/should be the role of physicists and physics departments re. energy?

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• Certainly many opportunities for applied physics research in energy technologies
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— Clarifies relevance of abstract material

— Helps to unify the field of physics; threads tie together different subfields

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At MIT and elsewhere, problems in applied energy systems have been used to enhance the physics curriculum.

Mechanics, EM, thermodynamics, . . .

To the faculty in the audience: consider incorporating aspects of energy relevant to contemporary energy issues in your classes.

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1. Physical science lies at the core of real-world energy systems and problems

2. As physical scientists we should understand energy systems
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3. We should educate others about energy science

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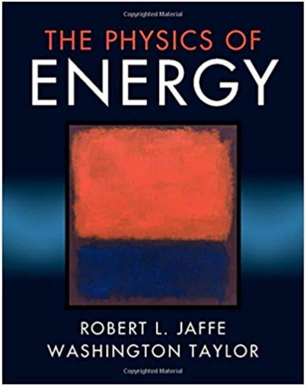

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