Today's Class

1. R&R – review and reinforcement ☺ – from last time
2. Earth's Radiation Balance: Incoming solar radiation and albedo – how they compare to thermal emission/absorption

R&R:

Power, Energy flux, black bodies and gray bodies

Assume the initial temperature of the coffee, *T*, is the same in each cup

R&R: Power

Which of the following is true about the initial power (heat) output from each of the cups of coffee?

A. $P_S > P_T > P_G > P_V$

B. $P_V > P_G > P_T > P_S$

C. $P_V = P_G = P_T = P_S$

Assume the initial temperature of the coffee, *T*, is the same in each cup

R&R: Power

What are the units of power?

A. J

B. Js

C. J s^{-1}

D. J s^{-1} m^{-2}

E. W m^{-2}

R&R: Energy Flux

Which of the following is true about the energy flux from each of the cups of coffee?

(*hint:* remember the units of energy flux)

A. $E_S > E_T > E_G > E_V$
B. $E_V > E_G > E_T > E_S$
C. $E_V = E_G = E_T = E_S$

Day 3 worksheet, #1

T_R = 280 K

T_L = 280 K

Is there a net transfer of energy from

A. Right to Left

B. Left to Right

C. Not at all

Day 3 worksheet, #2

T_L = 280 K

T_R = 280 K

Which wall changes its temperature with time?

A. Right

B. Left

C. Neither

D. Both

Day 3 worksheet, #3

T_L = 280 K

T_R = 280 K

Which wall will emit the most radiative flux?

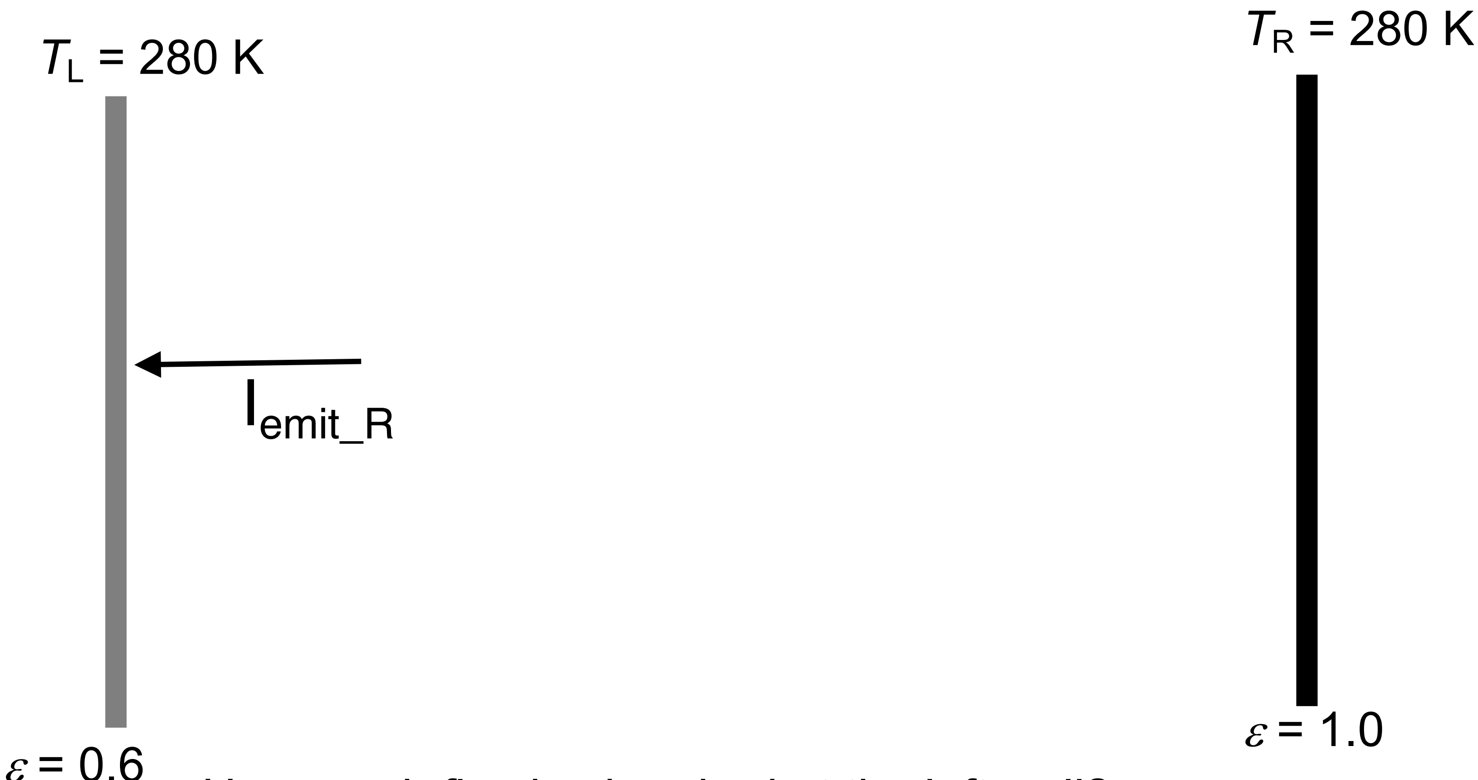
A. Right

B. Left

ε = 0.6

ε = 1.0

Day 3 worksheet, #4

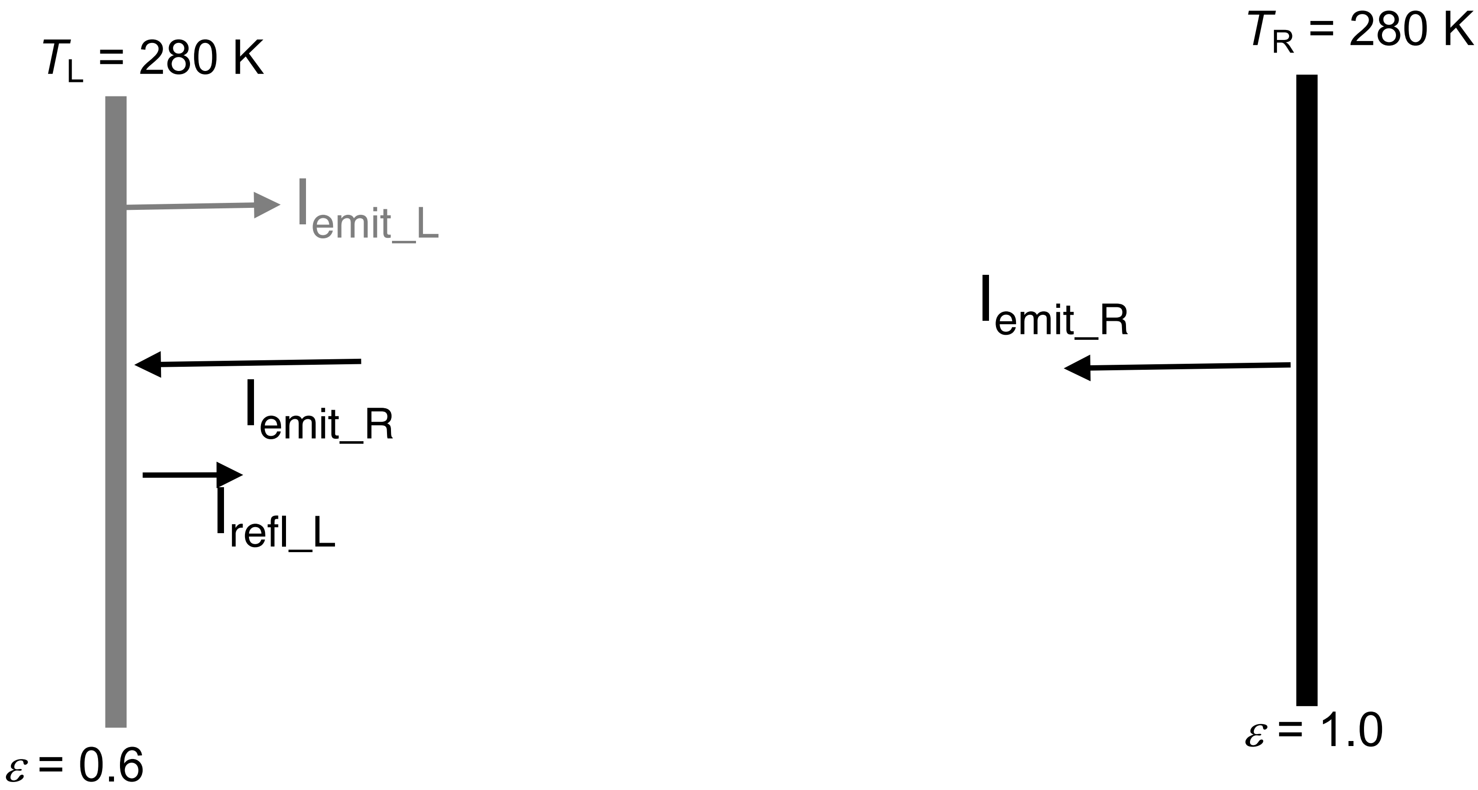


How much flux is absorbed at the left wall?

Assume Kirchoff's law is true, e.g. abs=Ɛ

Then $absI_{right} = \varepsilon I_{right}$

Day 3 worksheet, #5



At the LH wall $I_{emit\_R} > I_{emit\_L}$ so some flux must be reflected, or temperature of LH wall would change, in violation of the 2nd law of thermodynamics

So 2nd law requires: $I_{refl-L} + I_{emit-L} = I_{emit\_R}$

Notes about emissivity:

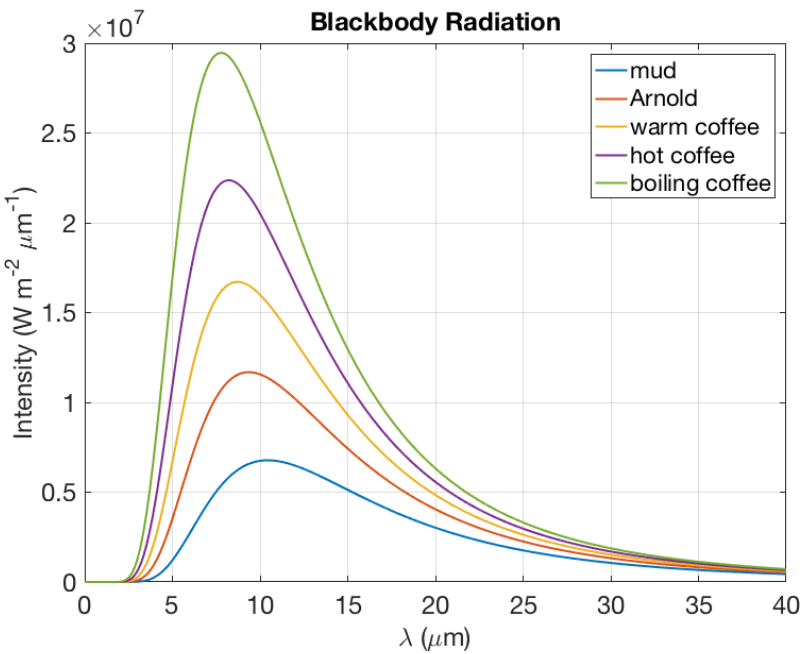
- Just because a body in equilibrium emits the same amount of flux as it absorbs does **not** mean that the outgoing radiation will be at the same wavelength (e.g. the ocean absorbs shortwave radiation and emits longwave radiation).

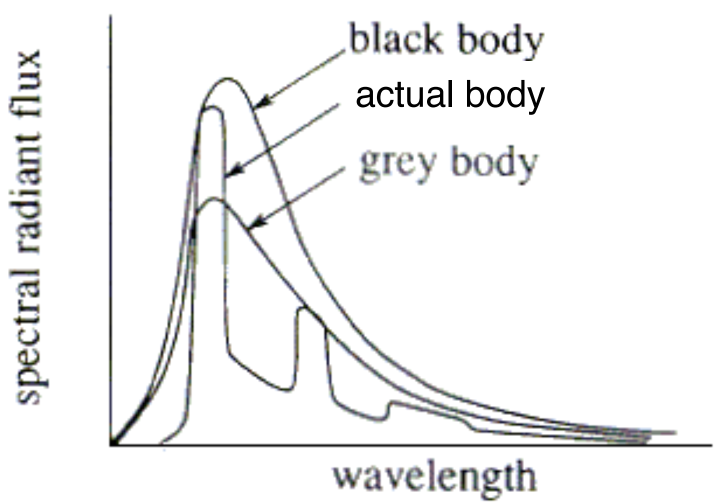
- Different surfaces/layers have different colors because their reflectivity changes with wavelength. For the same reason, their emissivites and absorptivities also change with wavelength.

Grey body radiation

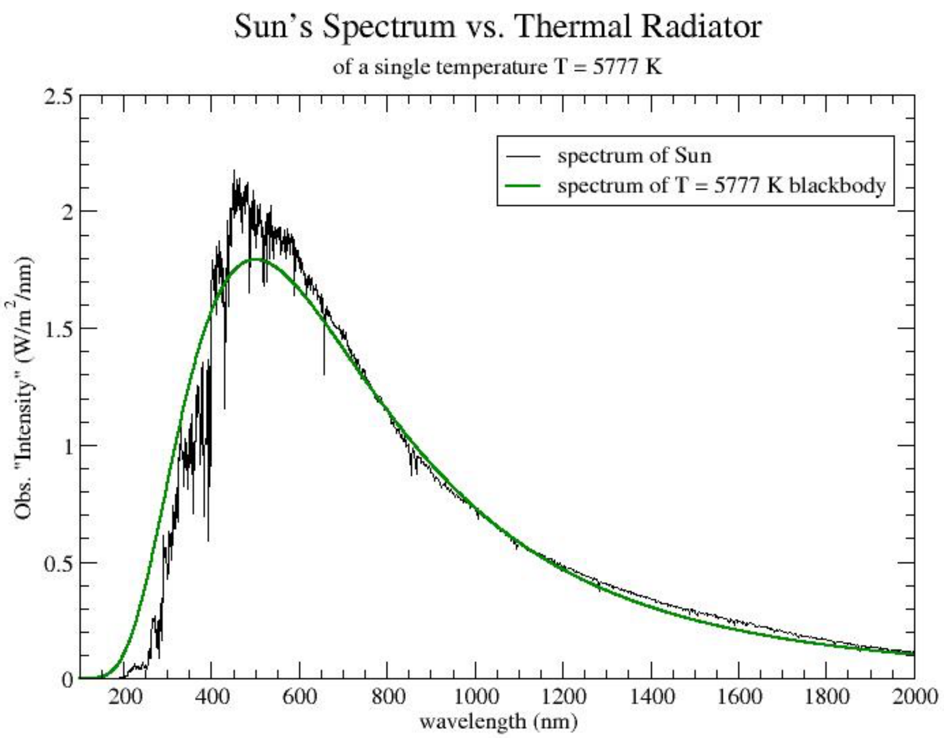
'Grey body' is an approximation for a real body whose emission is different from a black body in a way that depends on wavelength.

We approximate this by a constant factor, the broadband emissivity, ε, that is the ratio of the area under the true grey body curve c.f. area under the black body curve. → Grey body energy flux = $\varepsilon\sigma T^4$





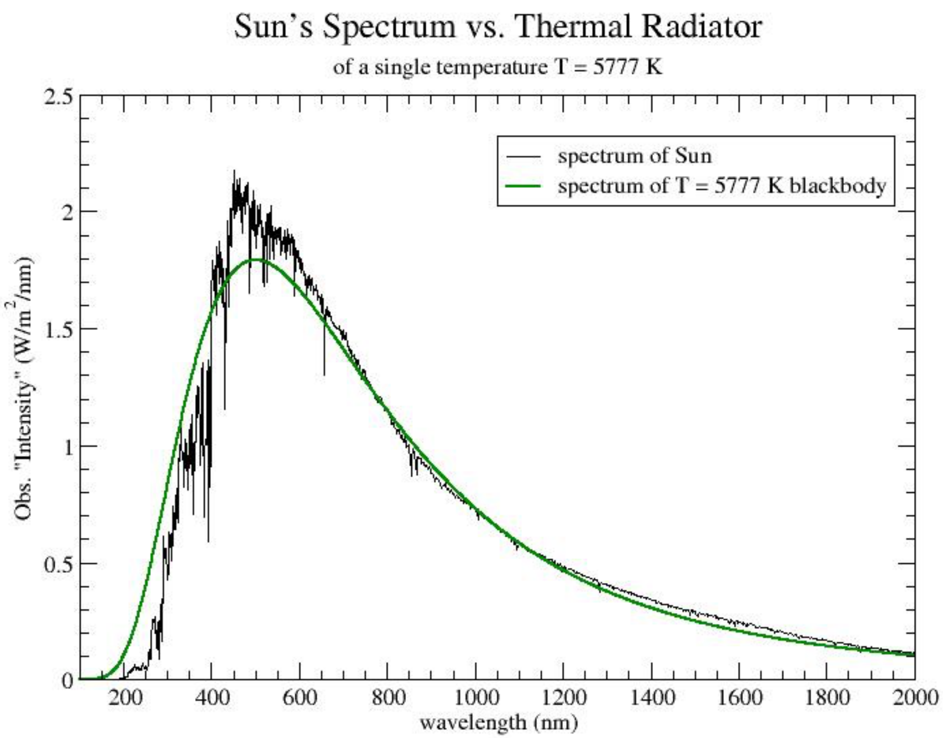
R&R: Black body spectrum



BTW: this figure shows that the actual spectrum (black) of the Sun really looks like that of a black body (green curve) with a temperature T ~ 5800 K

Black body spectrum

What corresponds to the area under this curve?



A. Power

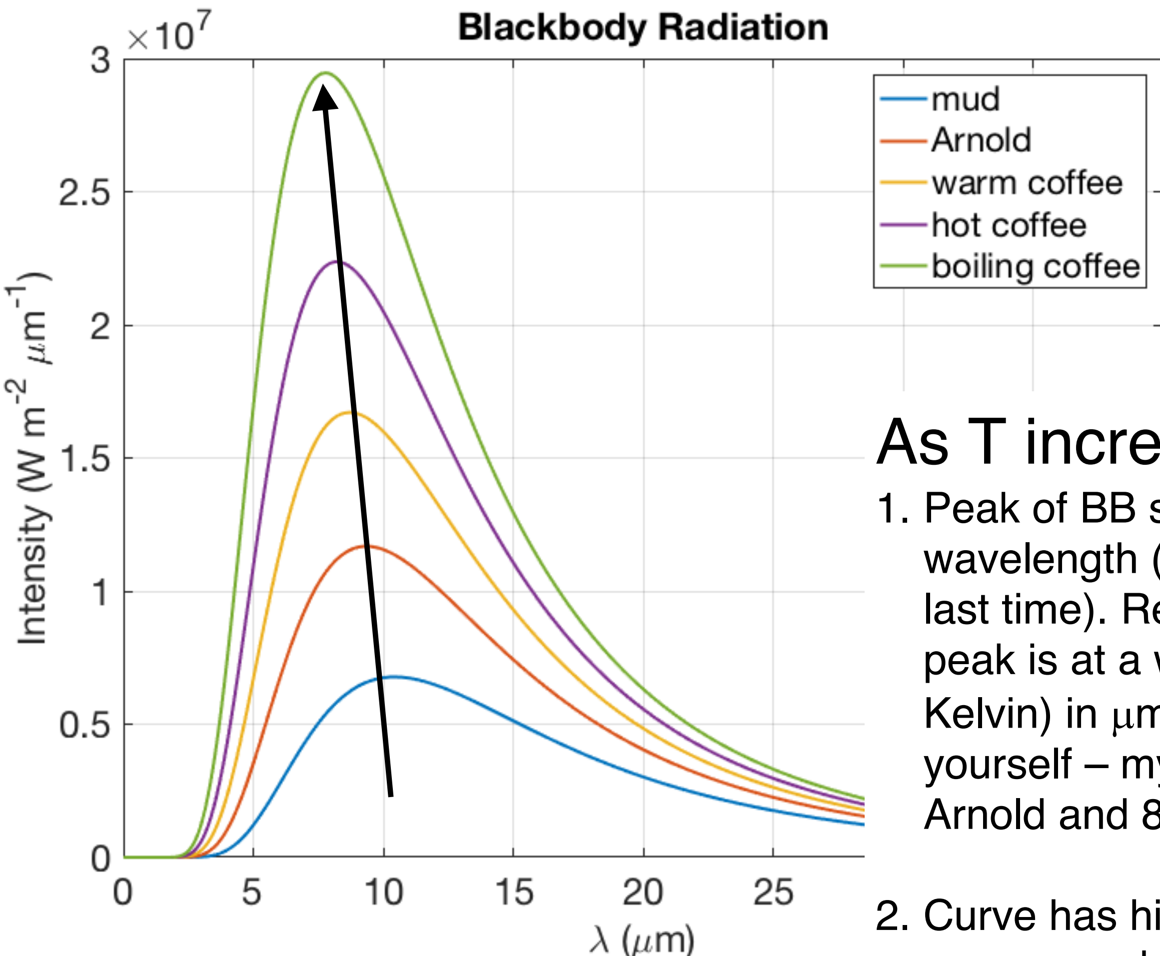
B. Energy flux

C. Neither of the above

D. idk

BTW: this figure shows that the actual spectrum (black) of the Sun really looks like that of a black body (green curve) with a temperature T ~ 5800 K

BB with different T



As T increases

1. Peak of BB spectrum moves to shorter wavelength (or bigger wavenumber – see last time). Remember from the text book, the peak is at a wavelength of 2897/T (T in Kelvin) in μm. Check these peaks for yourself – my T = 5°C for mud, 37°C for Arnold and 80°C for hot coffee.

2. Curve has higher intensity at all wavelengths, so area under curve increases – we know it must b/c area under curve is equal to σT^4

Greybodies: An approximation

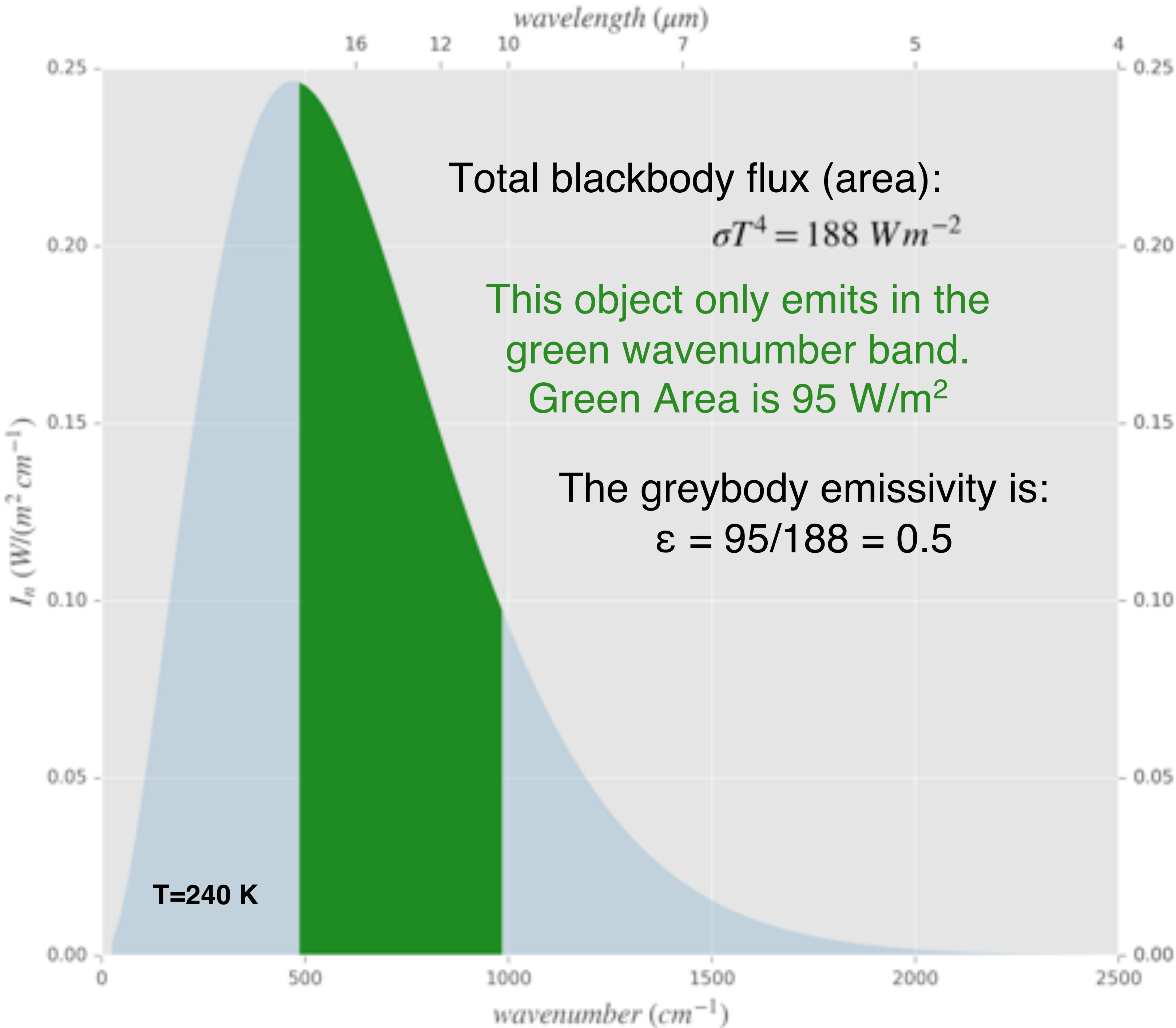
Most real objects do NOT emit equally well at all wavenumbers (although water comes close in the longwave).

Instead, real objects radiate a fraction of the EM energy an ideal black body at the same temperature would radiate

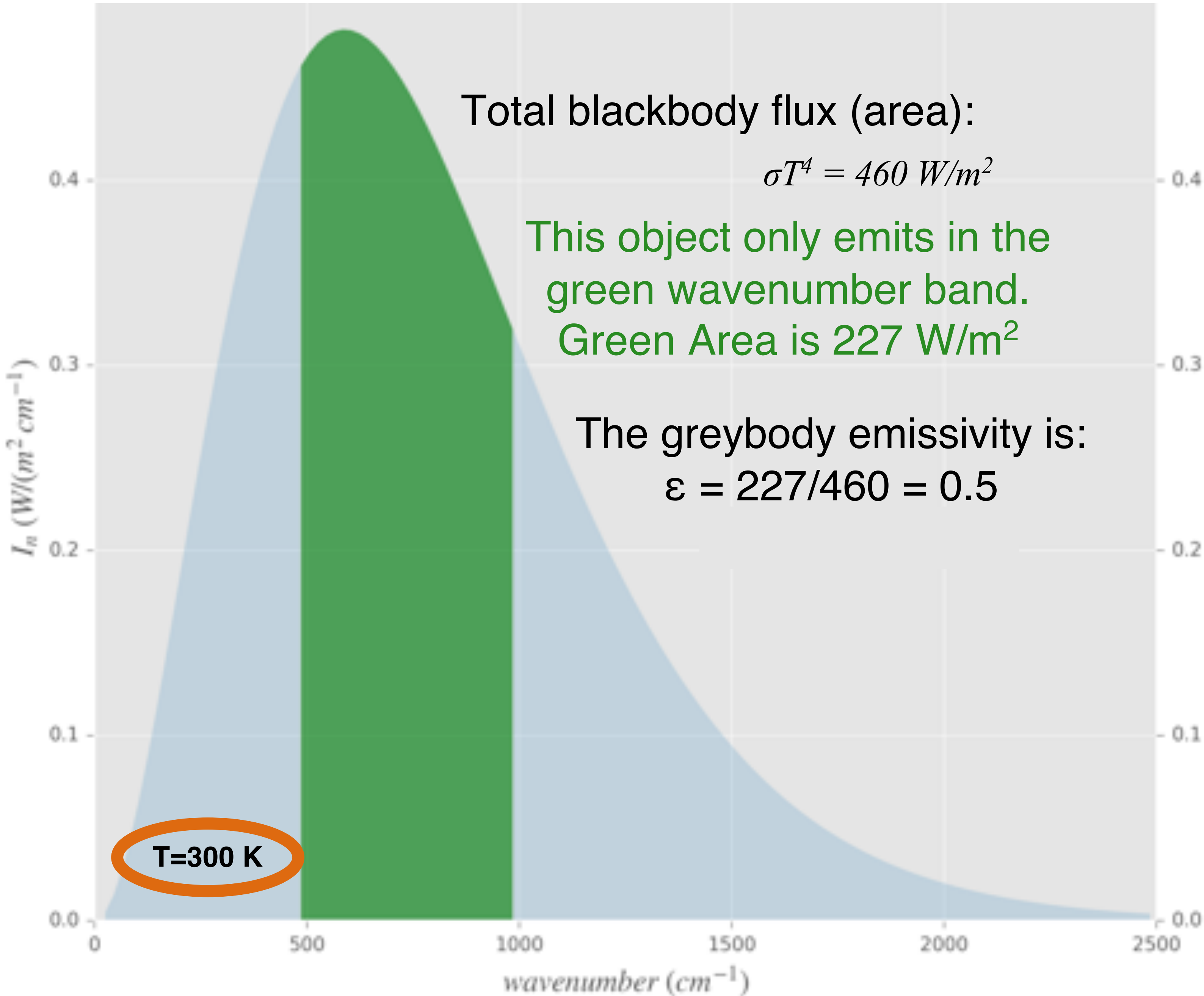
We call this the “greybody” approximation:

$$I = \varepsilon\sigma T^4$$

This is the RATIO of the actual energy emitted I to that which a blackbody would emit


wavelength (μm)
16
12
10
7
5
4
0.25
0.20
0.15
0.10
0.05
0.00
I_n ($W/(m^2 cm^{-1})$)
0
500
1000
1500
2000
2500
wavenumber (cm^{-1})
Total blackbody flux (area):
$\sigma T^4 = 188\ Wm^{-2}$
This object only emits in the
green wavenumber band.
Green Area is 95 W/m^2
The greybody emissivity is:
$\varepsilon = 95/188 = 0.5$
T=240 K

Emissivity is NOT a function of temperature



Total blackbody flux (area):

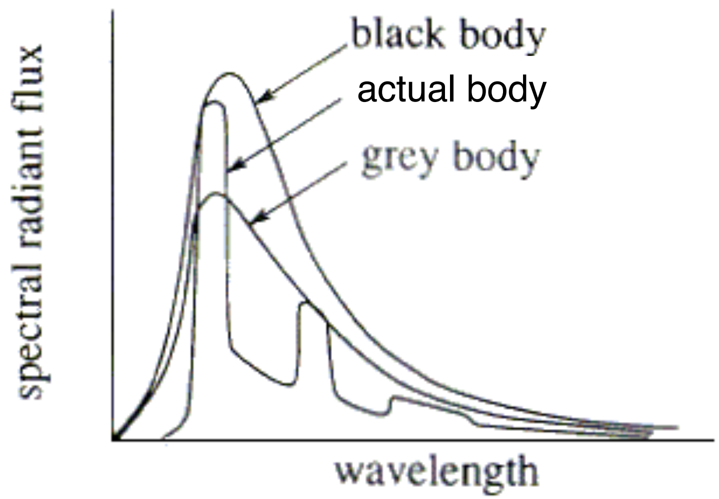
$$\sigma T^4 = 460\ W/m^2$$

This object only emits in the green wavenumber band. Green Area is 227 W/m^2

The greybody emissivity is:

$\varepsilon = 227/460 = 0.5$

Grey body radiation

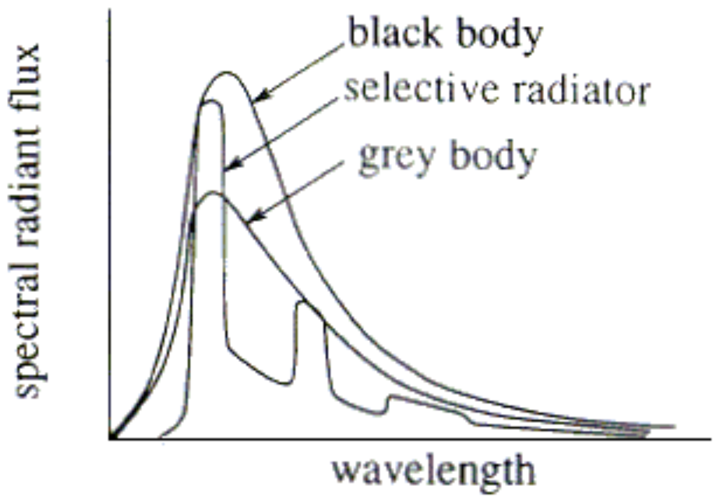


The emissivity of a gray body must be less than 1.

A. True

B. False

Black vs. grey bodies



What is the point of the greybody approximation? We get to ignore the details of the complex absorption/emission bands, and approximate their effect by a single number, the greybody emissivity ε. In climate models the radiation calculations typically use about 20-30 bands spanning the long and short wavelengths.

The world in the infrared

- IR vs. visible video
- Crucial point – at 2:30 he puts a sheet of paper (cold) over his face (hot) – note that the paper absorbs the IR flux from his face and emits much less – it is absorbing radiation and heating up. This is the definition of the greenhouse effect.

The story so far:

- The atmosphere absorbs and emits thermal radiation
- We are increasing the absorbtivity/emissivity by adding greenhouse gasses
- The total radiation emitted (the “emission” or emitted flux” I) depends on both the emissivity and the temperature:
  $I = \varepsilon \sigma T^4$
- The atmosphere is colder than the surface, so it absorbs more from the surface than emits to space, heating the planet
- This doesn’t violate the 2nd law, because ????

Day 4: Earth's Radiation Balance

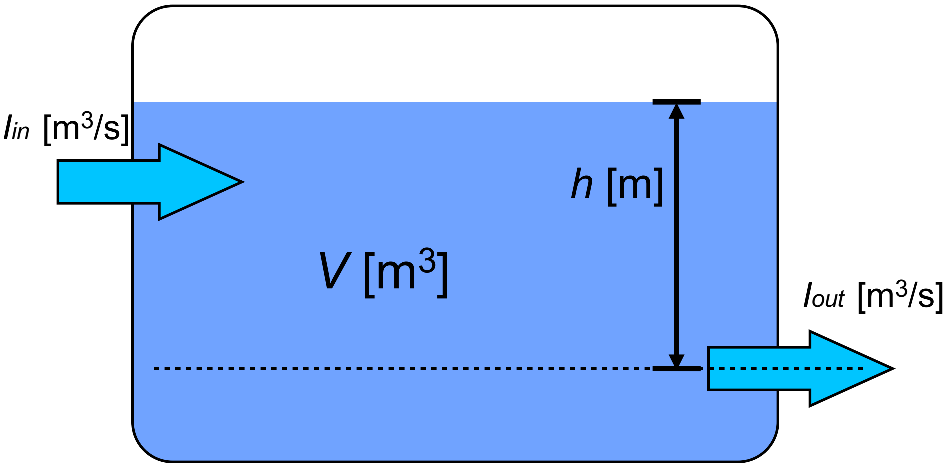
Incoming solar radiation and albedo

Goals:

1. Apply systems dynamics concepts of stock and flow to Earth's energy budget. $dE/dt = I_{down} + I_{up} = I_{down} - |I_{up}|$
2. Figure out the incoming solar radiation for Earth and other planets
3. Compare reflectivity of different parts of the Earth system, both on the surface and in the atmosphere.
4. Predict the impacts of altering solar energy or reflectivity on flows of energy in Earth's climate system, and therefore Earth's temperature (left side of Earth's energy budget diagram)
5. Classify particular changes in incoming solar radiation and albedo as forcings or feedbacks.
6. Calculate planetary temperature response to an instantaneous forcing due to the Planck feedback alone.

Earth's Climate - A Stock & Flow analogy

The "Bathtub" Balance



The stock (volume of water) in the bathtub changes according to:

$dV/dt = I_{in} - I_{out}$

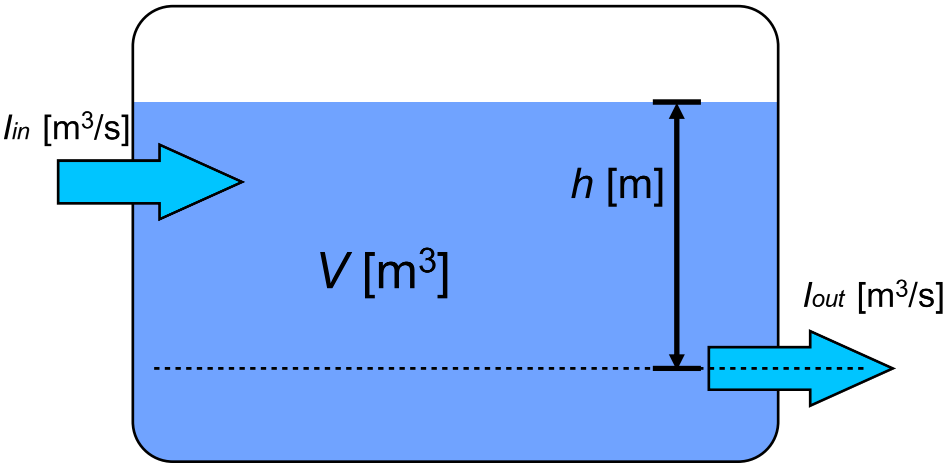
where the outflow depends on the current stock:

$I_{out} = (const) \times h$

notice the feedback mechanism

Earth's Climate - A Stock & Flow analogy

The "Bathtub" Balance



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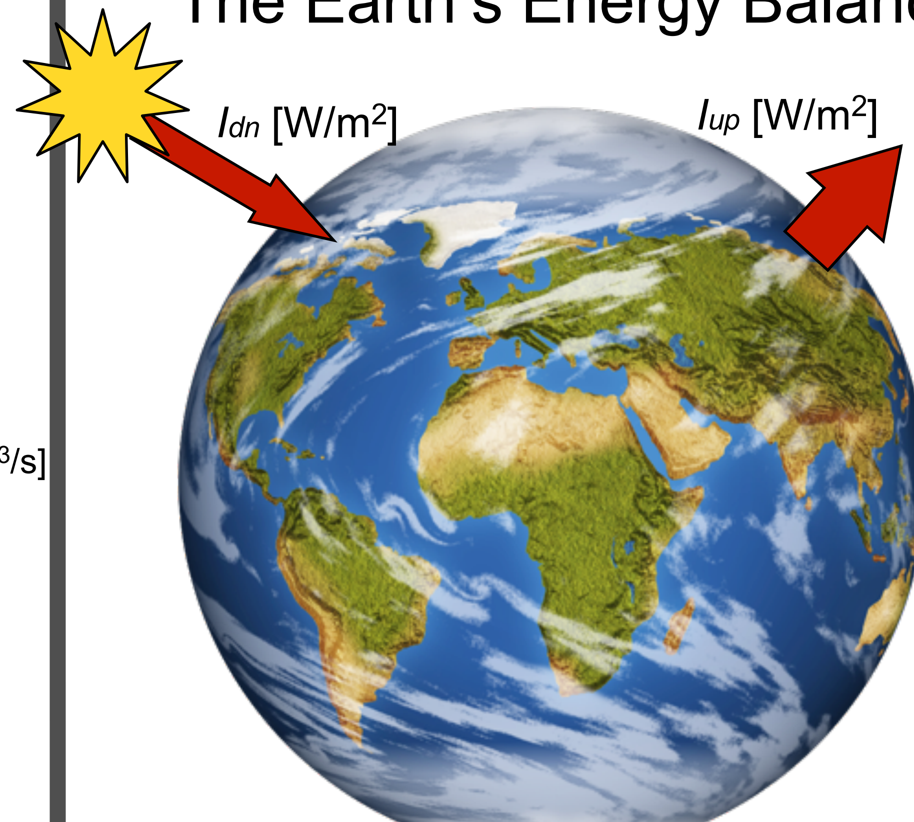
The Earth's Energy Balance



The Earth's energy budget behaves according to:

$dE/dt = I_{dn} + I_{up}$

where the radiation out depends on the current stock (Stefan-Boltzmann):

$I_{up} = -\varepsilon\sigma T^4$

How much energy does the Earth receive from the Sun???

Let's calculate the solar constant (use pen & paper)

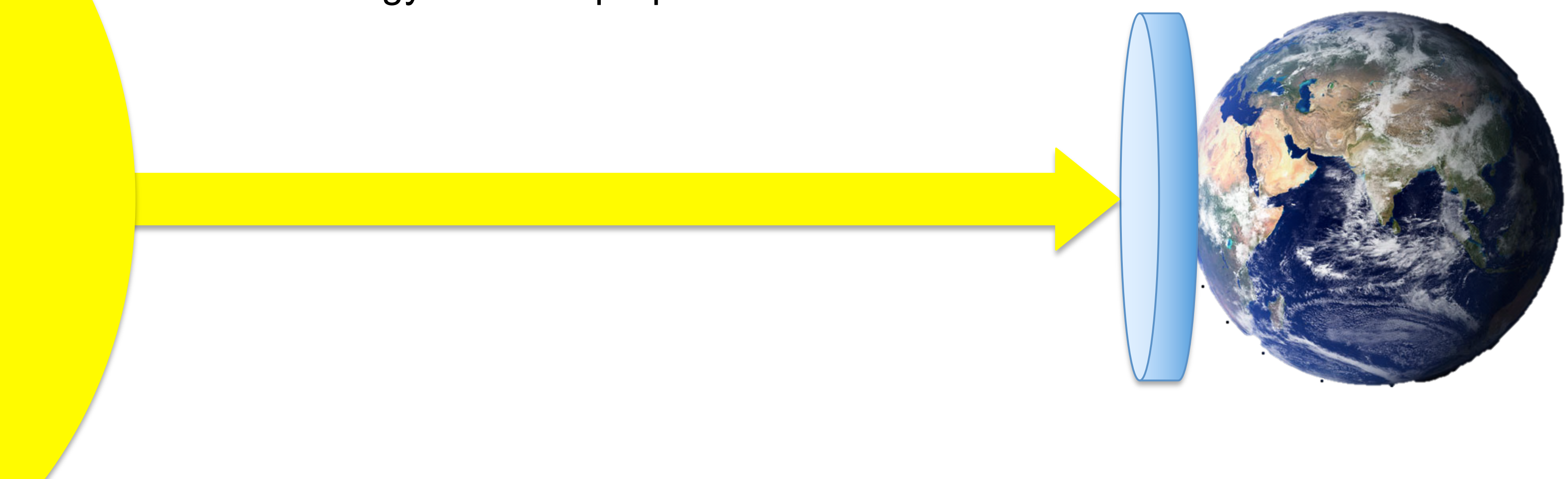
Need following information

- Sun outputs 3.8×10^{26} W   (1W = 1J/s)
- Mean sun-earth distance is 150×10^{9} m
- Area of the distance-sphere is 2.8×10^{23} m^2

Energy received at the Earth is known as the "solar constant" and is $S = 1{,}360$ W/m^2

How much energy does the Earth absorb? Need radius of the earth $R = 6.4 \times 10^{6}$ m

- Solar constant is 1360 W/m^2
  - At the top of the atmosphere directly facing the Sun, Earth receives 1360 W/m^2
- The Earth "blocks" an area in space equal to the area of a circle with Earth's radius (πR^2)
  - Each square meter of that imaginary circle gets 1360 W
  - Total energy received proportional to area of that circle



- The **TOTAL** energy Earth captures is $1360 \times \pi R^2$ [W]
- Distribute total energy received over the surface area of the Earth: $(1360 \times \pi R^2) / 4\pi R^2 = 1360 / 4 = 340$ [W/m^2].
- Aside: Trenberth was working with about 1365 W/m2 for the solar constant → 341 W/m^2

Image credit: NASA

CLICKER: Earth's radiation balance

If the distance between the Earth and the Sun doubles
AND
the radius of the Earth shrinks to half its current value,

how will the amount of radiation per unit area (W/m^2) received at the surface of the Earth change?

A. Decreases by a factor of 2

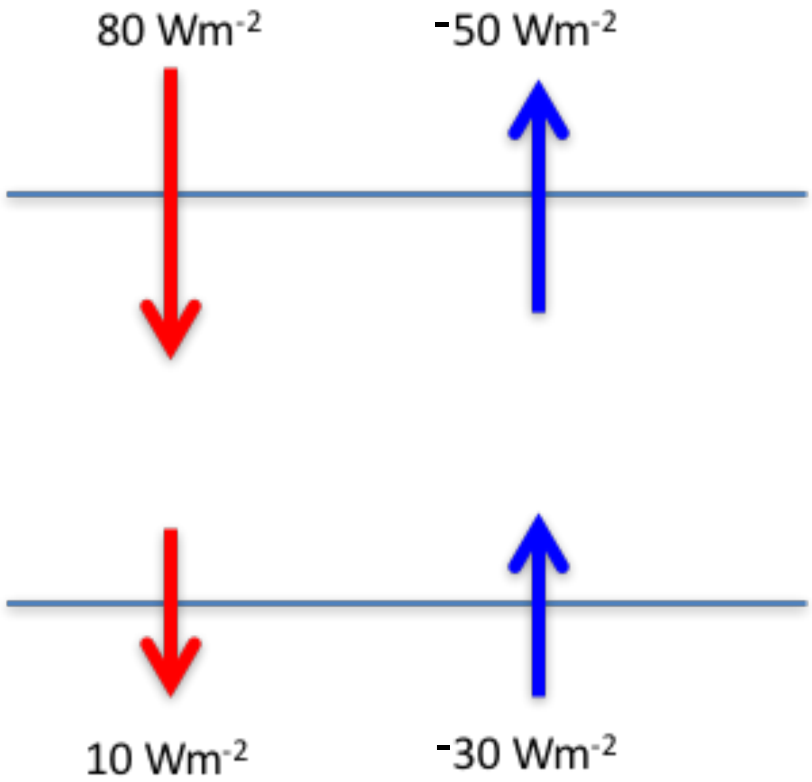
B. Decreases by a factor of 4

C. Decreases by a factor of 8

D. Decreases by a factor of 16

CLICKER: Heating rates?

At what rate does this atmosphere (the area between the lines) heat up (+) or cool down (-)?



A. -10 Wm^{-2}

B. -20 Wm^{-2}

C. +20 Wm^{-2}

D. +50 Wm^{-2}

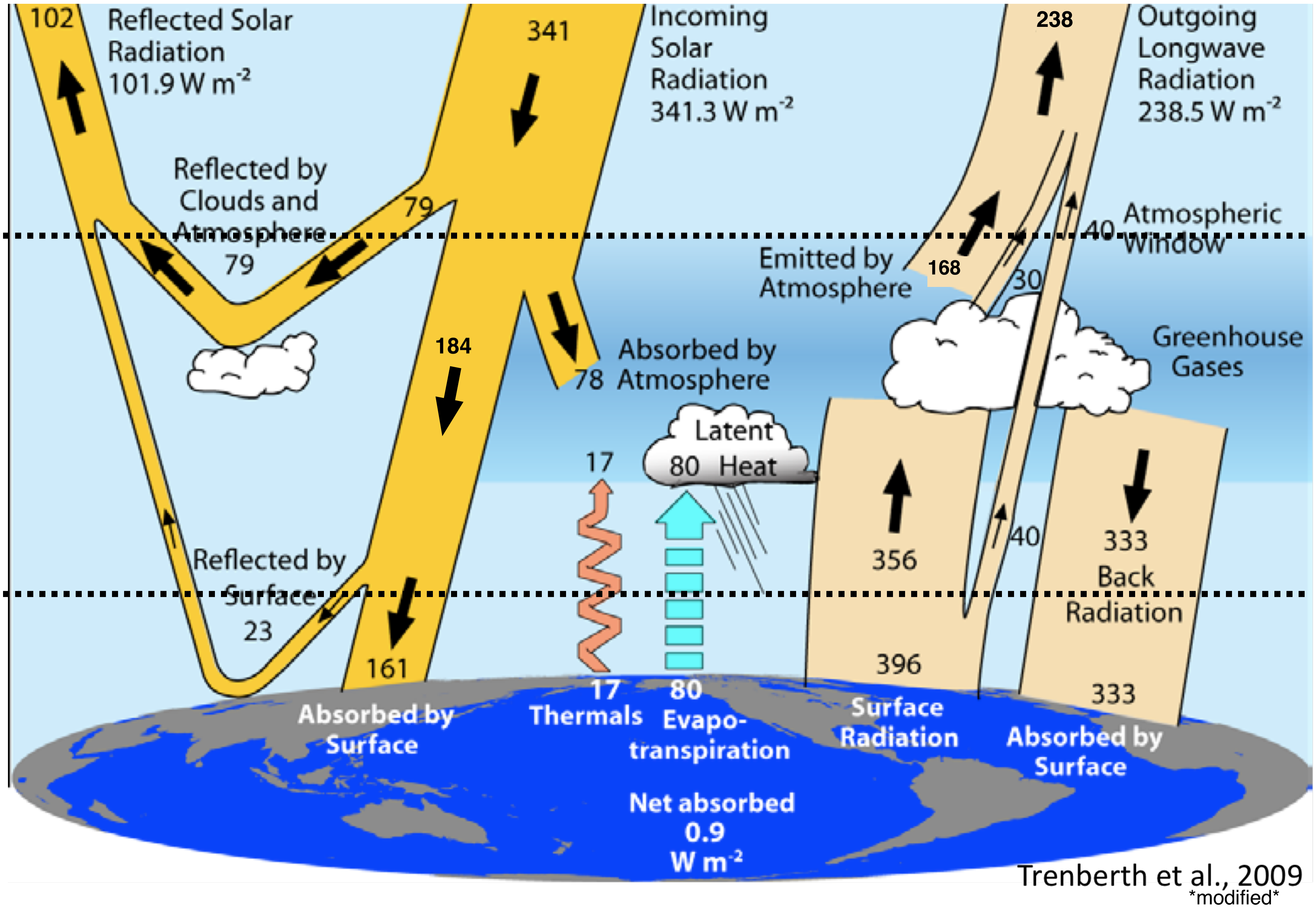
E. +70 Wm^{-2}

Worksheet: The Earth as a Stock and Flow Problem

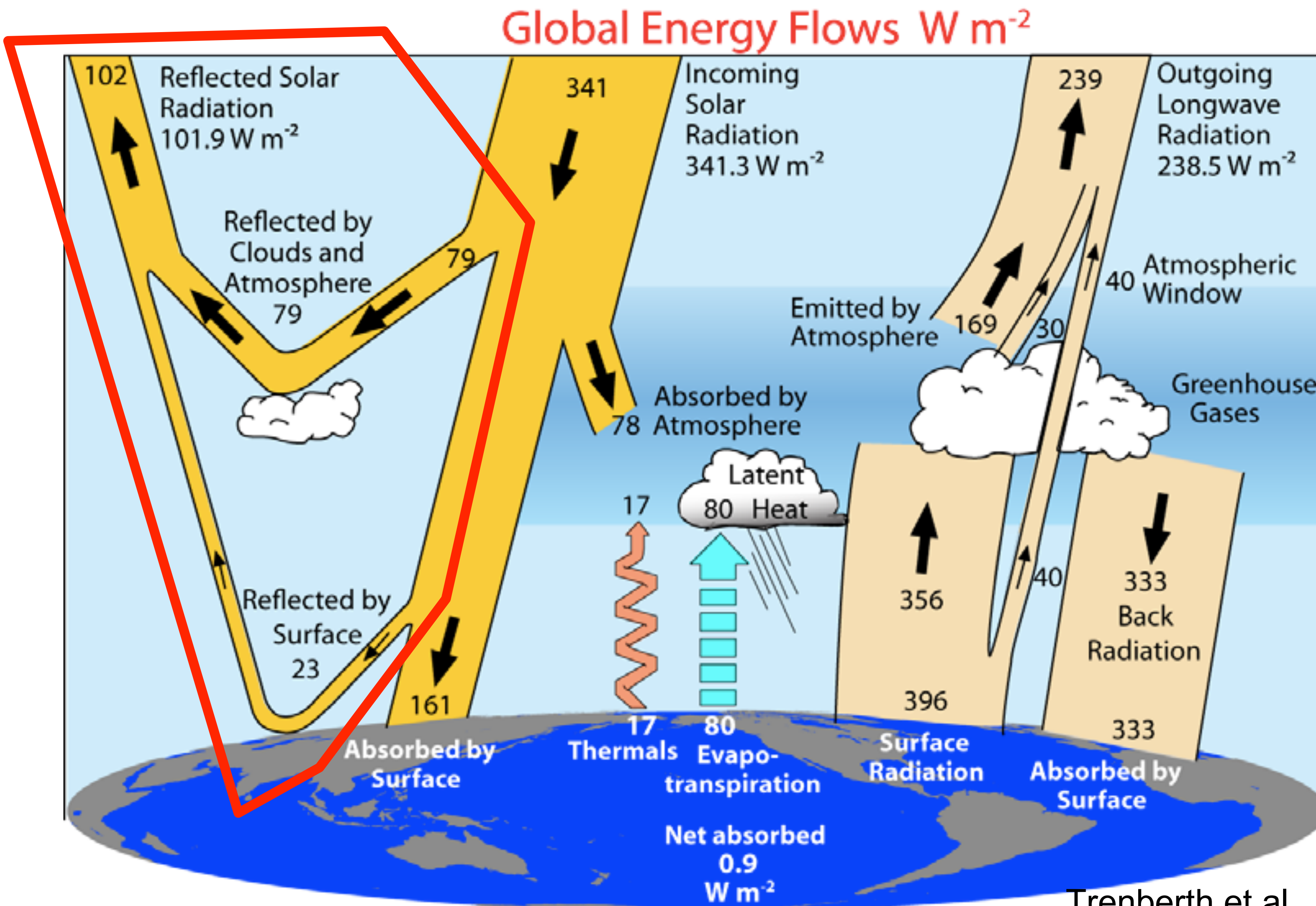
1

2

3



Focus on Albedo – left side of diagram



Trenberth et al., 2009

Summary

1. Balances of flows of energy in, out, and within Earth's climate system determine Earth's temperature.
2. We use the "grey body approximation" to estimate the emissivity/absorptivity of the atmosphere
3. Kirchoff's law guarantees that ε=abs because otherwise we violate the 2nd law of thermodynamics
4. Solids, liquids and gasses emit radiation according to their temperature and their emissivity via the Stefan-Boltzman equation: $I = \varepsilon\sigma T^4$
5. These same objects absorb radiation with constant abs=ε that is independent of temperature.
6. That means that cold air can absorb radiation from a warm surface, but not re-radiate all that it has absorbed This is heating because of the imbalance is called the "greenhouse effect"
7. This doesn't violate the 2nd law because this system is not isolated – the surface is warmer that the atmosphere because it is absorbing sunlight that passes straight through air.