Class 1
What Determines Earth's Temperature?

OLLI

L80X Climate Change

July 2013

QUESTIONS

Your Questions

- Clarification: anytime

- Substantive – disagreement, implications: question break and beginning of next class

- Comments on outside sources: raise at question break or by e-mail – generally posted response

Some Yes/No Questions

- Is average global temperature higher today than in 1900?
- Is the atmospheric concentration of carbon dioxide (CO_2) higher today than in 1900?
- Has more atmospheric CO_2 “contributed” to higher temperatures?

Kinds of Questions

- Yes/no questions
- Quantitative questions
- Major climate science issues
  - Yes/no: generally little (but not zero) uncertainty
  - Quantitative: often much greater uncertainty

Comparing Temperature and CO_2

- Issue: Can we measure 1900 and current temperature and CO_2 with enough accuracy?

- Temperature: Global instrument readings

- CO_2: Instrument reading and ice cores

Role of CO_2

- Issue: Can we infer a causal relationship between CO_2 rise and temperature rise?
- Science: CO_2 traps thermal radiation
- Observation:
  – General correlation between temperature and CO_2
  – We can (mostly) explain exceptions
- Conclusion: Very high probability that CO_2 contributed to temperature rise

A Quantitative Question: How Warm Will It Get?

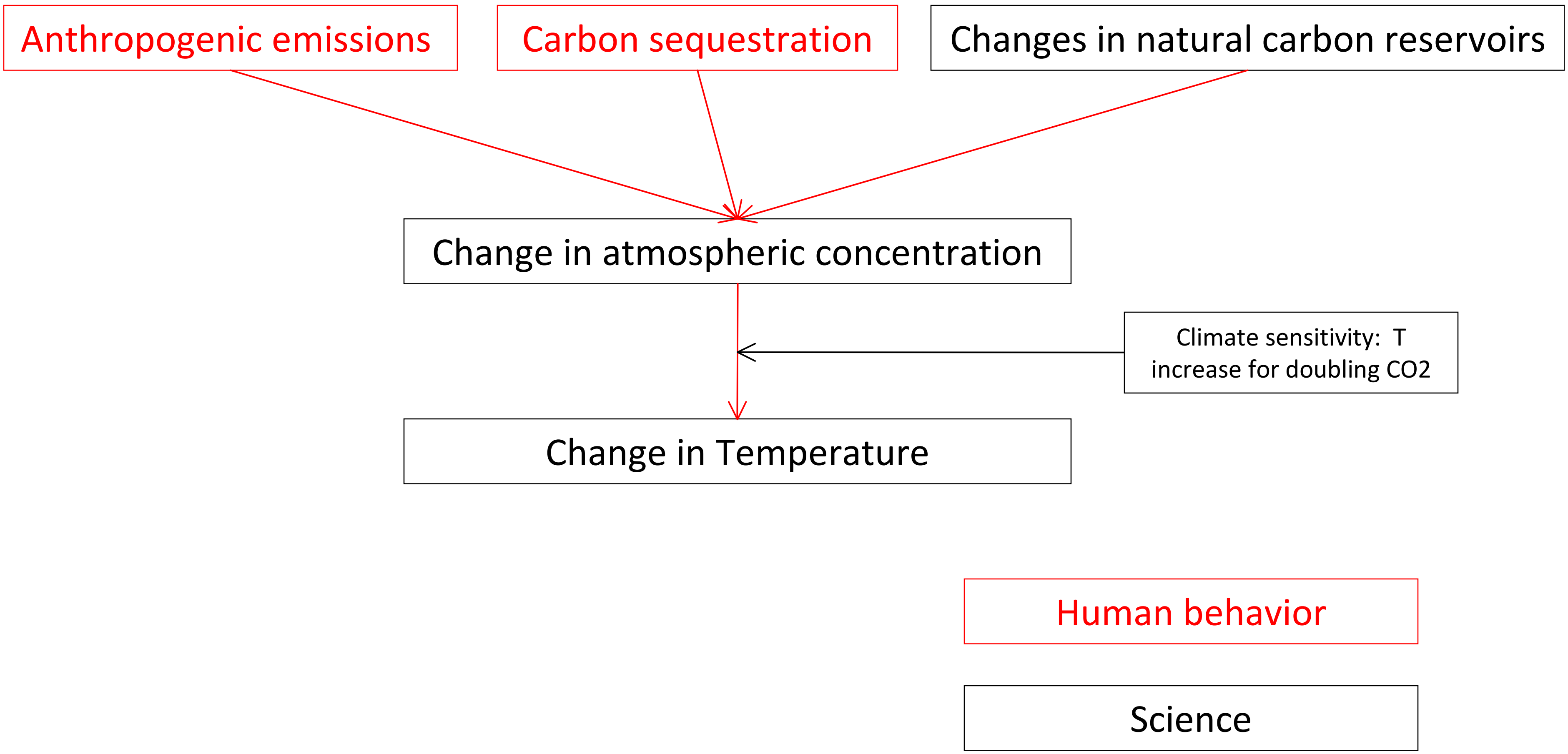
- Behavioral issue: Future CO_2 emissions

- Scientific issue: CO_2 absorption by ocean and biosphere

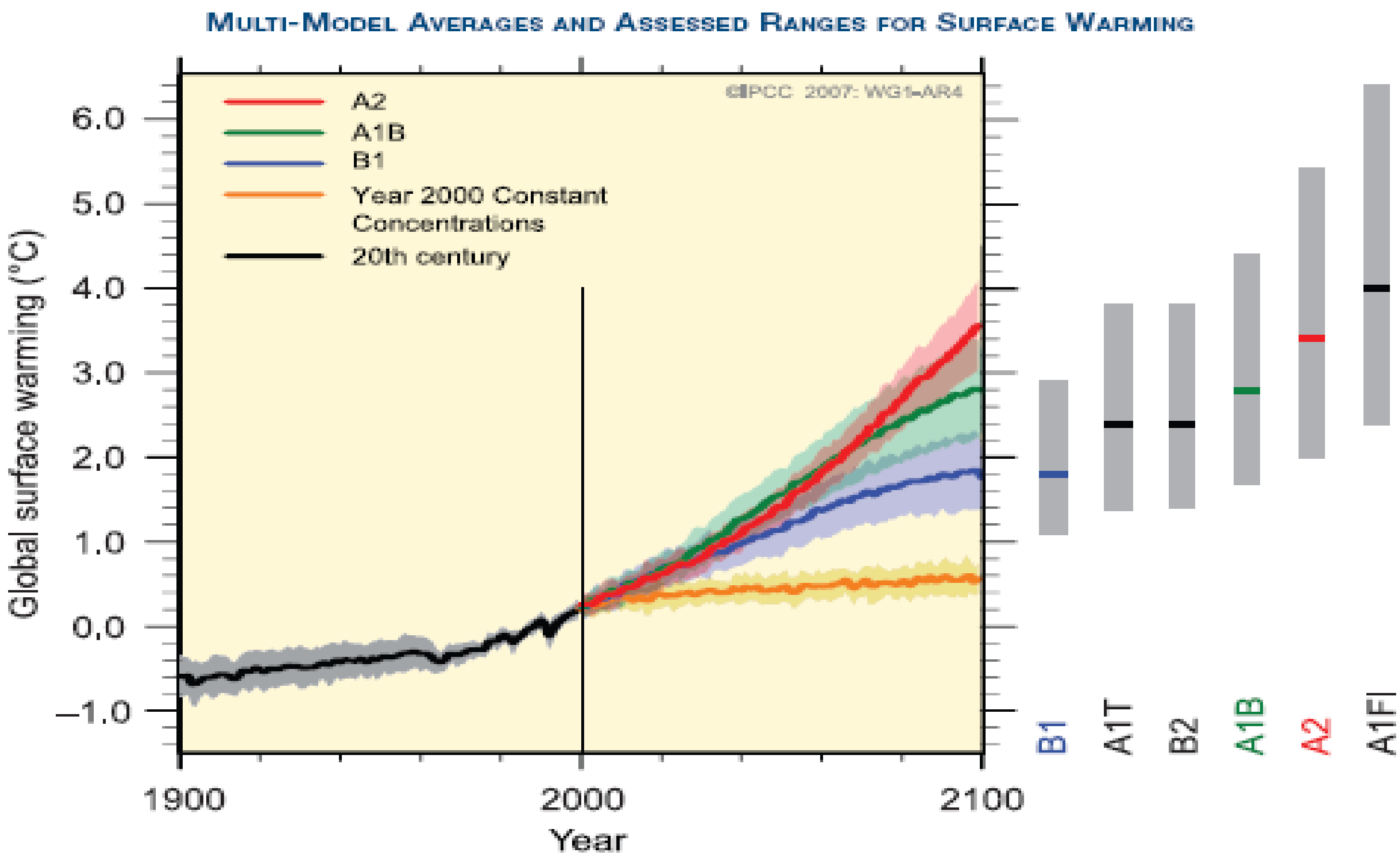
- Behavioral issue: Sequestration of CO_2

- Scientific issue: Quantitative CO_2-temperature relationship (climate sensitivity)

The Causal Chain
(without radiation management)



IPCC 2007 Projections



What Should We Do?
Three Climate Policy Questions

- A moral question: How much should we sacrifice for the future?

- An economic and technological question: What form of sacrifice will do the most good?

- A political question: What amount and form of sacrifice is politically feasible?

WHAT DETERMINES EARTH'S TEMPERATURE?

Basic Principles

- A system's temperature measures its atom's average kinetic energy (energy of movement)

- Implications
  - Average temperature changes when there is an imbalance between energy added and energy lost
  - Equal energy additions and losses → unchanging average temperature

Applying the Principles to a Planet

- Planets receive and lose energy only through radiation – like perfect vacuum bottles
- Radiation
  - Incoming from their sun
  - Outgoing thermal and reflected solar
- <u>Radiative forcing:</u> Imbalance between incoming and outgoing radiation

Radiative Forcing: Long ago in a galaxy far way

- Planet Keeling ejected from its system
- Characteristics
  - Heat from home star lost during interstellar journey
  - Geologically dead – no internal source of heat
  - Dull black – reflects nothing
  - No atmosphere

Keeling Arrives

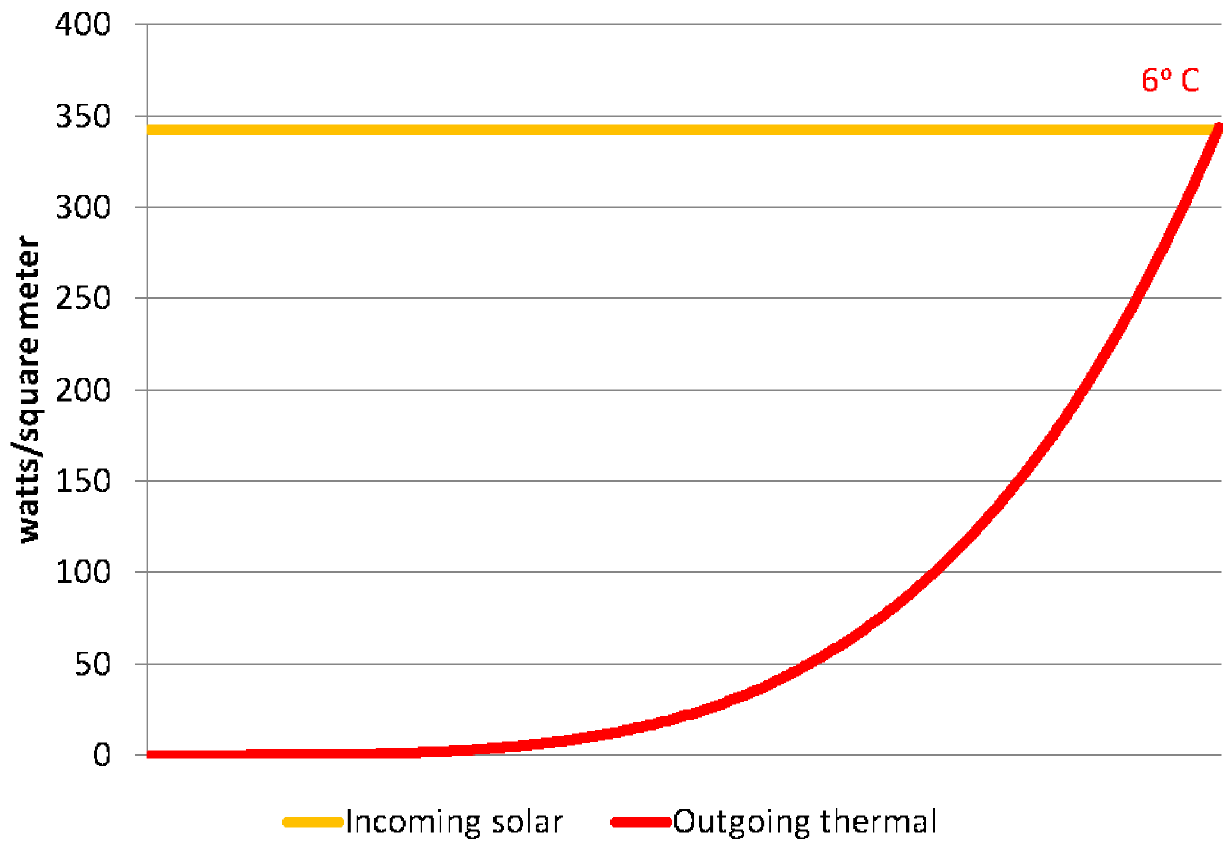
- Captured by Sun-like star in near-circular orbit of 150 million km radius
- Incoming solar radiation:
  - Cross-section perpendicular to sun's rays: 1366 watts/meter^2
  - Average for Keeling's surface: 342 watts/meter^2
- Initial outgoing radiation: ~none
- Radiative forcing: 342 watts/meter^2

Now What?
The Path to Equilibrium

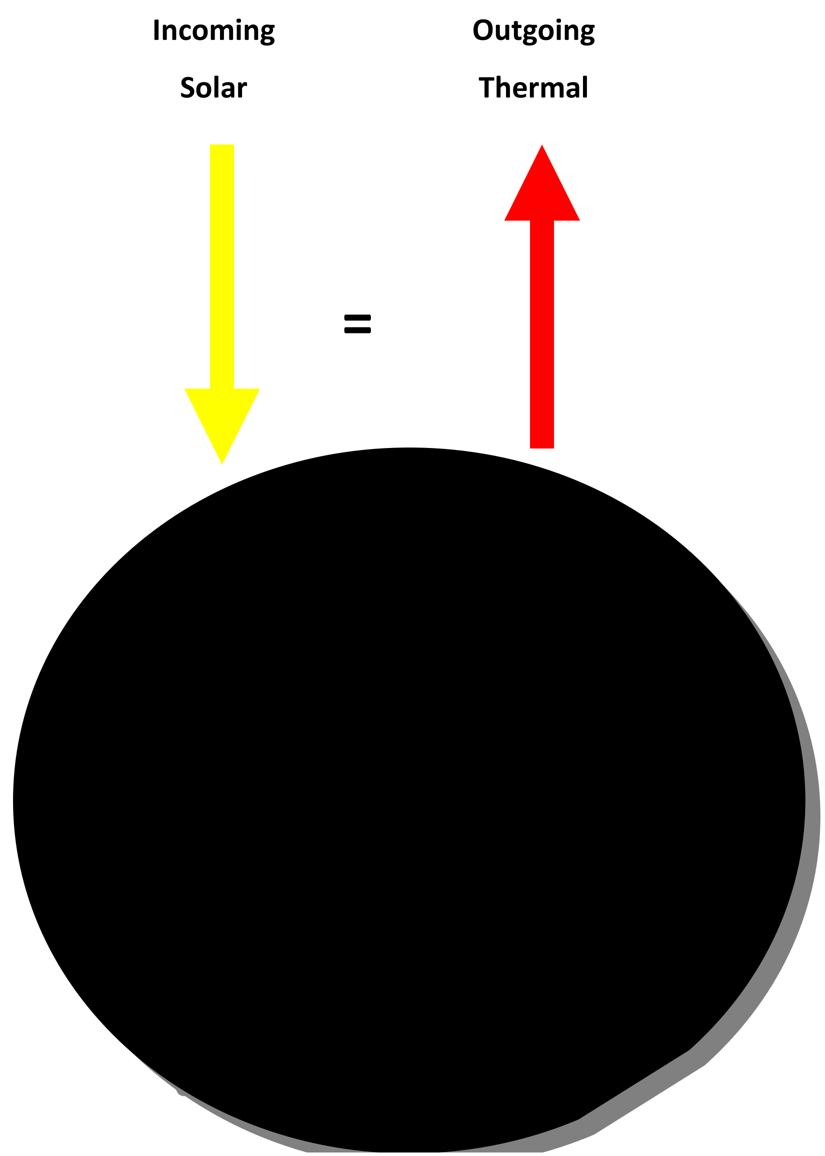
- Radiative forcing adds energy to the planet → temperature rises
- Higher temperature → more outgoing thermal radiation*
- More outgoing radiation → shrinking radiative forcing
- No radiative forcing or temperature change when thermal radiation equals incoming solar radiation: 279^o K = 6^o C

* For the curious, radiation = σT^4 where radiation is in w/m^2, temperature is in degrees Kelvin (centigrade + 273) and $\sigma = 5.67 \times 10^{-8}$ watts

The Path to Equilibrium



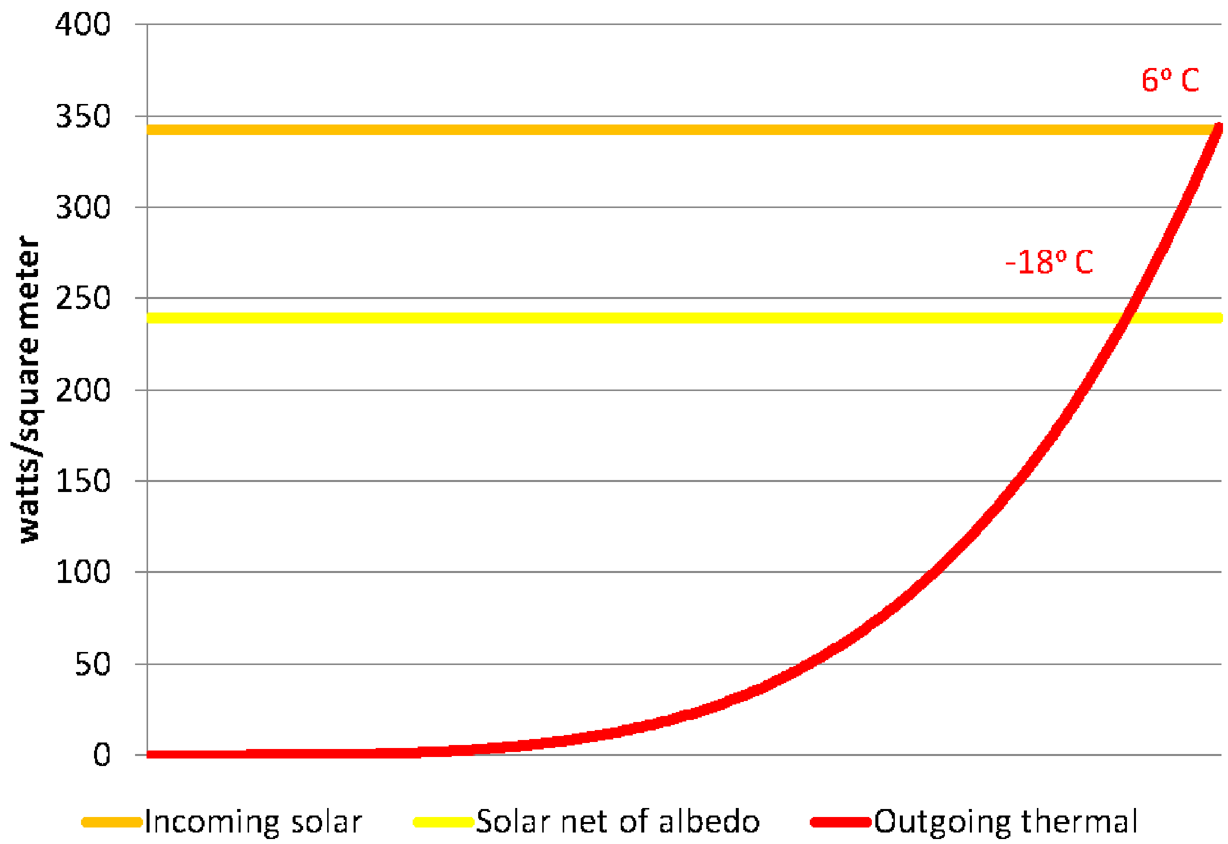
Equilibrium for Planet Keeling



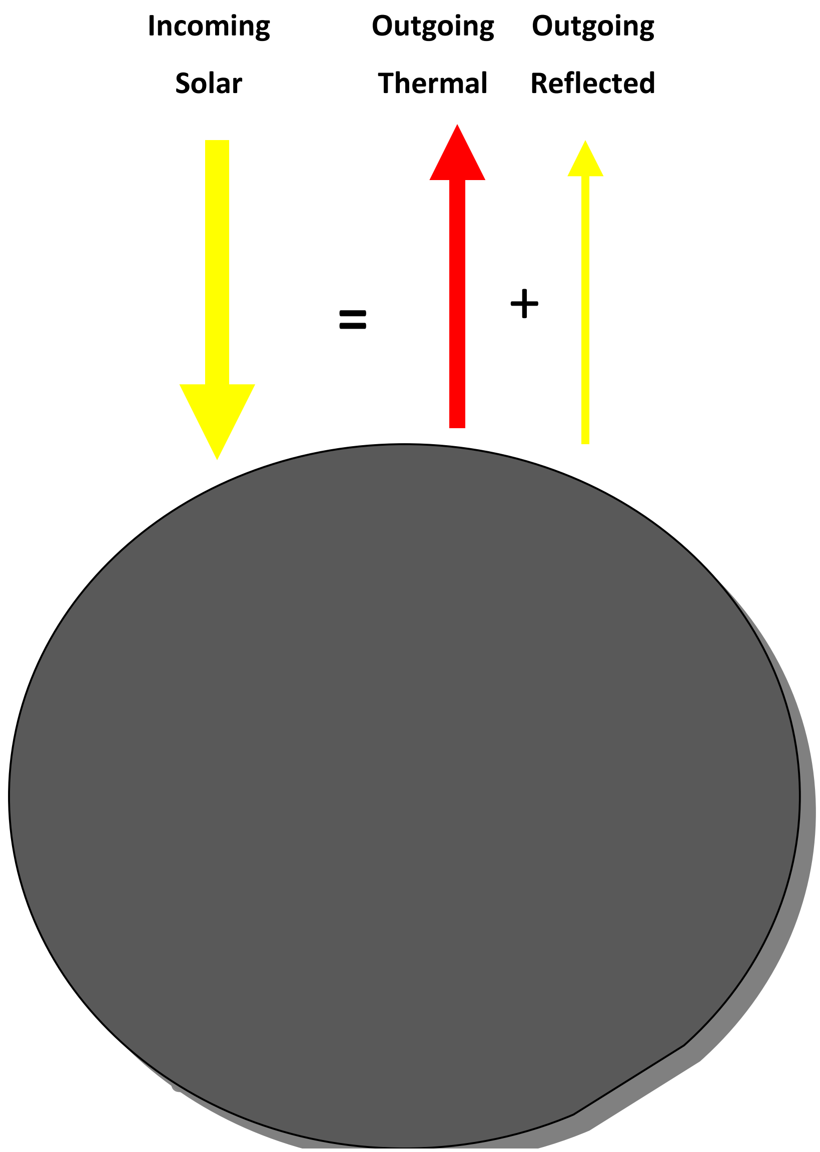
Planet Keeling Mark II: Add Albedo

- Albedo (reflectivity) = 0.3 (Earth's average)
  - 30% of incoming solar radiation reflected
  - Doesn't add energy to planet
- Solar radiation now balanced by:
  - Keeling's own thermal radiation <u>plus</u>
  - Reflected solar radiation
- Equilibrium requires less thermal radiation → reached at lower temperature

The New Path to Equilibrium



Equilibrium for Planet Keeling II



Review: Processes

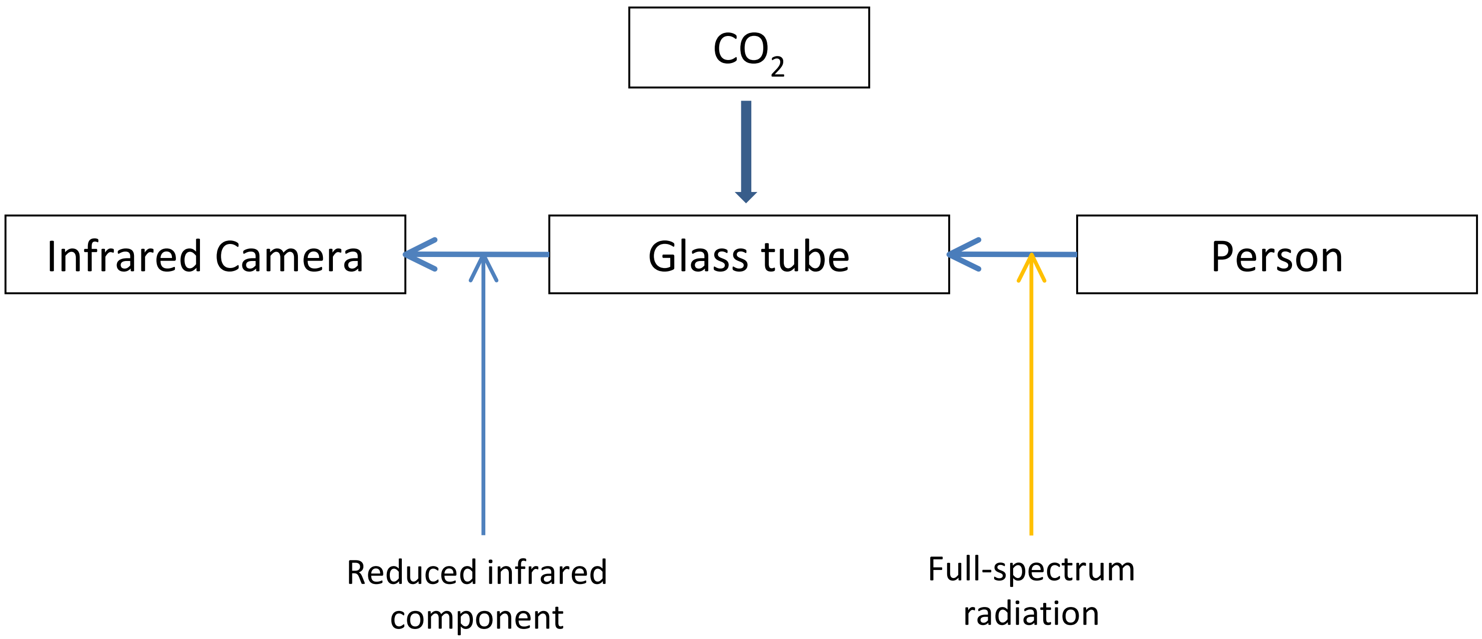
- Temperature of planetary system changes if and only if there is radiative forcing
- Other factors relevant only through effect on incoming or outgoing radiation.
- Path to equilibrium with constant solar radiation and albedo: radiative forcing produces temperature change that reduces forcing

THE GREENHOUSE EFFECT

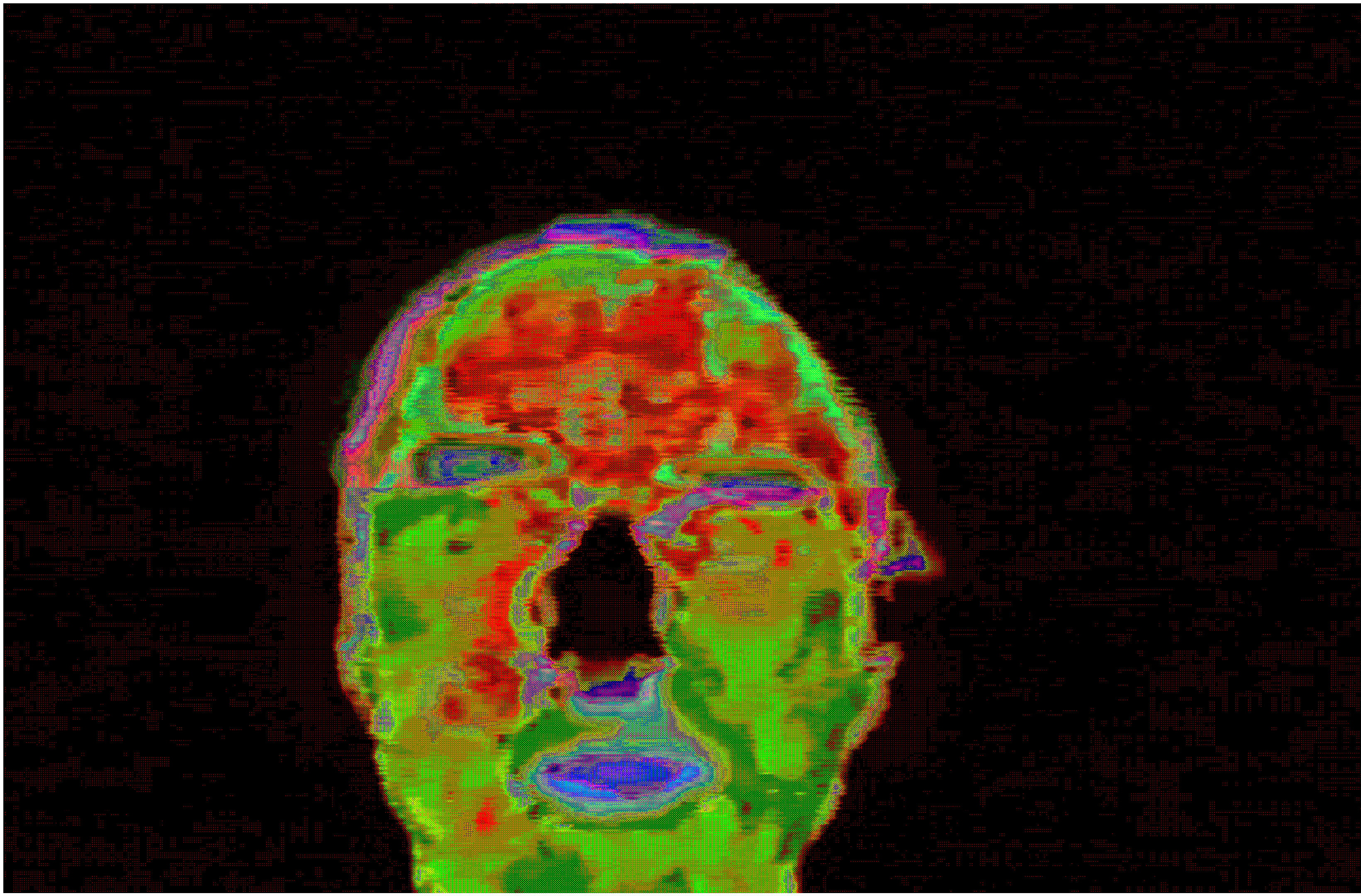
Something's Missing

- Calculated temperature is too low:
  - Solar radiation and albedo match Earth
  - But Earth is not a snowball
- Fourier (1824): Atmosphere must trap heat
- Tyndall (1859): Determines what part of atmosphere does this
  - Oxygen and nitrogen (99% of atmosphere) are transparent to infrared radiation
  - Water, CO_2 and methane (CH_4) are not

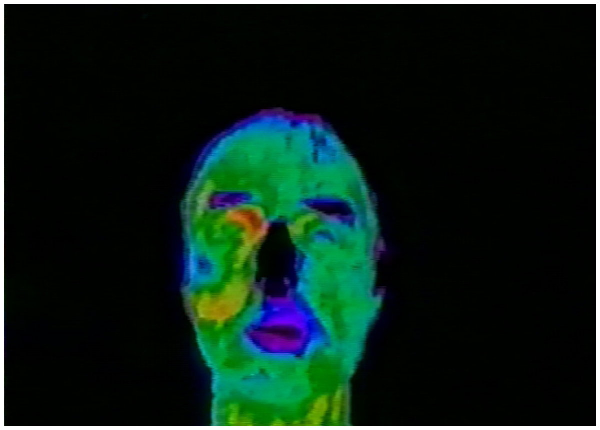
Tyndall Experiment: Modern Version

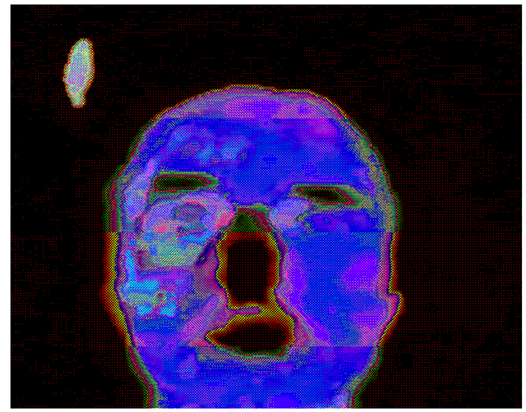


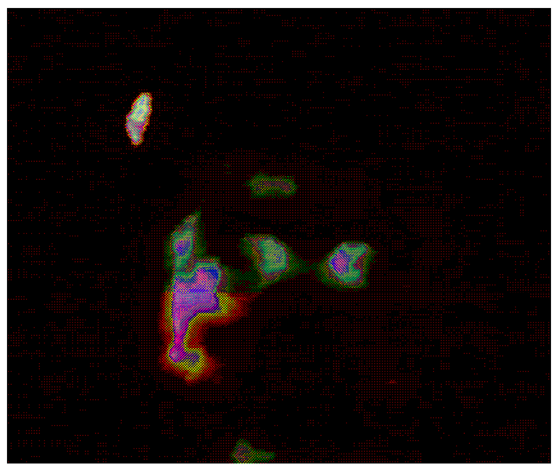
Infrared Image of Face with Normal Atmosphere



Add CO_2 to Tube – And More, and More

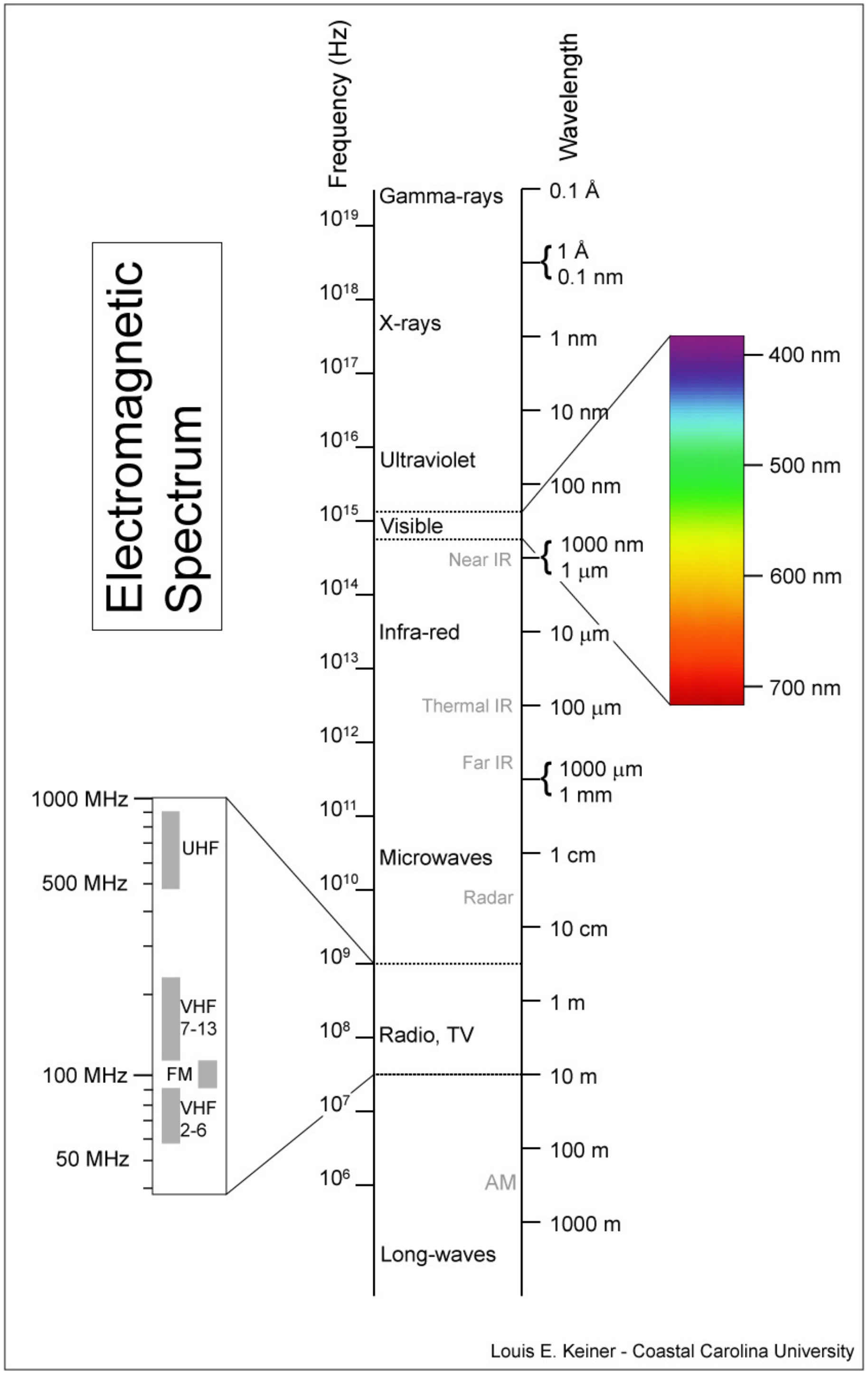






What's Happening I
Electromagnetic Radiation

- Includes visible light, X-rays, radio waves and others
- Behaves as particles (photons) <u>and</u> waves
- High/low-energy photons = short/long wavelength

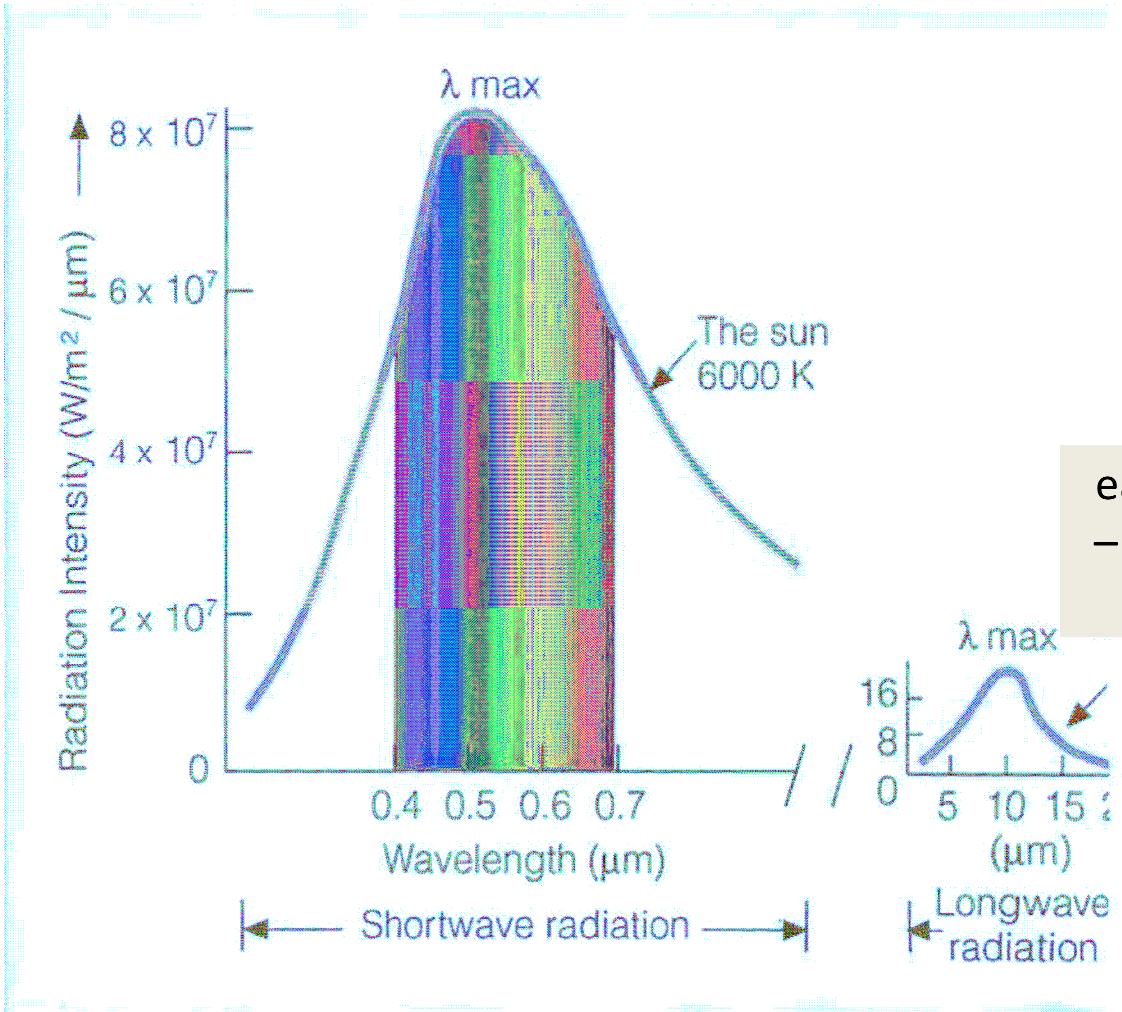


Shorter wavelength =
More energetic photons

Sun and Earth

- Photon energy/radiation wavelength determined by temperature of source
- Incoming solar radiation: high energy photons/short wavelength
- Outgoing thermal radiation: low energy photons/long wavelength

Solar Radiation
And Earth's Thermal Radiation



earth – 278 K

What's Happening II
Molecules and Greenhouse Gases

- Molecules can only occupy certain energy states – like guitar strings and pitch

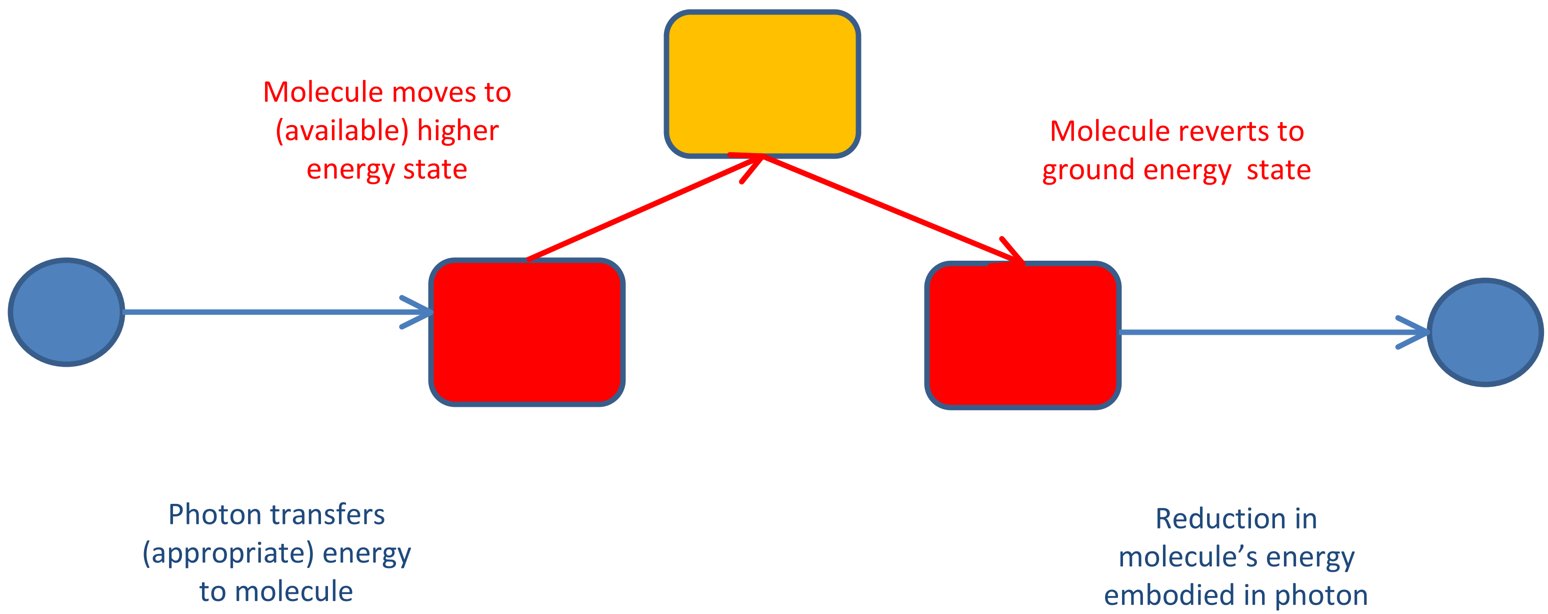
- Molecules absorb a photon if its energy matches an energy interval of the molecule

- Greenhouse gases absorb photons from Earth's thermal radiation

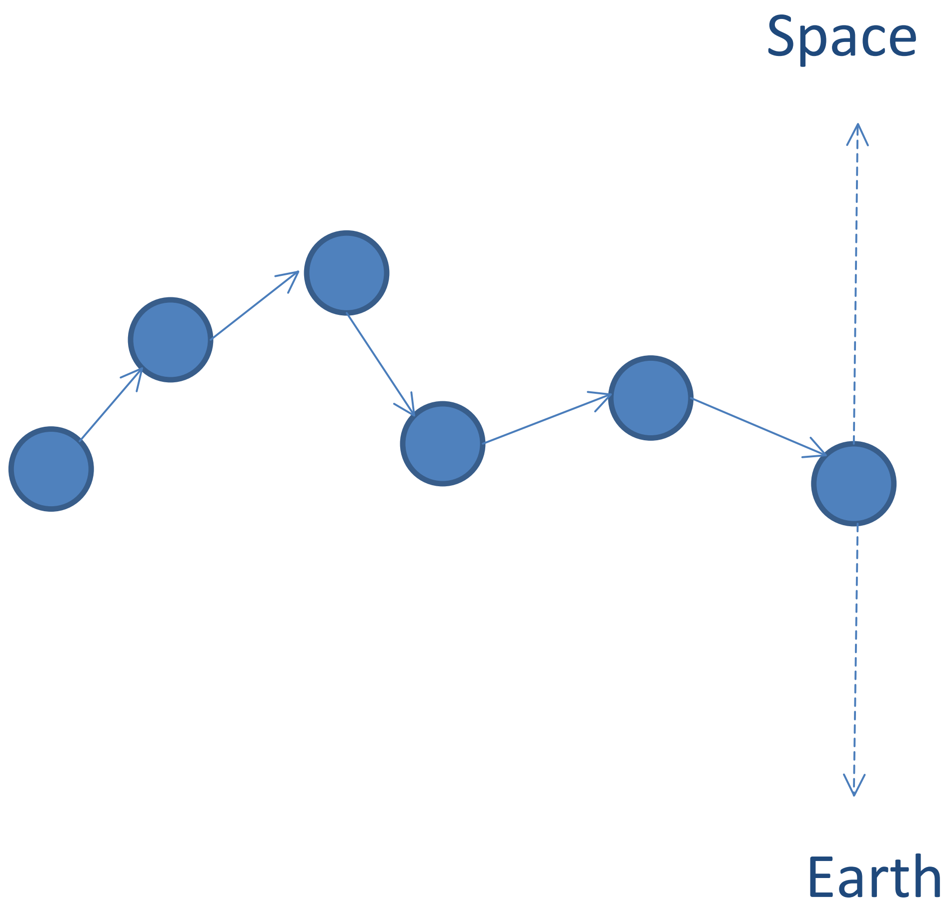
The Process Continues

- Molecule drops back to original energy level
- Emits photon
  - Same energy as before
  - But in random direction
- Further collisions repeat process
- Ends when photon escapes into space or strikes Earth's surface

From Photon to Photon: Nothing Lost and Nothing Gained



Molecular Bumper Cars



Planet Keeling Mark III (preliminary edition)

- Add CO_2 to atmosphere
- Part of outgoing radiation re-radiated back to surface
- Higher surface temperature
- But not enough higher

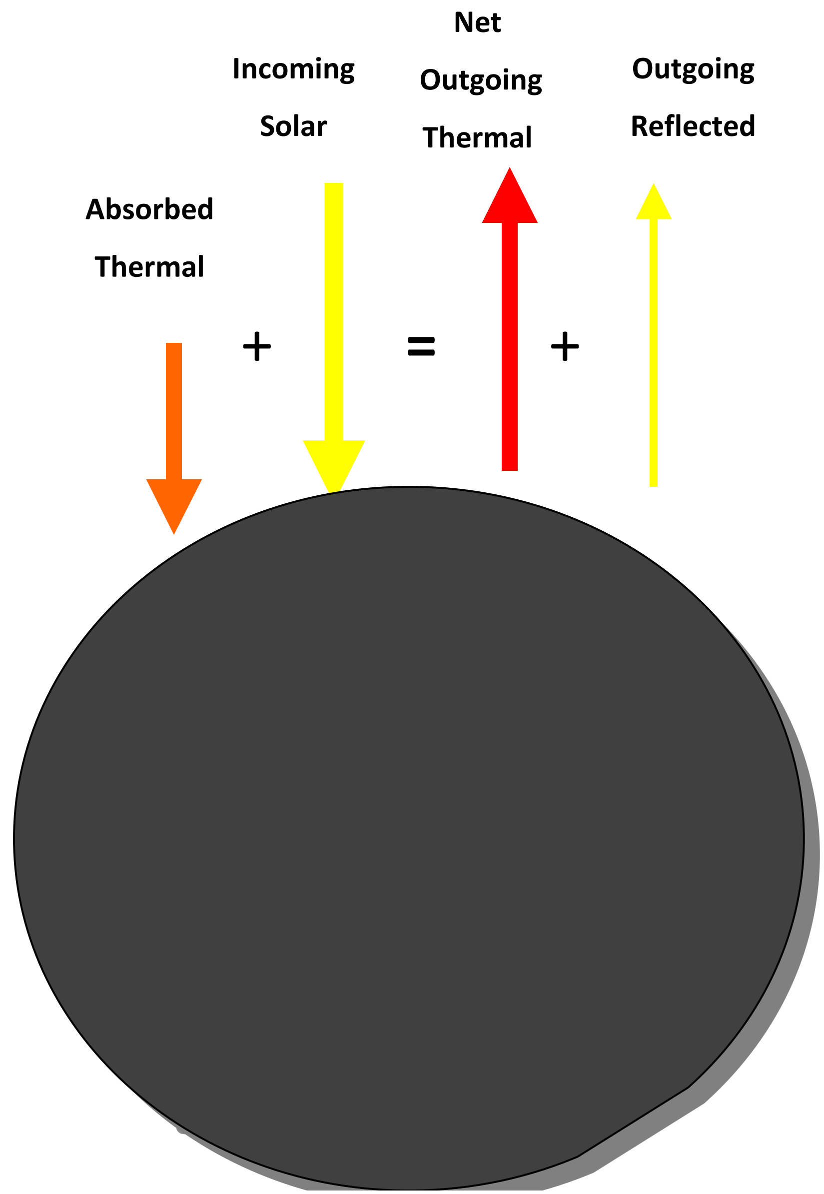
Just Add Water

- Water vapor is a greenhouse gas
- But atmospheric content determined by temperature
- CO_2: the control knob
- Water vapor: positive feedback
  - CO_2 causes temperature rise
  - Higher temperature adds water vapor to atmosphere
  - Roughly doubles effect of CO_2

Planet Keeling Mark III
The New Equilibrium

- Radiation into space now consists of:
  - Reflected solar radiation
  - Part of thermal radiation from Earth's surface
- Equilibrium requires making up thermal radiation trapped by greenhouse gases:
  - Thermal radiation from surface must increase
  - Requires higher temperature
- Equilibrium: 18^o C or 65^o F

Planet Keeling Mark III



A Tale of Two Houses

- Two houses on dark side of Mercury identical except House A is insulated and House B is not.
- Heated by identical electric heaters, which run continuously
- At end of year , thermal radiation from each house is measured.
- What is the relation between the thermal radiation from the two houses? A is greater? B is greater? They are equal?

THE DISCOVERY OF GLOBAL WARMING

Determinants of Earth's Temperature: Implications

- Earth's temperature is determined by solar radiation, albedo and greenhouse gases

- Temperature will rise if solar radiation or greenhouse gases increase or albedo declines

A Global Warming Issue?

- Points wouldn't have surprised Tyndall
- But prevailing view: these factors would not change (uniformitarianism)
- View challenged by discovery of traces of past glaciation
- World could change, but would it warm?

How It Could Warm: Svante Arrhenius

- 1896 analysis: Perhaps fewer volcanic eruptions caused ice age → less CO_2 → cooler → less water vapor → more cooling
- To be complete, lets look at the reverse
  - More eruptions → more CO_2 → more water vapor → warmer world
  - Burning fossil fuels also could serve – <u>but not for centuries</u>

Quantifying the Impact

- Considers CO_2 and water vapor feedback
- Tools: pen and paper
- Result: 5^o-6^o C warming for doubled CO_2 – within range of modern calculations
- Moral: Basic idea of global warming isn't complicated

But is there a problem?

- ArrCO_2 will not double anytime soon
- A large increase in emissions is far in the future
- Oceans will absorb the CO_2

Roger Revelle

- Grant to study ocean chemistry (1957)
  - Expects to find that ocean absorb CO_2
  - It does but (surprise) most pops back out again

- Disproves one reasons for putting problem far into the future

- But other reason remains: expected slow growth in emissions

The Issue Around 1960

- Basic science is settled
  - Tyndall
  - Arrhenius
  - Revelle

- What is lacking: measurements
  - Is CO_2 concentration increasing
  - Are global temperatures increasing