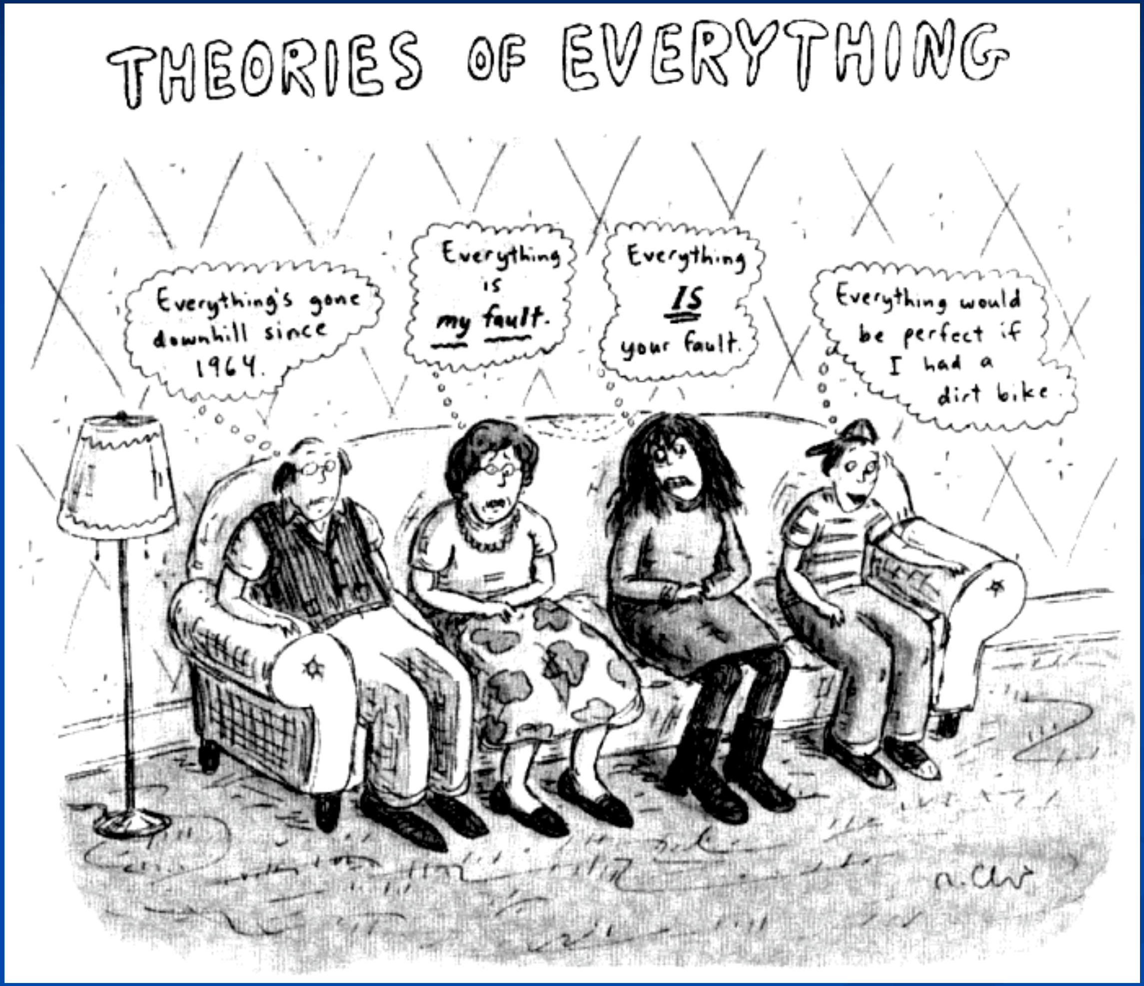
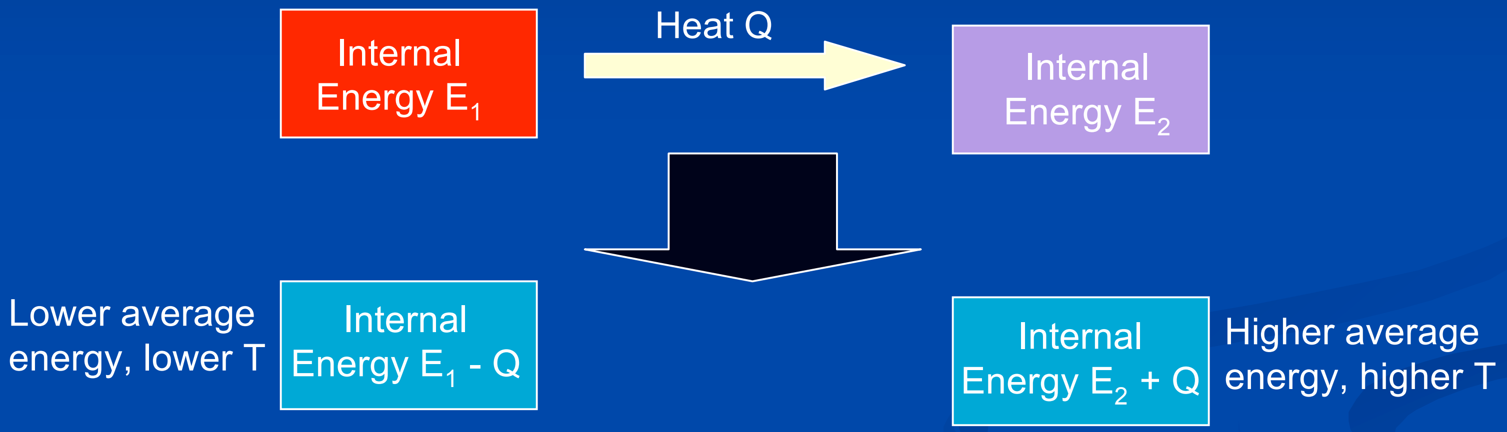

THEORIES OF EVERYTHING
Everything's gone downhill since 1964.
Everything is my fault.
Everything IS your fault.
Everything would be perfect if I had a dirt bike.
R. Chr

Energy in Transit: Heat

If a fast marble hits a random scatter of slow marbles, does the fast marble usually speed up or slow down? Which lose(s) kinetic energy and which gain(s) kinetic energy, the initially fast-moving marble or the initially slow ones? How do these questions relate to the direction of heat flow?



Internal Energy E_1

Heat Q

Internal Energy E_2

Lower average energy, lower T

Internal Energy E_1 - Q

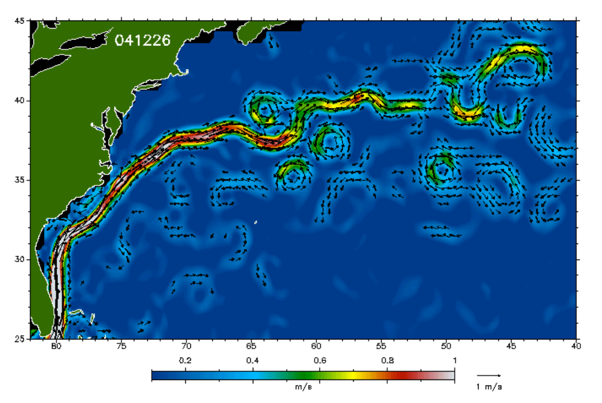
Internal Energy E_2 + Q

Higher average energy, higher T

When we transfer heat to an object, its atoms and molecules have more energy, which means the temperature is higher. One object lowers its total and average energy and thus (usually) its temperature; the other does the opposite.

Can you think of an everyday situation where you add heat to something and its temperature stays the same?

Ocean Currents and the Heat Capacity of Water



Gulf stream brings warm water to northern Europe (note the vortices!)

Summer on a beach in Norway

Summer on a ‘beach’ in Greenland (same latitude)

Not so clear what happens when the Gulf Stream (and the rest of the global ocean circulation pattern) shuts down, which is one of the possible outcomes from global warming. Oh, but never mind, global warming is a myth (hopefully).

The 'Laws' of Thermodynamics

- Equilibrium: if A is at the same T as B and B is at the same T as C, in then A must be the same T as C
- **Energy is conserved**
- Total system entropy can never decrease
- As the temperature goes to zero, the entropy approaches a constant value—this value is zero for a perfect crystal lattice

Demo: conducting blocks

Heat Engine Concept

- Any time a *temperature difference* exists between two bodies, there is a *potential* for *heat flow*
- Examples:
    - heat flows out of a hot pot of soup
    - heat flows into a cold drink
    - heat flows from the hot sand into your feet
- Rate of heat flow depends on nature of contact and *thermal conductivity* of materials
- If we're clever, we can channel some of this flow of energy into mechanical work

Heat → Work

- We can see examples of heat energy producing other types of energy
    - Air over a hot car roof raises, gaining *kinetic energy*
    - That same air also gains *gravitational potential energy*
    - All of our *wind* is driven by temperature differences
    - We already know about *radiative* heat energy transfer
    - Our electricity generation thrives on temperature *differences*: no steam would circulate through a turbine and power plant if everything was at the same temperature

Demo: Stirling engine

Power Plant Arrangement

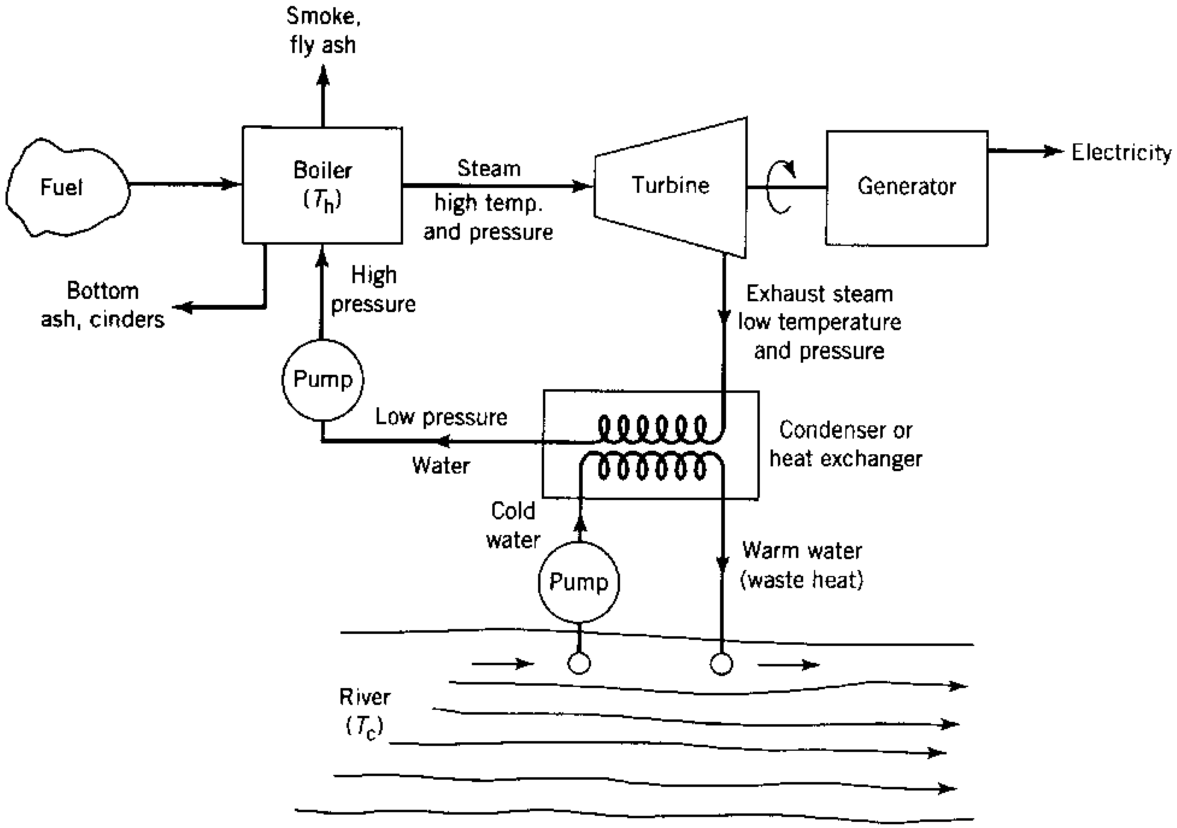


Figure 3.4 A diagram of a fuel-burning electric power plant. Here a river provides cooling water to the condenser, but lake water or a cooling tower could serve the same purpose.

Heat flows from T_h to T_c, turning turbine along the way

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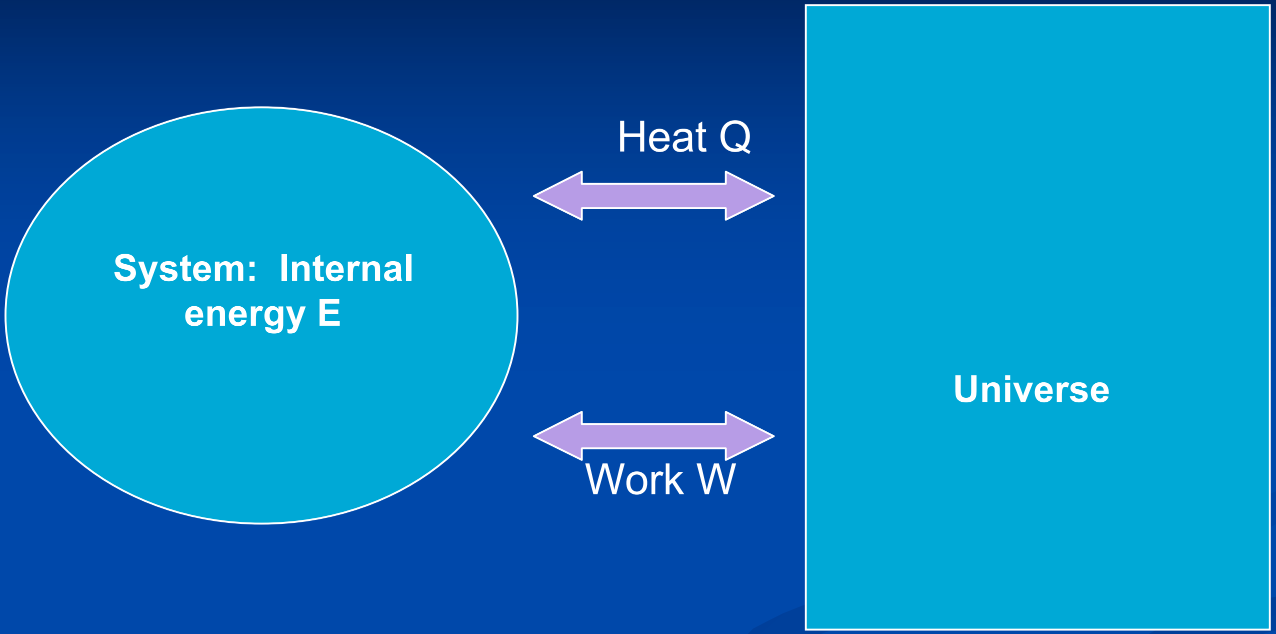
- **Energy is conserved**
- Total system entropy can never decrease
- As the temperature goes to zero, the entropy approaches a constant value—this value is zero for a perfect crystal lattice
- The concept of the "total system" is very important: entropy can decrease locally, but it must increase elsewhere by *at least* as much
  - no energy flows into or out of the "total system": if it does, there's more to the system than you thought

Demo: fire syringe

The First Law of Thermodynamics



Heat added the system Q = increase in system energy E + work done by the system W

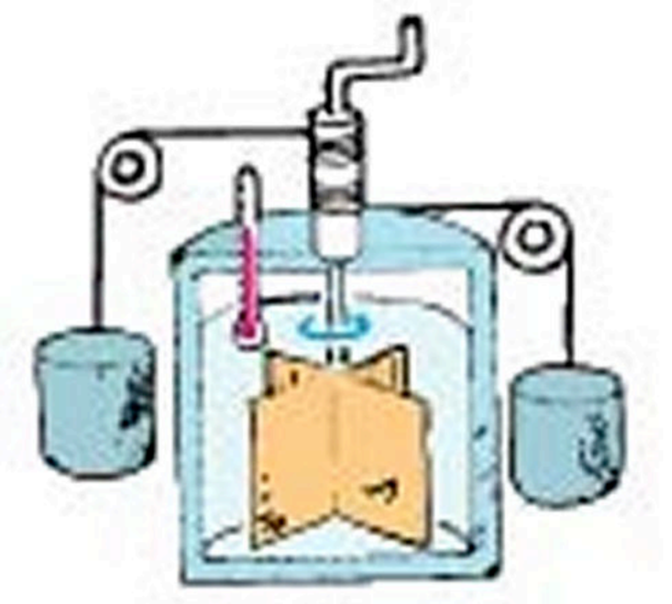
Essence: You can’t win. The total energy must remain constant.

If 100 J of heat is added to a system that does no external work, by how much is the internal energy of that system raised?

If 100 J of heat is added to a system that does 40 J of external work, by how much is the internal energy of that system raised?

These are the sorts of questions that needed answers 200 years ago.

Joule-Like Experiments: Converting Mechanical Energy to Heat



This is easy – you've all converted mechanical energy to heat.

Masses fall, lowering their gravitational potential energy;

This energy gets converted to heat, and the temperature rises.

Say the total mass is 10 kg, they fall 1 m, and there is 1 liter of water being heated. How much does the temperature rise?

We can think of the whole system as isolated so the total energy remains constant. Then the gravitational energy just gets turned into heat.

Work done = force x displacement = (10kg)(10m/sec^2)(1 m) = 100J

$Q = C \times m \times \Delta T$

100J = 0.1 kJ = 4.2 kJ/kg-^{o}C x 1 kg (of water!) x ΔT

ΔT = 0.1 kJ/(4.2 kJ/kg-^{o}C x 1 kg) = 0.3^{o}C (not much – Joule did more work than this)

The ‘Laws’ of Thermodynamics

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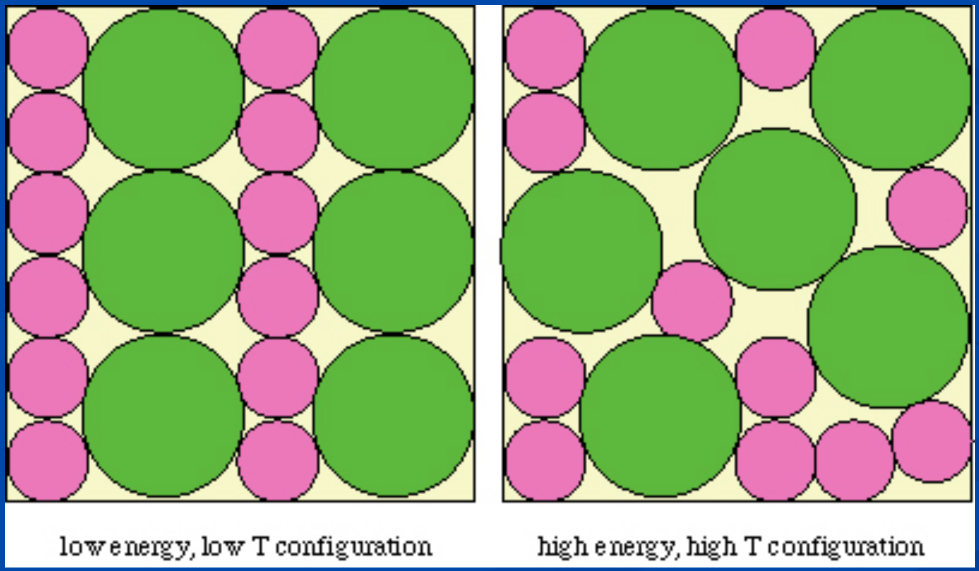
What's this *Entropy* business?

- Entropy is a measure of disorder (and actually quantifiable on an atom-by-atom basis)
  - Ice has low entropy, liquid water has more, steam has a lot



Heat Energy and Entropy

- We've already seen examples of quantifying heat
  - 1 Calorie is the heat energy associated with raising 1 kg (1 liter) of water 1 °C
  - In general, $\Delta Q = c_p m \Delta T$, where c_p is the heat capacity

- A transfer in heat energy accompanies a change in entropy:

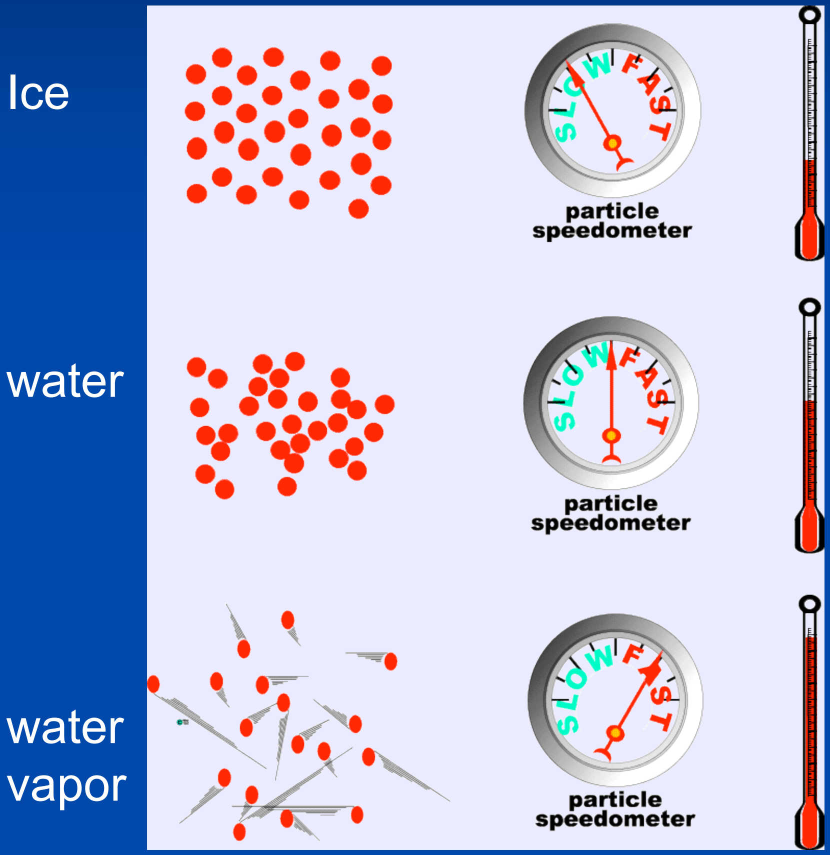
$$\Delta Q = T \Delta S$$

- Adding heat increases entropy
  - more energy goes into random motions→more randomness (entropy)

- What entropy is flowing in the operation of a refrigerator???

- Important : those T's are absolute T's. . . . in Kelvin

Absolute Temperature Scale



Temperature measures the average kinetic energy of the atoms in a substance.

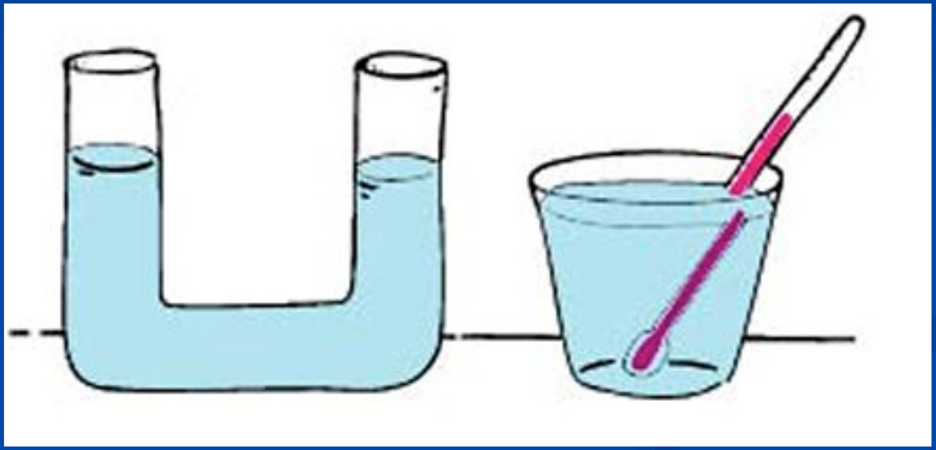
It does not measure the total kinetic energy: 1000 kg of water at 68^{o}F has more energy than 1 kg of water at 68 ^{o}F, but they are at the same temperature.

Temperature is not heat. We can transfer a quantity of heat to 1000 kg of water at some temperature, but we cannot transfer a quantity of temperature to it.

At what temperature does all molecular motion stop? 32^{o}F? 0^{o}C?

Intensive Properties

Temperature is like pressure – these are intensive. Temperature and pressure are defined at all points in a system. Objects in contact tend to equilibrate at the same temperature and pressure.

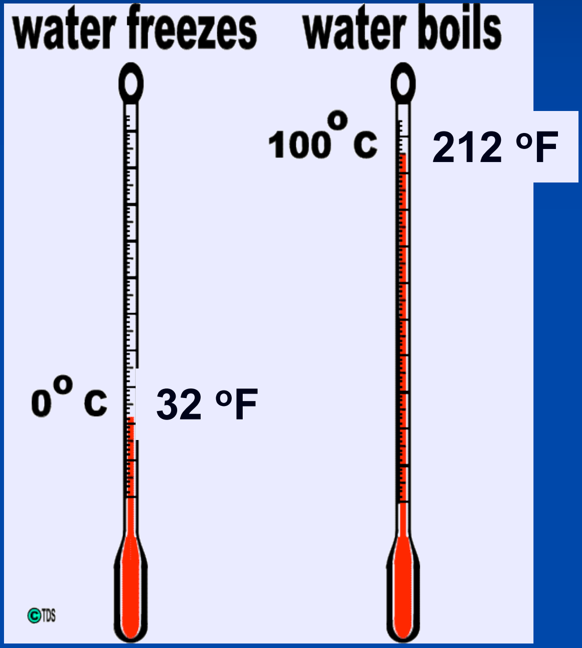


Energy, mass, particle number and volume are extensive. If you duplicate a system, they double. Temperature and pressure do not.

For a uniform substance, is density intensive or extensive? Note that density = mass/volume – the ratio of two extensive parameters.

Temperature Scales

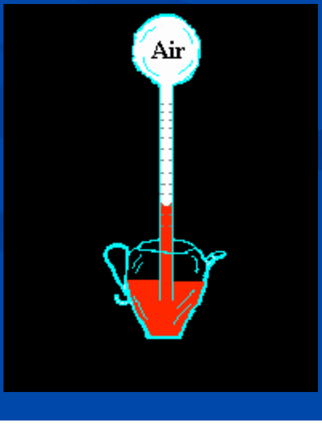
Here's one where physicists actually have it right . . .



Centigrade: 100 division between the melting and boiling temperatures of water (now called this the Celsius scale, after some Swedish guy →)

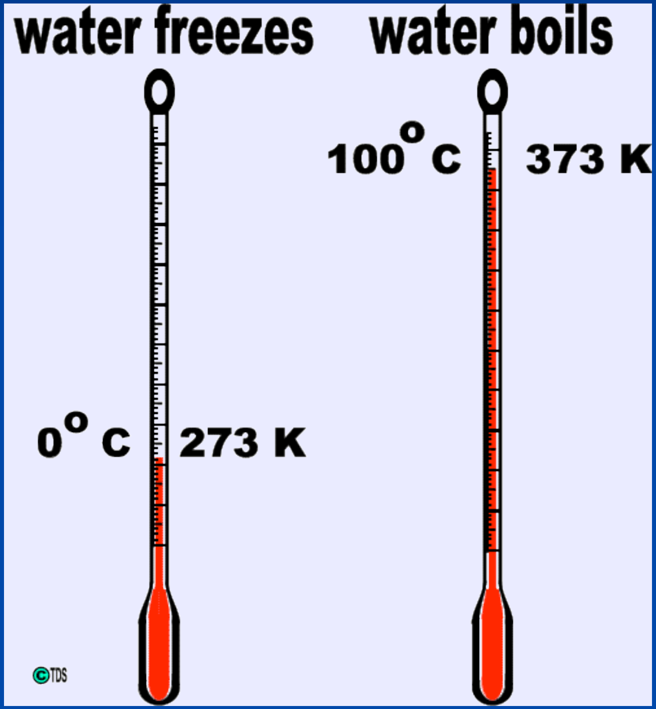
Fahrenheit: 180 divisions between the same two temperatures, with an offset of 32 (huh? no pix on the web?).

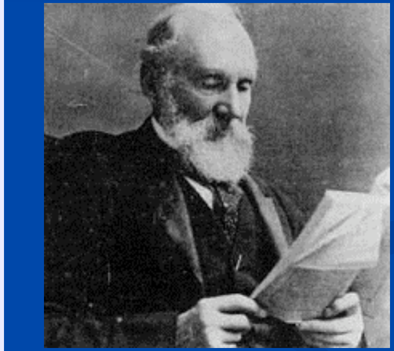
Did Fahrenheit have $\sqrt{180}$ fingers or what?? Don't know – no pictures. Hmm. . .



Galileo made the first thermometer, using gases and liquids.
Fahrenheit and Celsius developed liquid-based thermometers.
What's the advantage of a liquid-based thermometer?

Or Do They. . . . The ‘Absolute’ Temperature Scale?



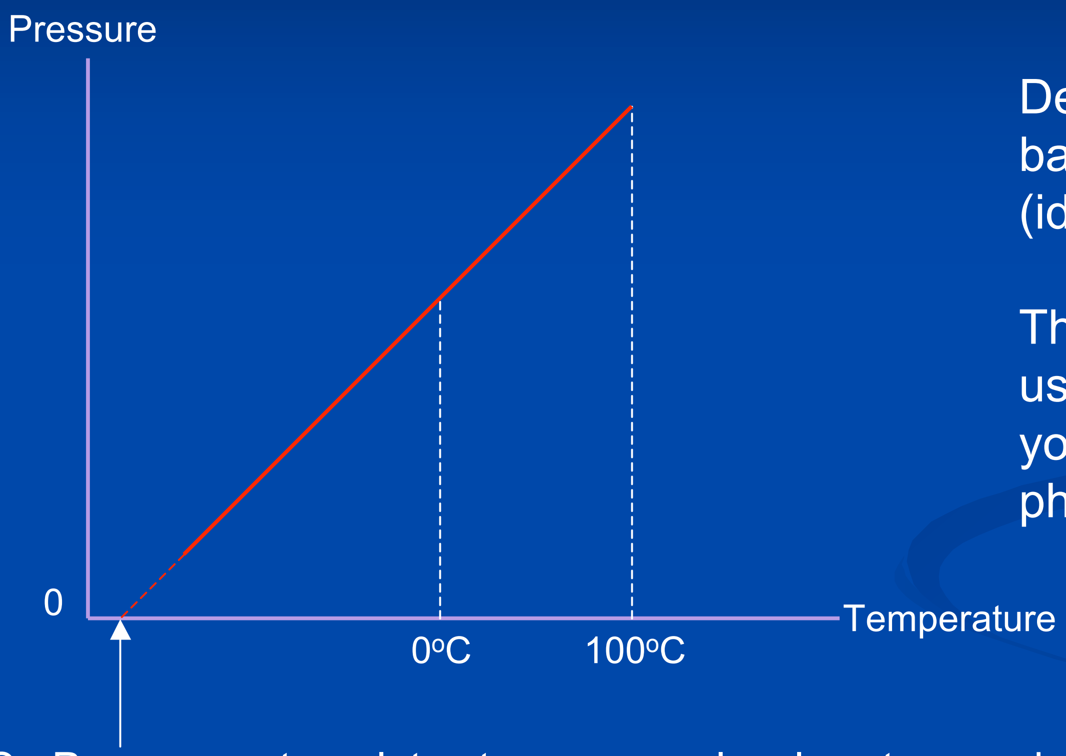


Lord Kelvin, a.k.a William Thompson. Why do we measure absolute T in degrees K, not degrees Thompson?

Why do we drive on a parkway and park on a driveway?

Anybody wanna guess what the ‘Rankine’ temperature scale is?
Hint: it’s used by engineers who think in units like BTU’s and slugs.

Huh? Ice Melts at 273 Degrees K?



Define a temperature scale based on the behavior of (ideal) gases.

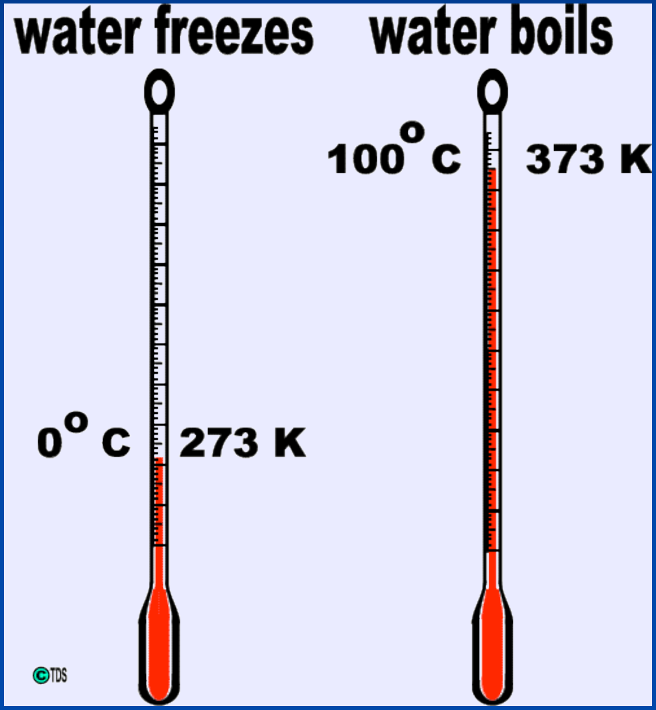
The Kelvin scale is not so useful for everyday use, but you can easily guess that physicists find it very useful.

-273^oC: Pressure extrapolates to zero – molecules stop moving! Energy is zero at 'absolute zero'. We can heat something as hot as we like, but there is a limit to how cold we can go.

$$T(K) = T(^oC) - 273$$

(and yes, by convention the lordly K does not get a ^{o})

Liquid Thermometers Operate on Relative Thermal Expansion

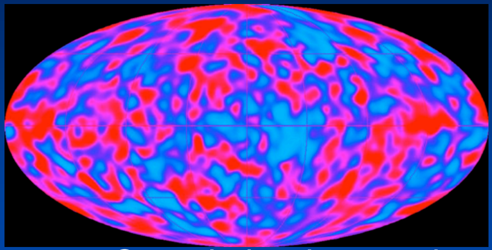


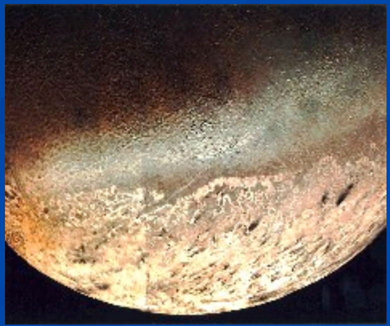
. . . between glass and the liquid.

Below 4°C, the glass would expand more than water so the temperature would appear to go up while it was actually going down.

Some Common Temperatures

cosmic blackbody background	2.726K
helium boiling point (at P = 1 atm)	4K
hydrogen boiling point (at P = 1 atm)	20K
Neptune's moon Triton	38K
nitrogen boiling (at P = 1 atm)	77K
boiling point of tungsten	5828K


Cosmic background variations from COBE

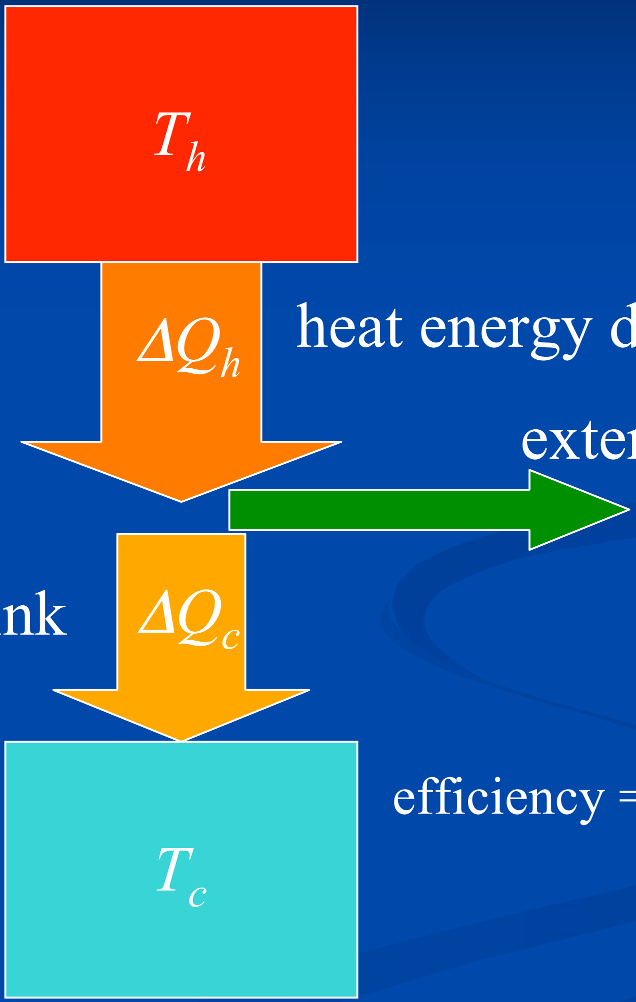

The coldest spot in the solar system

How low can we go? How close to absolute zero? Less than 10^{-9} K.

The 'Laws' of Thermodynamics

- Equilibrium: if A is at the same T as B and B is at the same T as C, in then A must be the same T as C
- Energy is conserved
- Total system entropy can never decrease
  - Or, one cannot make a heat engine with perfect efficiency; there must always be some waste heat when you convert heat into work
  - Or, or can not go from a disordered system to an ordered system without inputting external energy
  - Or, . . .

How much work can be extracted from heat?



Hot *source* of energy

T_h

ΔQ_h

heat energy delivered from source

externally delivered work:

$$\Delta W = \Delta Q_h - \Delta Q_c$$

conservation of energy

heat energy delivered to sink

ΔQ_c

Cold *sink* of energy

T_c

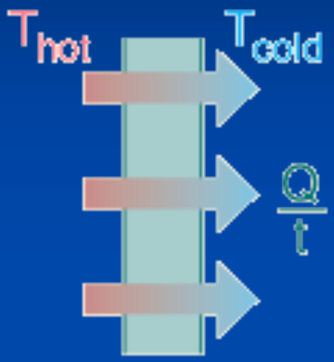
$$\text{efficiency} = \frac{\Delta W}{\Delta Q_h} = \frac{\text{work done}}{\text{heat supplied}}$$

Heat and Heat Transfer

- Heat vs. temperature: heat is energy in motion and is related to temperature change by heat capacity; temperature is a measure of the average kinetic energy the atoms inside something have
- Heat is energy in motion - we do not ask ‘how much heat does something have in it’ (at least physicists don’t); it goes into the energy balance described by the first law - the ‘conservation of energy’
- Controlling heat transfer is a key ingredient of ‘energy conservation’ and cooking. How is heat transferred?

Heat Transfer: Conduction

- Heat moves ‘from the hot end to the cold end’



$$\frac{Q}{t} = \frac{\kappa A(T_{hot} - T_{cold})}{d}$$

Q = heat transferred in time t

A = cross-sectional area

κ= thermal conductivity

d = thickness of material

Metals, eg., copper: high thermal conductivity

Insulators, e.g., wood, low thermal conductivity

What are the units of thermal conductivity?

Heat Conduction and Insulation R-factors

- Ever shop for insulation? If so, you've run up against R-factors or R-values. These are essentially d/κ, which is a normalized efficiency for insulation
- Large R means good insulation: $Q/t = A \times \Delta T/R$
- Example: 6" of fiberglass insulation has an R-value of 19 in units of ft^2-hr-^oF/Btu. With a temperature difference of 30 ^oF, what is the rate of heat flow through 100 square feet of R-19 fiberglass?

$Q/t = 100\ ft^2 \times 30^oF/19\ ft^2\text{-hr-}^oF/Btu = 158\ Btu/hr = 46\ Watts$

This ignores other forms of heat transfer. . .

Star conductor demo
Water balloon demo . . . Huh?
Boiling water demo . . .
Conducting block demo, again

Radiant Energy

- Really just a special case of electromagnetic energy in the form of waves traveling at the speed of light c = 3×10^8 m/sec (a classical notion of light)

- Encompasses everything from radio waves to gamma rays – the entire EM spectrum of wavelengths and frequencies

- We will have more to say about this later in the context of photovoltaic and solar energy, e.g., the solar constant: on average, about 1400 J of radiant energy strikes every square meter of the earth's upper atmosphere every second.

Energy from Light

- The tremendous energy from nuclear reactions in the sun is released as light. So light carries energy.
- How much??
- Best way to get at this is through the process of "blackbody" radiation, or thermal radiation…
- All objects emit "light"
  - Though almost all the light *we* see is *reflected* light
- The color and intensity of the emitted radiation depend on the object's temperature

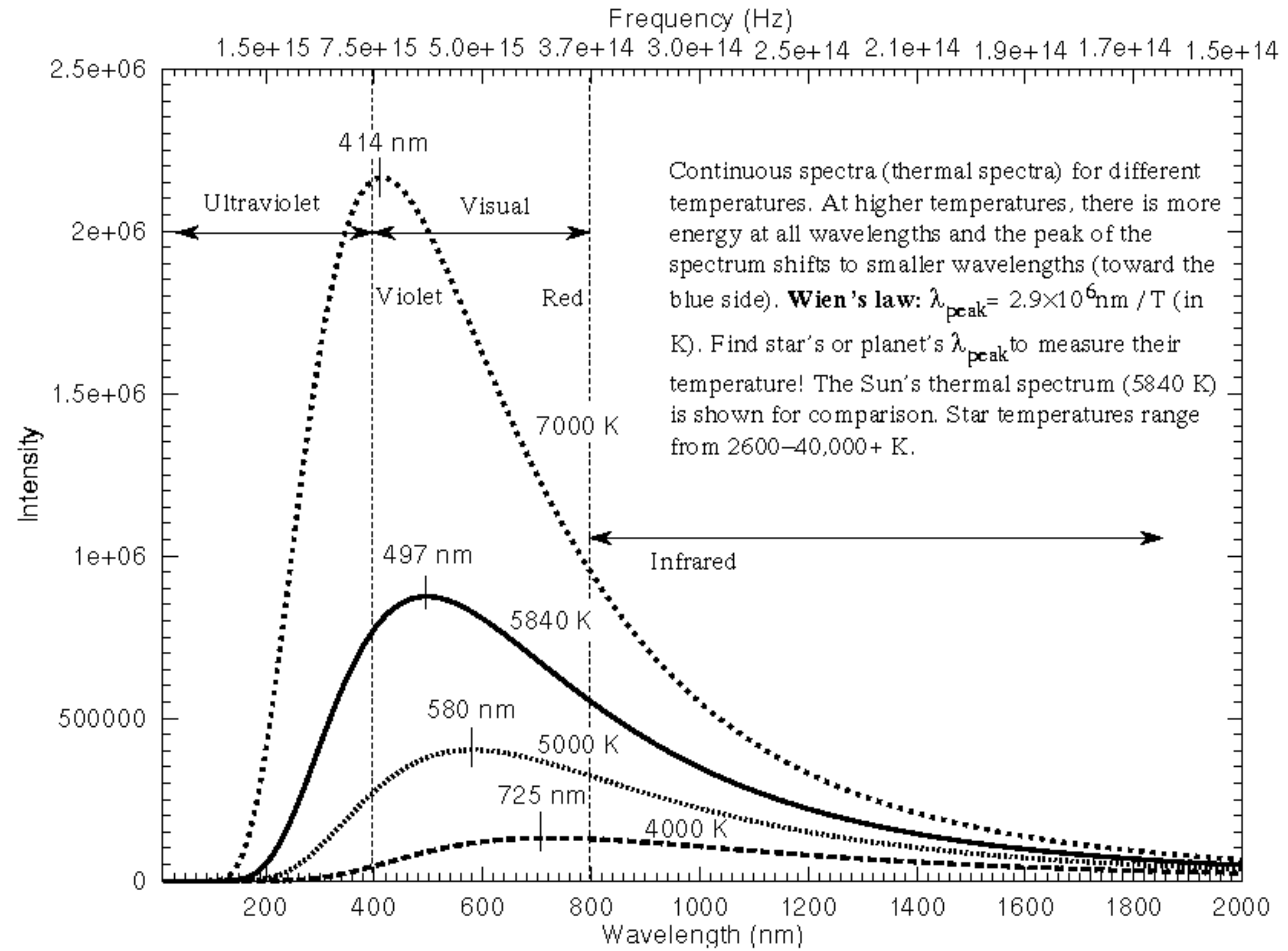
Demo: Radiation detector

Emitted Radiation's Color and Intensity depend on Temperature*

Object	Temperature	Color
You	~ 30 C	Infrared (invisible)
Heat Lamp	~ 500 C	Dull red
Candle Flame	~ 1700 C	Dim orange
Bulb Filament	~ 2700 C	Yellow
Sun's Surface	~ 5500 C	Brilliant white

The hotter it gets, the "bluer" the emitted light
The hotter it gets, the *more intense* the radiation (more energy)

"Blackbody", or Planck Spectrum



Continuous spectra (thermal spectra) for different temperatures. At higher temperatures, there is more energy at all wavelengths and the peak of the spectrum shifts to smaller wavelengths (toward the blue side). **Wien's law:** $\lambda_{peak} = 2.9\times10^{6}$ nm / T (in K). Find star's or planet's λ_{peak} to measure their temperature! The Sun's thermal spectrum (5840 K) is shown for comparison. Star temperatures range from 2600–40,000+ K.

Heat Transfer by Radiation

- This is called Blackbody Radiation: any object not at T = 0K radiates energy

$F = \sigma T^4$ in Watts per square meter $\sigma = 5.67\times10^{-8}$ W/°K^4/m^2

- Except we have not talked about emissivity ε, which is a measure of how efficiently something radiates; black things radiate efficiently and have emissivity of ~1, white and shiny things do not and have emissivity below 0.1.

- In reality, $F = \varepsilon\ \sigma T^4$ and power = P = $\varepsilon\ \sigma T^4$ A

Okay, but how much energy?

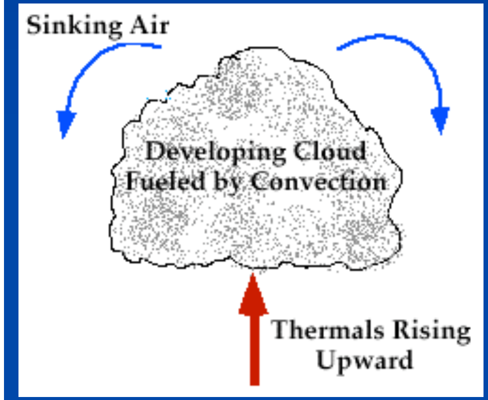
- The power given off of a surface in the form of light is proportional to the *fourth power* of temperature!
- $F = \sigma T^4$ in Watts per square meter
  - the constant, σ, is numerically 5.67×10^{-8} W/°K^4/m^2
  - easy to remember constant: 5678
  - temperature must be in Kelvin:
    - °K = °C + 273
    - °C = (5/9)×(°F –32)
- Example: radiation from your body:
  - $(5.67\times10^{-8})\times(310)^4 = 523$ Watts per square meter
  - (if naked in the cold of space: don’t let this happen to you!)

Radiant Energy, continued

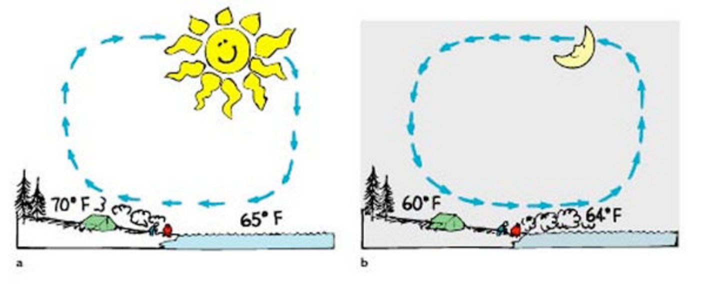
- Example: The sun is 5800°K on its surface, so:
  - $F = \sigma T^4 = (5.67\times10^{-8})\times(5800)^4 = 6.4\times10^7$ W/m^2
  - Summing over entire surface area of sun gives
  - 3.9×10^{26} W
- Compare to total capacity of energy production on earth: 3.3×10^{12} W
  - Single power plant typically 0.5–1.0 GW (10^9 W)
- In earthly situations, radiated power out partially balanced by radiated power in from other sources
  - Not 523 W/m^2 in 70°F room, more like 100 W/m^2
    - goes like $\sigma T_h^{\,4} - \sigma T_c^{\,4}$

Heat Transfer by Convection

Transfer of heat due to the actual motion of a fluid. You've seen this above your toaster or a hot parking lot.




-- Photograph by Ronald L. Holle --



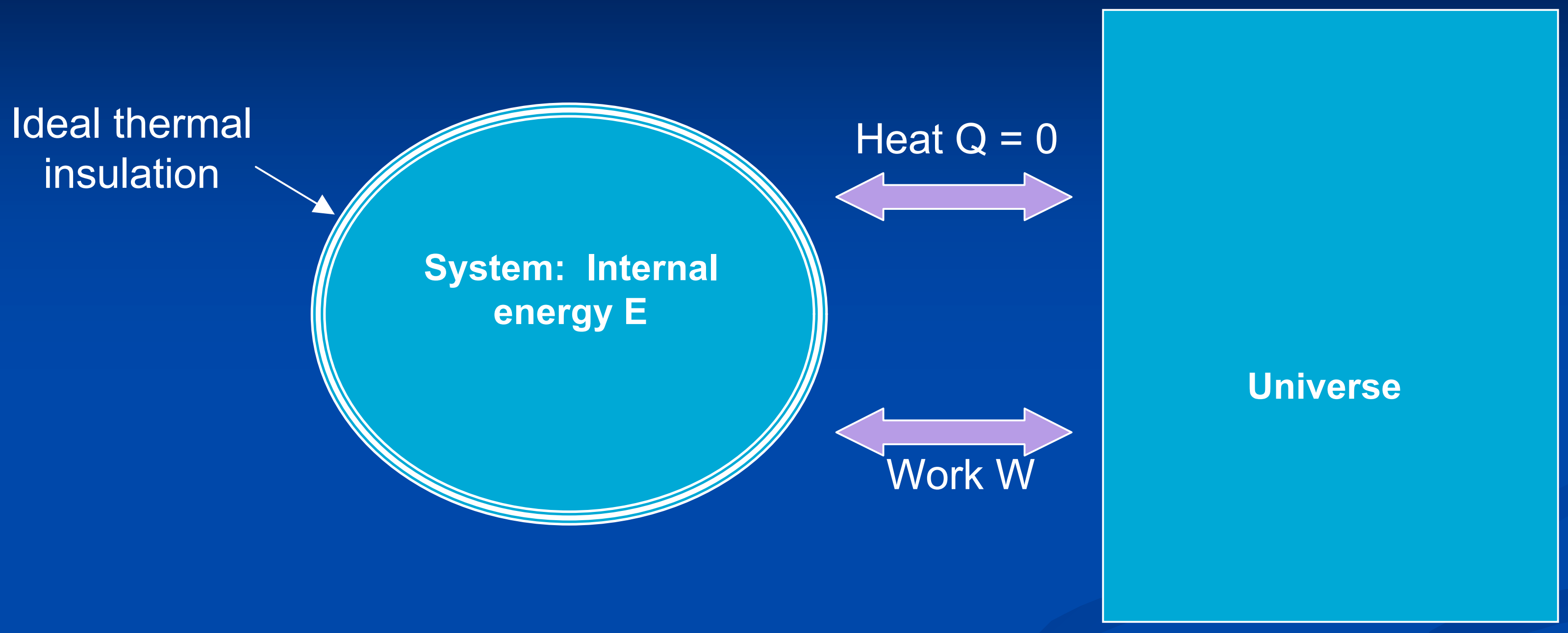
On-shore vs. off-shore breezes.

Convection often entails 'rolls' of fluid motion, with cool fluid being warmed and thus having its density lowered in a localized region. It then rises locally, but falls elsewhere. It is often the dominant mechanism of heat transfer in everyday life.

Geothermal convection drives plate tectonics as well as many astrophysical phenomena.

Convection chamber demos

A Special Kind of Process: Adiabatic Processes with Q = 0

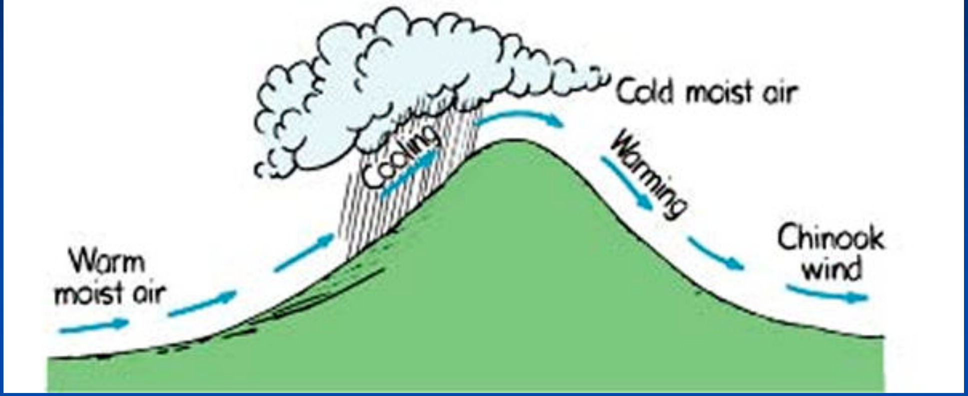


We insulate the system so that essentially no heat flows on the time scale of our observation. This is a reasonable approximation for many expansions and compressions of gases because the thermal conductivity of gases is small so little heat flows in any case.

In this case: increase in system energy = - work done by system

Makes sense: the system does some work (with no heat flow), its energy must decrease.

‘Forced’ Adiabatic Processes in the Atmosphere



You’ve experienced this if you’ve driven over the Cascades and into eastern Oregon.

If a parcel of dry air initially at 0°C expands adiabatically while flowing upward alongside a mountain a vertical distance of 1 km, what will its temperature be? When it has risen 5 km?

What happens to the air temperature in a valley when cold air blowing across the mountain tops descends into the valley?

Imagine a giant dry-cleaner's garment bag full of air at a temperature of −10°C floating like a balloon with a string hanging from it 6 km above the ground. If you were able to yank it suddenly to the ground, what would its approximate temperature be? Why is it cold outside an airliner at ~10 km?

Heat Transfer Summary

- Controlling heat transfer requires careful design, taking into account conduction, radiation, and convection.
- Building codes have evolved a lot over the past several decades to require better and better insulation - old houses lose a lot of heat compared to new houses
- On a global scale, heat transfer by convection and radiation are key ingredients of atmospheric physics. So are latent heats . . .