## Types of Heat Transfer

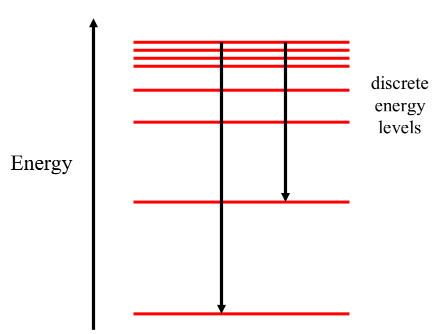
- $\frac{q_x}{A} = -k\frac{dT}{dx}$ •conduction (Fourier's Law)
- $\underline{v}\cdot\nabla T$ •forced convection (due to flow)
- $S$ •source terms
- $\frac{Dv_z^*}{Dt} = \left(\nabla^2 v_z\right)^* + \mathrm{Gr}T^*$ •free convection (fluid motion due to density variations brought on by temperature differences)
- $\Delta H_{vap}$ •heat transfer with phase change (e.g. condensing fluids)
- last subject in the course { **•radiation**

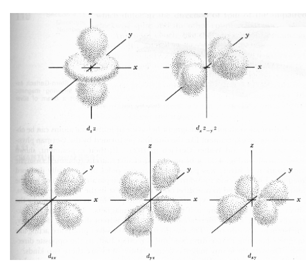


## Heat transfer due to radiation

•in atoms and molecules electrons can exist in multiple, discrete energy states

•transfers between energy states are accompanied by an emission of radiation



Sienko and Plane, Chemistry: Principles and Applications, McGraw Hill, 1979

Quantum Mechanics

## Radiation versus Conduction and Convection

Continuum view

- Conduction is caused by macroscopic temperature gradients
- Convection is caused by macroscopic flow
- Radiation? **NO CONTINUUM EXPLANATION**

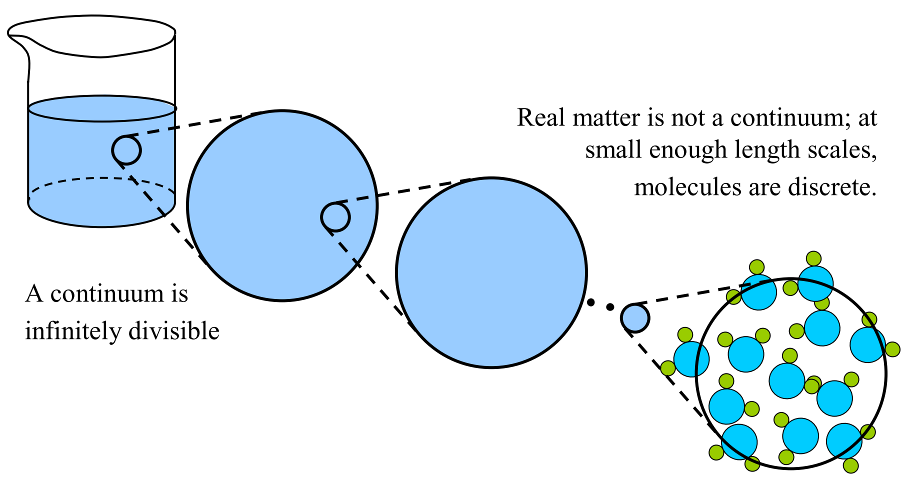
Molecular view

- Conduction?
- Convection?
- Radiation is caused by changes in electron energy states in molecules and atoms

***There is, of course, a molecular explanation of these effects, since we know that matter is made of atoms and molecules***



## Continuum versus Molecular description of matter

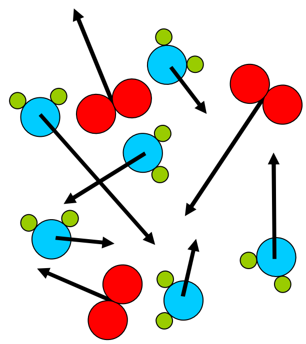


A continuum is infinitely divisible

Real matter is not a continuum; at small enough length scales, molecules are discrete.

Individual molecules carry:

- •chemical identity
- •macroscopic velocity (speed and direction)
- •internal energy (Brownian velocity)



When they undergo Brownian motion within an inhomogeneous mixture, they cause:

- •diffusion (mass transport)
- •exchange of momentum (momentum transport)
- •conduction (energy transport)

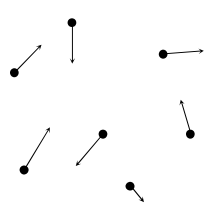


## Kinetic Theory J. C. Maxwell, L. Boltzmann, 1860

- •Molecules are in constant motion (Brownian motion)
- •Temperature is related to $E_{k,av}$ of the molecules

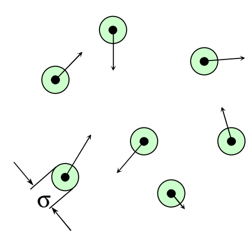
**Simplest model**

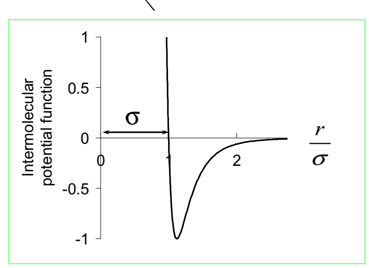
- •no particle volume
- •no intermolecular forces



**More realistic model**

- •finite particle volume
- •intermolecular forces



**Kinetic Theory**

Is based on Brownian motion (molecules in constant motion proportional to their temperature)

Predicts that properties that are carried by individual molecules (chemical identity, momentum, average kinetic energy) will be transported **DOWN** gradients in these quantities.

==> Transport laws are due to Brownian motion

**Heat Transfer by Radiation**

Is due to the release of energy stored in molecules that is **NOT** related to average kinetic energy (temperature), but rather to the population of excited states.

==> Radiation is NOT a Brownian effect



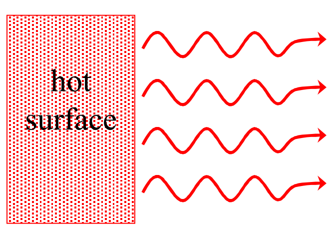
## Radiation

•does not require a medium to transfer energy (works in a vacuum)

•travels at the speed of light, $c = 3 \times 10^{10}$ cm/s

•travels as a *wave*; differs from x-rays, light, only by wavelength, $\lambda$

•radiation is important when temperatures are high




*examples:*
•the sun
•home radiator
•hot walls in vacuum oven
•heat exchanger walls when $\Delta T$ is high and a vapor film has formed

$$\frac{q}{A} \propto T^4$$

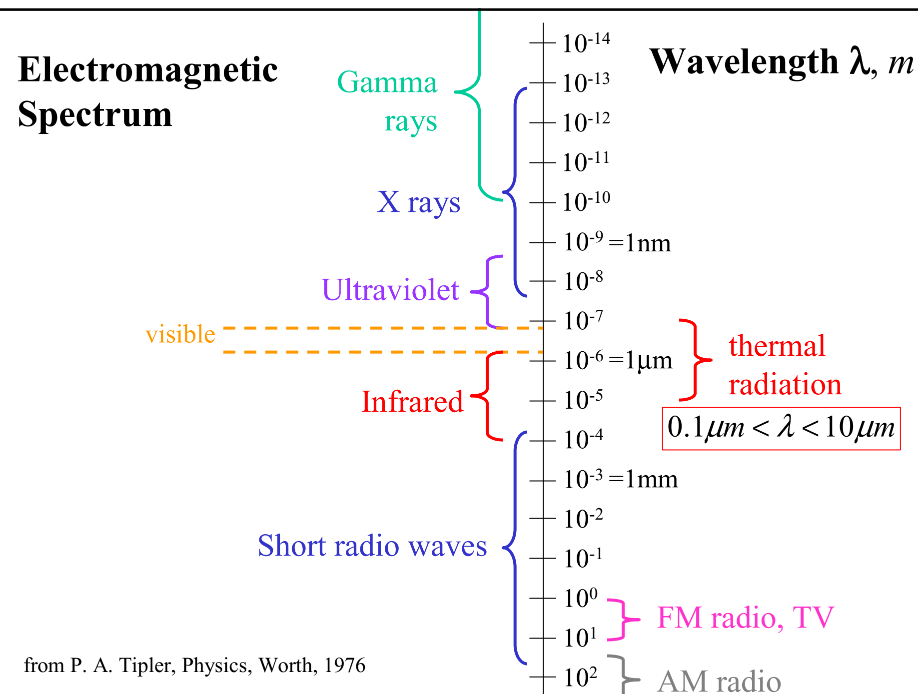
> Why does radiation flux scale with temperature, which is related to average kinetic energy?

As a molecule gains energy, it both speeds up (increases average kinetic energy) and increases its population of excited states.

The increase in average kinetic energy is reflected in temperature (directly proportional).

The increase in number of electrons in excited states is reflected in increased radiation flux. Electrons enter excited states in proportion to $T^4$.

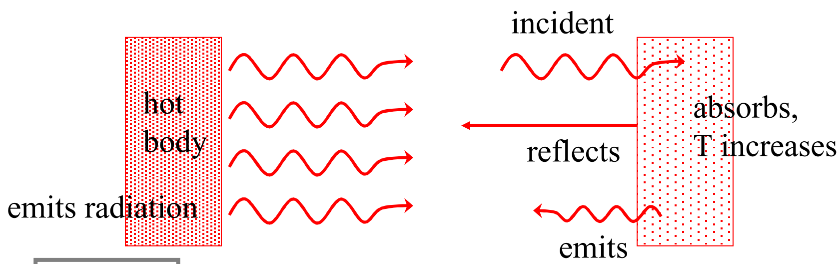





from P. A. Tipler, Physics, Worth, 1976

## What causes energy transfer by radiation?

- energy hits surface
- pushes some molecules into an excited state
- when the molecules/atoms relax from the excited state, they emit radiation




$$\frac{q_{emit}}{A} \propto T^4$$

$$\alpha = absorptivity$$

$$\alpha \equiv \frac{q_{absorbed}}{q_{incident}} < 1$$



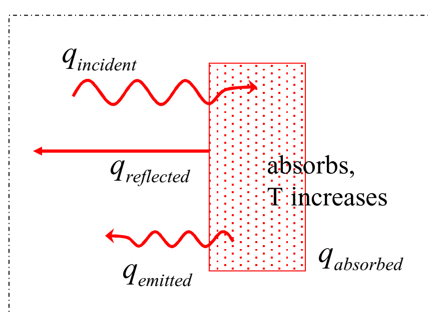
## Absorption

$$\alpha = absorptivity$$

$$\alpha \equiv \frac{q_{absorbed}}{q_{incident}} < 1$$

In general, α is a function of wavelength

$$\alpha = \alpha(\lambda)$$



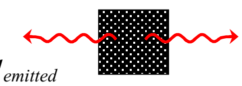

**gray body**: a body for which α is constant (does not depend on λ)
**black body**: a body for which α = 1, i.e. absorbs all incident radiation

# Emission

$$\varepsilon = emissivity$$

$$\varepsilon \equiv \frac{q_{emitted}}{q_{emitted,blackbody}} < 1$$

**gray body**: a body for which α is constant
**black body**: a body for which α = 1



$q_{emitted}$

$$\alpha = absorptivity$$

$$\alpha \equiv \frac{q_{absorbed}}{q_{incident}} < 1$$

*Kirchhoff's Law*: emissivity equals absorptivity at the same temperature

$$\alpha = \varepsilon$$

the fraction of energy absorbed by a material = the relative amount of energy emitted from that material compared to a black body

true for black and non-black solid surfaces



$$\varepsilon = emissivity$$

$$\varepsilon \equiv \frac{q_{emitted}}{q_{emitted,blackbody}} < 1$$

# Black Bodies

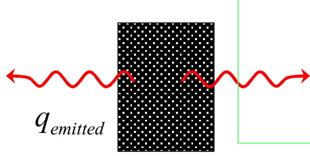
*Stefan-Boltzmann Law*: the amount of energy emitted by a black body is proportional to $T^4$

$$\frac{q_{emitted,blackbody}}{A} = \sigma T^4$$

absolute temperature

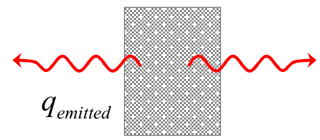
$$\sigma = 0.1712\times10^{-8} \frac{BTU}{h\, ft^2 R^4}$$

$$= 5.676\times10^{-8} \frac{W}{m^2 K^4}$$



$q_{emitted}$

## Non-Black Bodies




$\varepsilon = emissivity$

$$\varepsilon \equiv \frac{q_{emitted}}{q_{emitted,black\,body}}$$

$$\frac{q_{emitted,non-black\,body}}{A} = \varepsilon\, q_{emitted,black\,body}$$

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

Stefan-Boltzmann:

$$\frac{q_{emitted,black\,body}}{A} = \sigma T^4$$

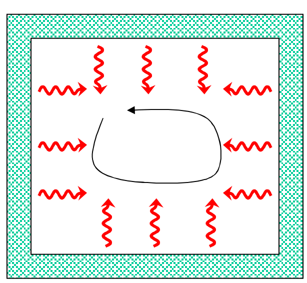
Energy emitted by a non-black body

$$\frac{q_{emitted,non-black\,body}}{A} = \varepsilon \sigma T^4$$



## How does this relate to chemical engineering?

Consider a furnace with an internal blower:



There is heat transfer due to convection:

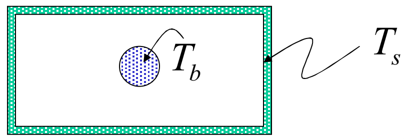
$$q_{convection} = h_{conv} A (T_s - T_b)$$

There is also heat transfer due to radiation:

$$q_{radiation} = h_{rad} A (T_s - T_b)$$

$$q_{total} = q_{conv} + q_{rad}$$

## Where do we get $h_{rad}$?




object in furnace: $q_{emitted, non-black\ body} = A\varepsilon|_{T_b} \sigma T_b^4$

using Kirchhoff's law

$$q_{absorbed} = \alpha|_{T_s} A\sigma T_s^4 = A\varepsilon|_{T_s} \sigma T_s^4$$

energy emitted by walls, which are acting as a black body

emissivity at $T_s$

net energy absorbed:

$$q_{\substack{transfered \\ to\ body}} = A\varepsilon|_{T_s} \sigma \left(T_s^4 - T_b^4\right)$$

*assuming* $\varepsilon|_{T_s} \approx \varepsilon|_{T_b}$



## **Finally, calculate $h_{rad}$**

net energy absorbed:

$$q_{\substack{transfered \\ to\ body}} = A\varepsilon|_{T_s} \sigma \left(T_s^4 - T_b^4\right)$$

*assuming* $\varepsilon|_{T_s} \approx \varepsilon|_{T_b}$

equating with expression for h:

$$A\varepsilon|_{T_s} \sigma \left(T_s^4 - T_b^4\right) = h_{rad} A \left(T_s - T_b\right)$$

$$h_{rad} = \frac{\sigma \varepsilon|_{T_s} \left(T_s^4 - T_b^4\right)}{T_s - T_b}$$

*Geankoplis 4th ed., eqn 4.10-10 p304*

## Example: Geankoplis 4.10-3

A horizontal oxidized steel pipe carrying steam and having an OD of 0.1683m has a surface temperature of 374.9 K and is exposed to air at 297.1 K in a large enclosure. Calculate the heat loss for 0.305 m of pipe from natural convection plus radiation. For the steel pipe, use an emissivity of 0.79.