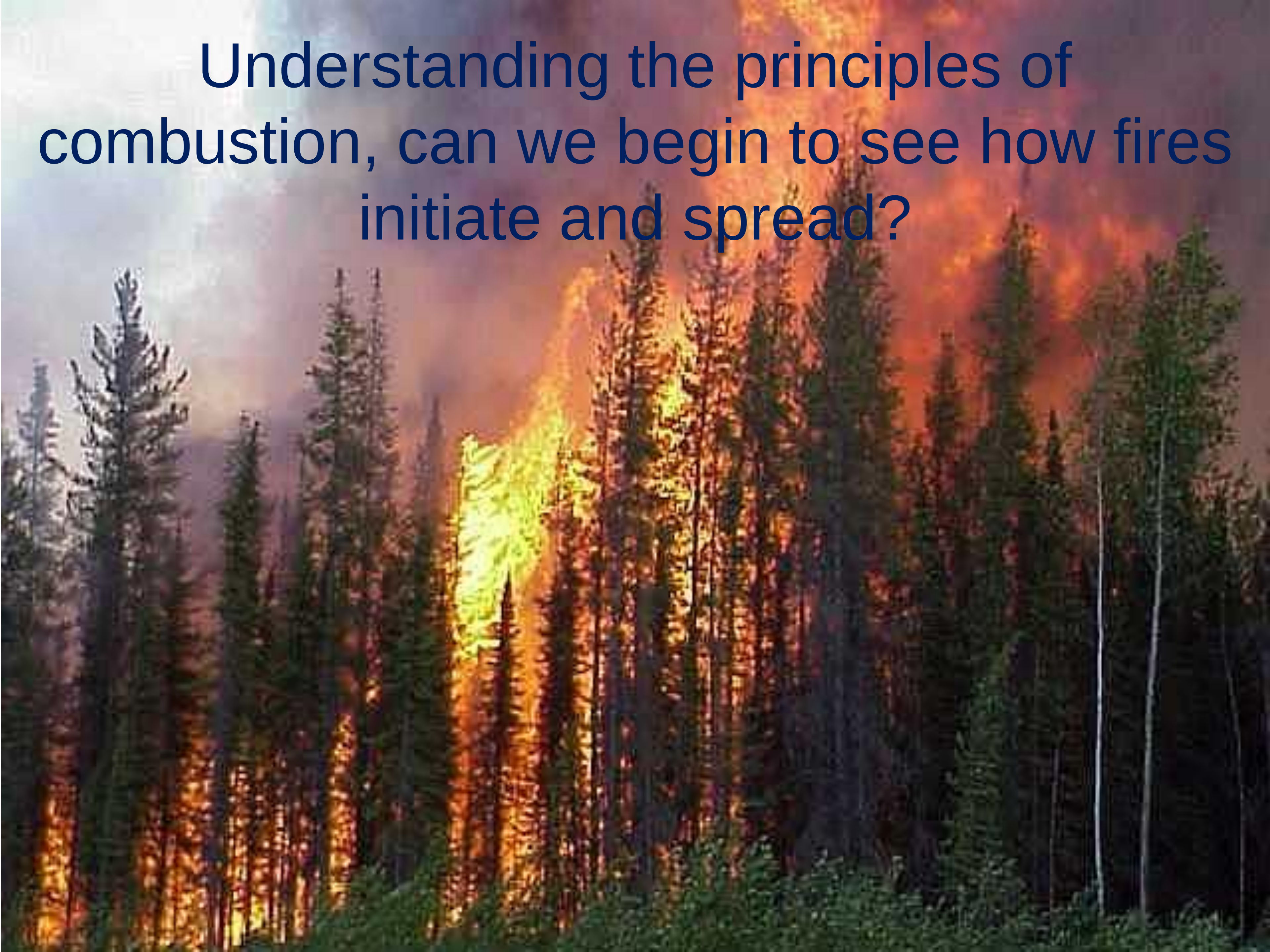
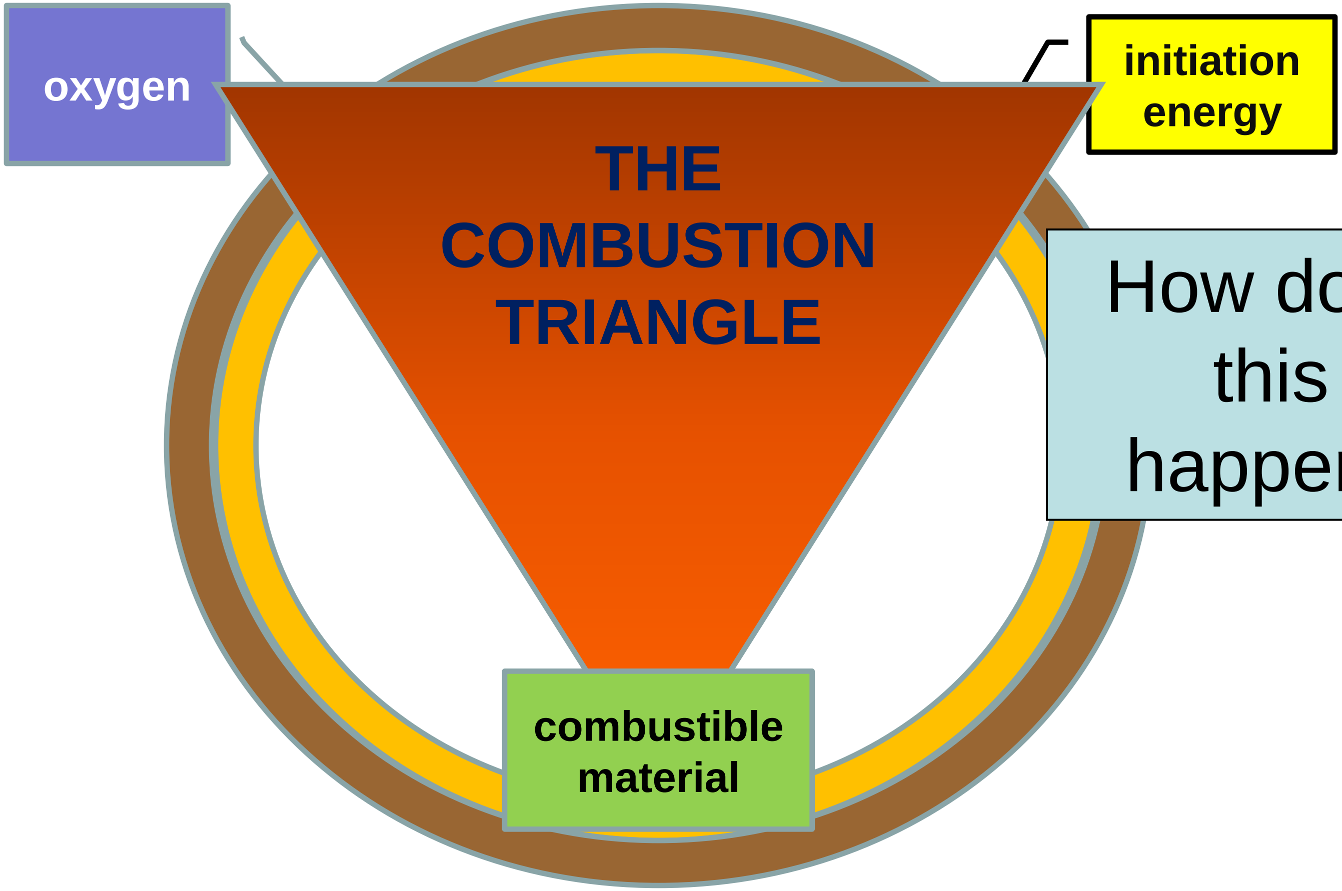
1.3
Energy transfer and the stages of combustion

Understanding the principles of combustion, can we begin to see how fires initiate and spread?



To complete the fire triangle, energy must move through space from a source to a “fuel”

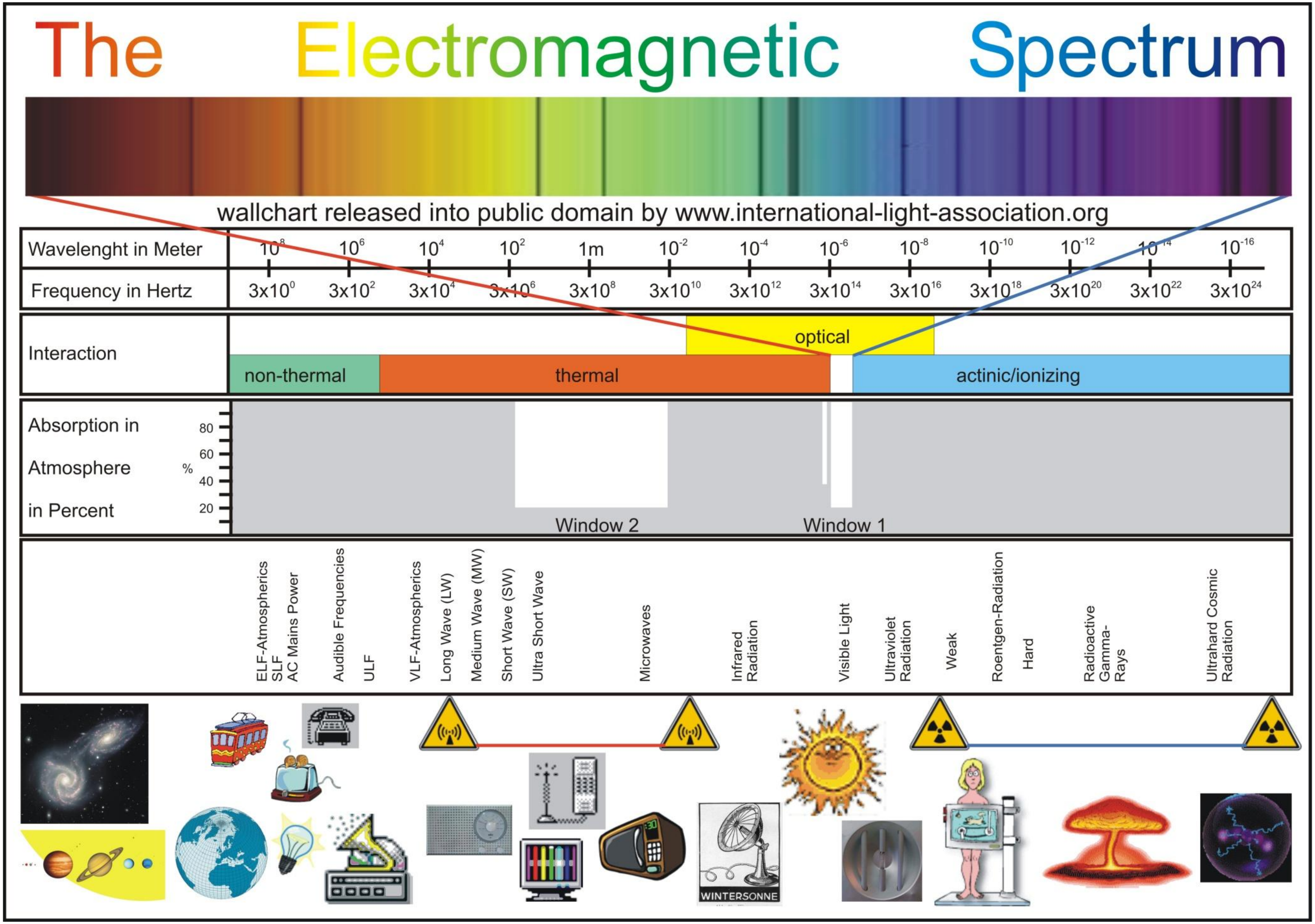


How does this happen?

Heat is a form of energy

- Heat (or thermal energy) is proportional to molecular movement of matter, i.e., kinetic energy (KE)
- The Kelvin scale measures the energy content of matter, starting at absolute 0 (- 273° C)
- Heated objects emit radiation in the electromagnetic spectrum (EMS):
  - In the range we will deal with, mostly in the infrared
  - Even higher velocities emit in higher-frequency bands of the EMS

See the "Ask a Scientist" excerpt posted for this lecture



international light association, http://www.international-light-association.org

Three basic modes of energy transfer:

Conduction

Radiation

Convection

A general principle of heat transfer:

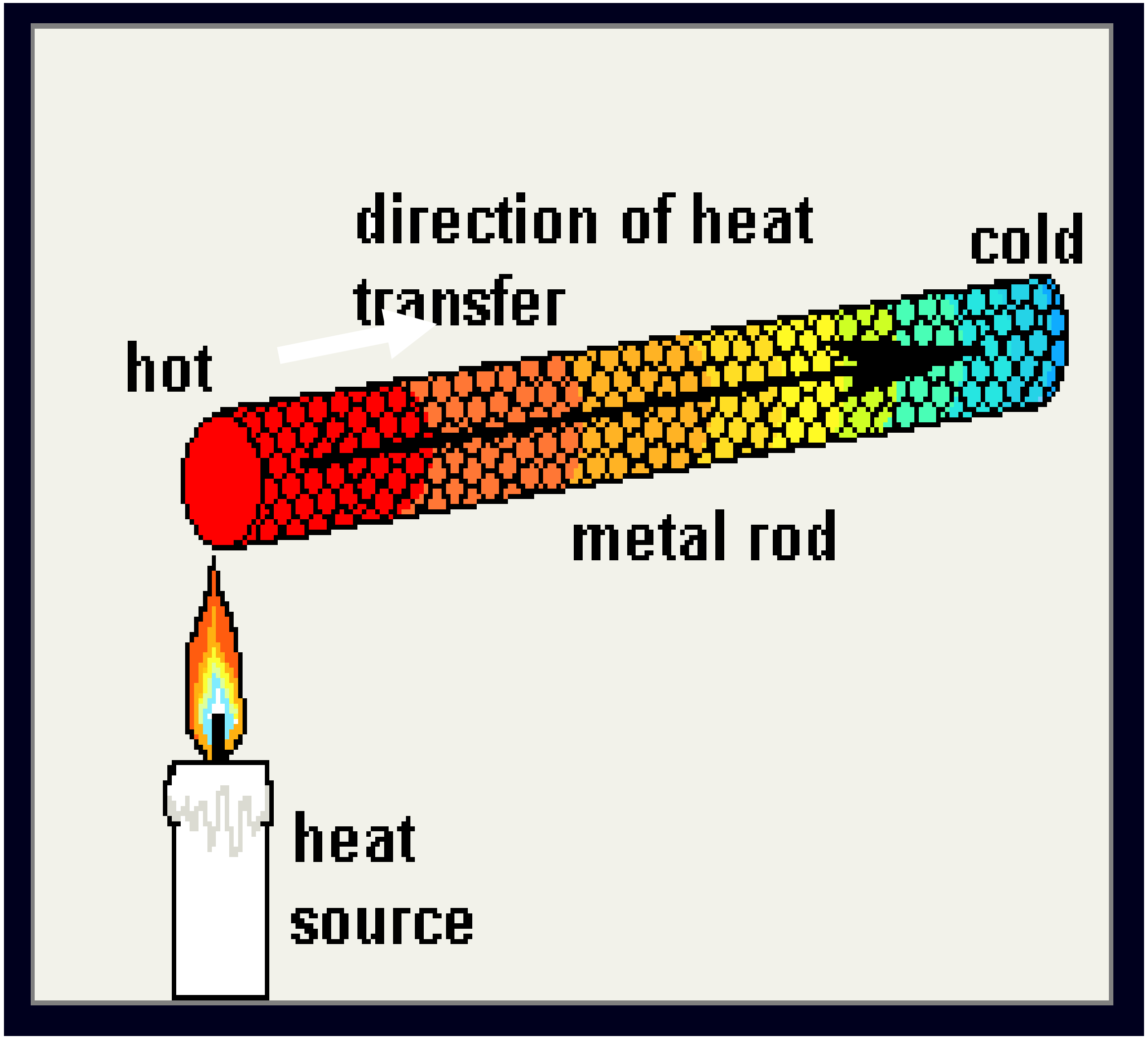
- Heat transfers between bodies according to the second law of thermodynamics (which in this case says that heat flows from high to low energy states, i.e., hot to cold bodies
  - In other words, heat flows down energy gradients
  - This goes a long way to explaining much of how fires behave

1. Conduction

Movement of energy through a solid, or between solids in contact by molecular motion

- Depends on *thermal conductivity* and *energy gradient* of material (conductors, insulators)
- Also depends on amount of *area* of contact
- Examples?
  - **touching a hot metal object, *e.g.* a saucepan handle**
  - **heating water by an immersion coil**
  - **melting lead solder with a soldering iron**
  - **putting an ice cube on your skin**

Conductivity (ability of a material to conduct energy)

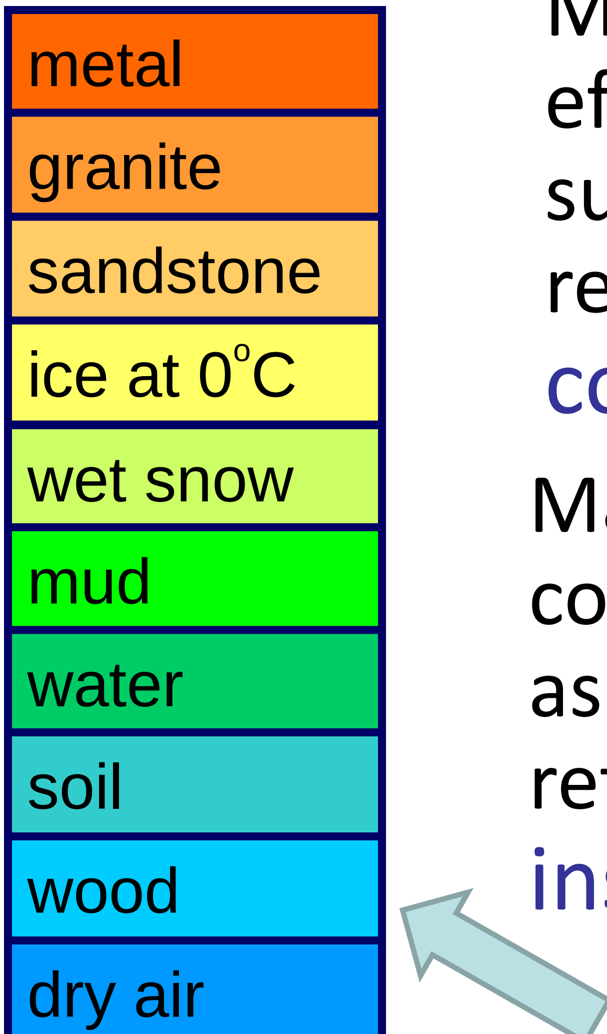


The transfer of heat between molecules <u>in contact with one another</u>.

How far and fast does conduction energy transfer?

- Depends on thermal conductivity and energy gradient of material (conductors, insulators)
- For most materials, conduction is a matter of centimeters, in extreme cases (e.g. geologic processes) tens of meters
- Rate of energy transfer depends on conductivity (inverse of "resistance")

Conductors and Insulators



Materials that allow for the efficient transfer of heat energy, such as metal and granite, are referred to as **conductors.**

Materials that are poor conductors of heat energy, such as dry air, wood, and water, are referred to as **insulators.**

2. Radiation

Movement of radiant energy via electromagnetic waves

- Propagates in a straight line, at the speed of light (depending on the medium)
- Strength is inversely proportional to square of distance from the source
- Examples?

  - **sunlight warming a solid object**
  - **heat from standing near a campfire or wildfire**
  - **“burns” from high-frequency radiation (gamma, x-rays, ultraviolet)**

Inverse square law

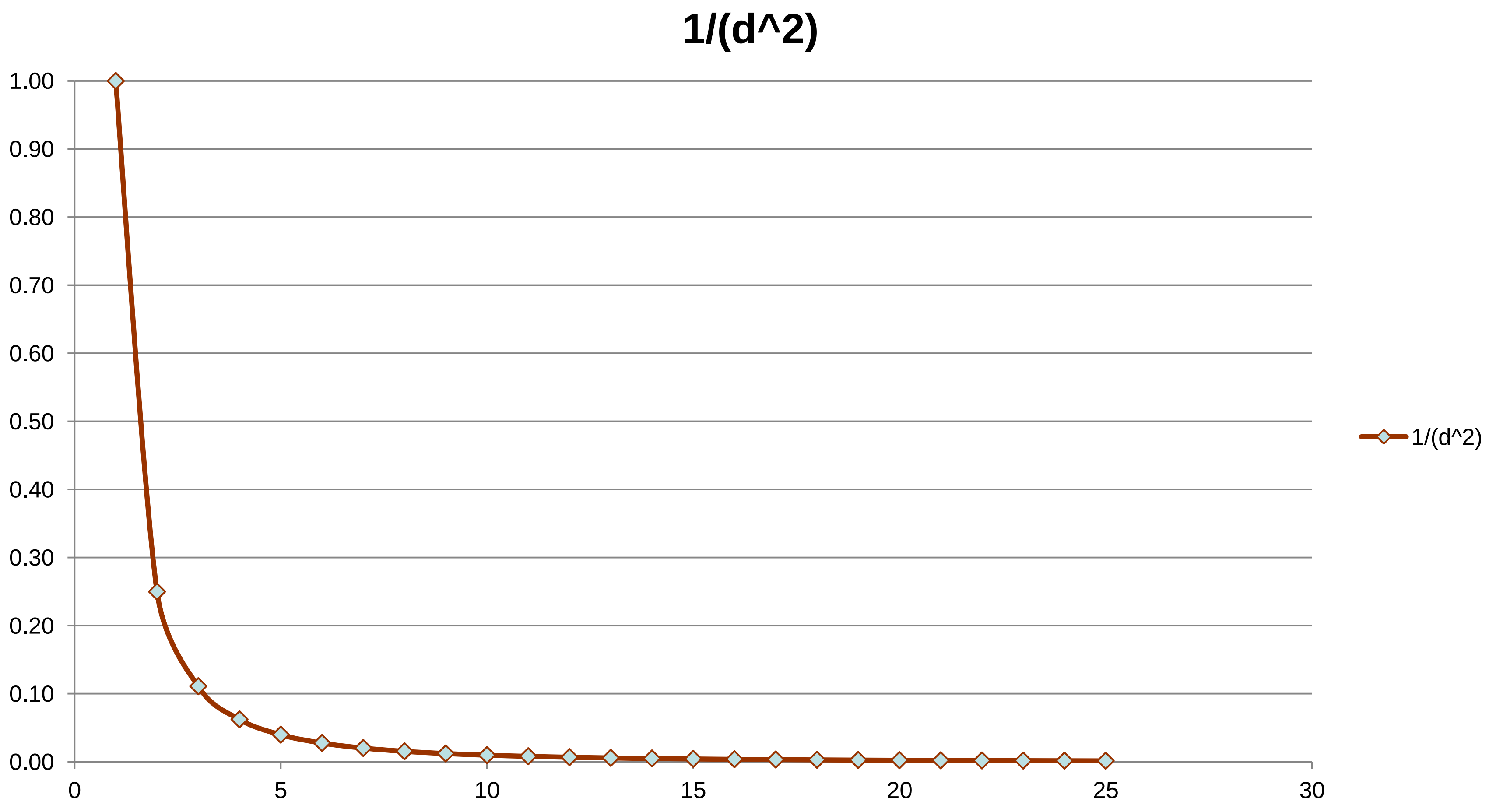
$$I = k\frac{e}{d^2}$$

$$I = ked^{-2}$$

$$I \propto ed^{-2}$$

These are all equivalent expressions!

Inverse square law in practice:



An example:

If a heat source is 1000 kJ at the source, what is the intensity at 10m (let k = 1)?

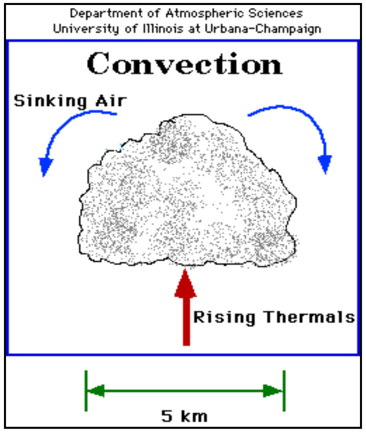
$= 1000 \text{ kJ} / (10 \text{ m})^2$

$= 10 \text{ kJ}$

3. Convection

Movement of energy through fluids (gas or liquid) by *mass transfer*

- Depends on *temperature, thermal gradient*, and *viscosity* of material
- Examples?



- **rising air above a hot highway**
- **water at a "rolling boil" in a container**
- **smoke plume above a crown fire**
- **steam rising from a boiling kettle**
- **warm air currents rising at the equator**
- **convection currents in Earth's mantle, which drive (what?)**

Convection can move energy large distances!

- Heat plume from a large fire can rise 1000's of meters into the atmosphere in minutes
- Mass movements of air into the troposphere from Earth's equatorial region drive the planet's climate system
- In a crown fire, turbulent air can lift large flaming objects and transport them 1000's of meters

How do these three basic modes of energy transfer work during fire?

Conduction: Heat passes through burning fuels (*e.g.* through a log or branch), driving off moisture and preparing it for burning; soil heating is mostly conductive

Convection: Heated air and gases rise above burning fuels into tree canopies, scorching and preheating them; smoke plumes are convective

Radiation: Heat radiated from a flaming front pre-heats grass, shrub, and tree fuels, causing the flaming front to move along

The stages of combustion

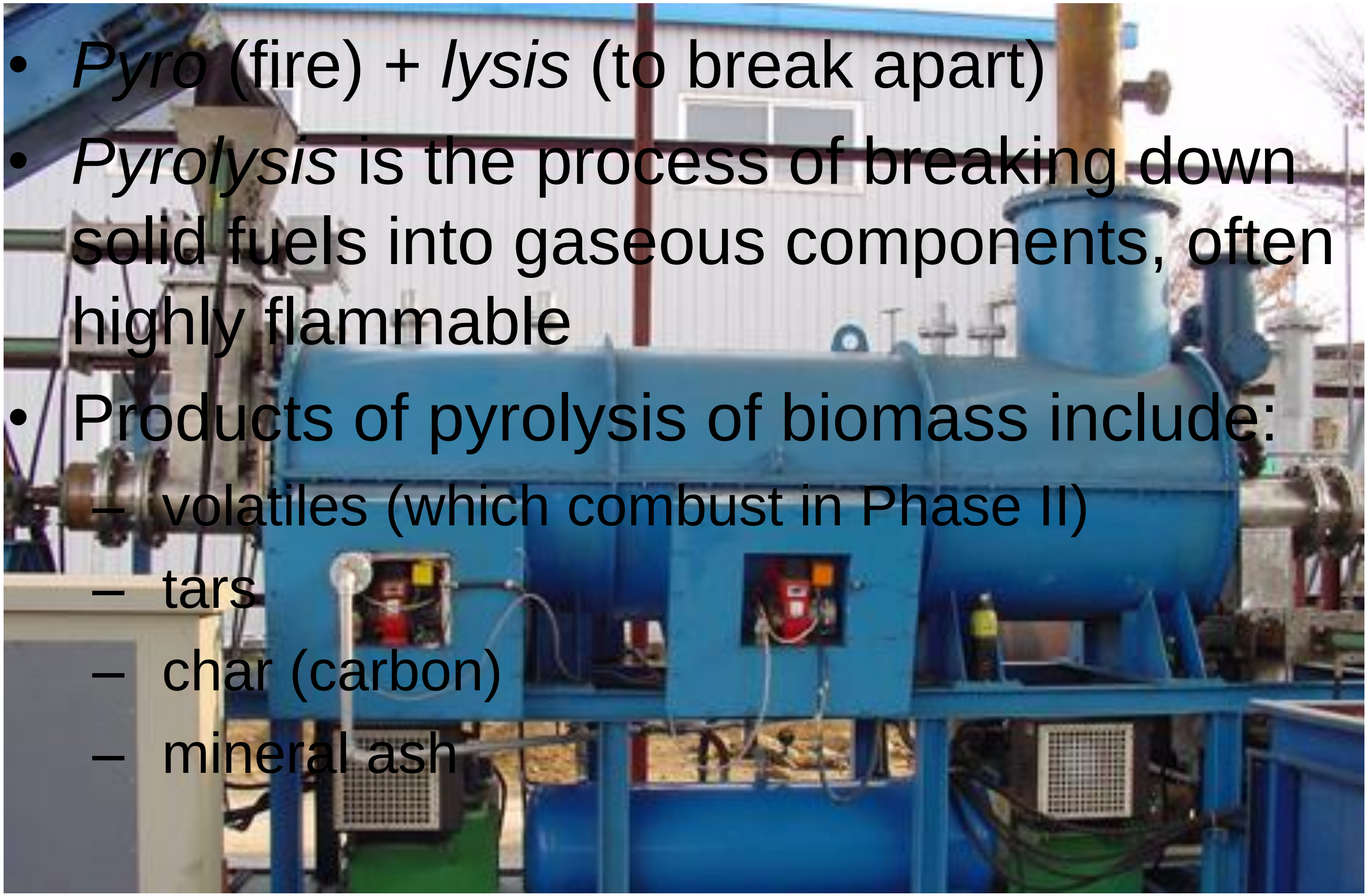
- Fact: Solid fuels don’t burn!
- Must be converted to gas in order to ignite
- Take home point to remember: fire is a **CHAIN REACTION**!

How does this work?

Phase I: Pre-heating (pre-ignition)

- Fuels ahead of the fire are pre-heated by convection and radiation
- Dehydration: Water is driven out of the fuel (so fuels become drier) ~ 100° C
- Volatiles (extractives) evaporate into gas phase
- *Pyrolysis* of solid fuels ~ 325° C
- These reactions are mostly *endothermic*
- Time ~ seconds

What is pyrolysis?



- *Pyro* (fire) + *lysis* (to break apart)
- *Pyrolysis* is the process of breaking down solid fuels into gaseous components, often highly flammable
- Products of pyrolysis of biomass include:
  - volatiles (which combust in Phase II)
  - tars
  - char (carbon)
  - mineral ash

Phase II: Gas (ignition) phase

- Volatiles generated in Phase I (by evaporation and pyrolysis) ignite and oxidize
- This is when we start to see *flames*
- Phase II is *exothermic* – chemical bond energy is being released
- H_2O and CO_2 released as by-products
- Time ~ minutes

Phase III: Smoldering phase

- After the volatiles have ignited, what's left?
  - Un-pyrolized wood, esp. lignin component and pieces that didn't ignite in Phases 1 and 2
  - Charcoal
  - Tars, ash
- Lower temperatures (300 – 400° C)
- Surface oxidation, heat travels by conduction (think of a glowing log)
- Time ~ hours to months!

Fire is a chain reaction!

- Initiation energy begins pre-heating and pyrolysis
- Pyrolysis is exothermic (generates more energy than it consumes)
- This energy further pre-heats more fuel, keeps the reaction going
- **The reaction stops when one of the legs of the combustion triangle is no longer present in sufficient quantity.**

Next: Ignition