# Temperature
# Measurements, Instruments, Calibrations

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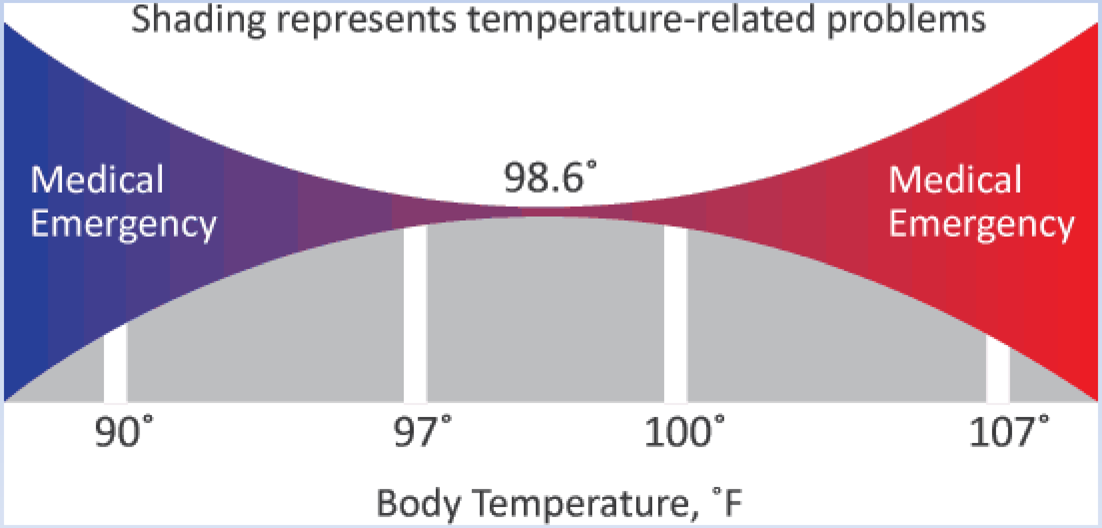
# Overview

- Definitions
- Conversions
- Measuring methods
  - Thermometers
  - Infrared thermometer
  - Satellite using infrared > Applications
  - Calibration

# What is temperature?

The degree or intensity of heat (or thermal energy) present in a substance or object, especially as expressed according to a comparative scale and shown by a thermometer or perceived by touch.

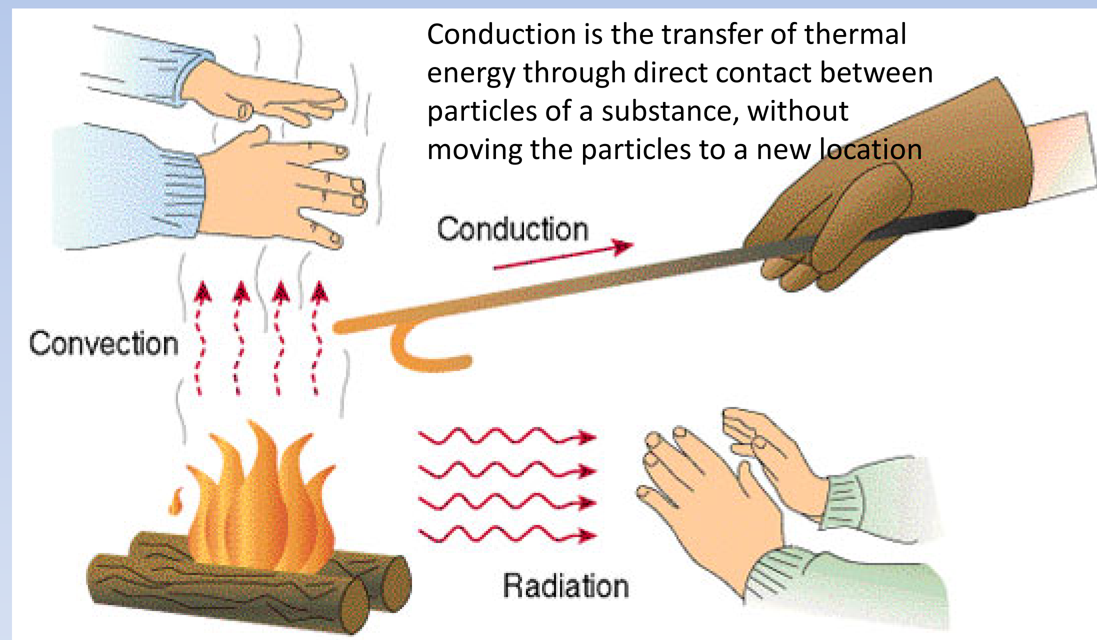


# What is Thermal Energy?

Thermal Energy is energy resulting from the motion of particles. It is a form of kinetic energy and is transferred as heat. Thermal Energy Transfer can occur by three methods:

- **Conduction**
- **Convection**
- **Radiation**

Conduction is the transfer of thermal energy through direct contact between particles of a substance, without moving the particles to a new location




Convection is the transfer of thermal energy through movement of particles from one location to another.
Usually occur in fluids
(liquids and air/gases)

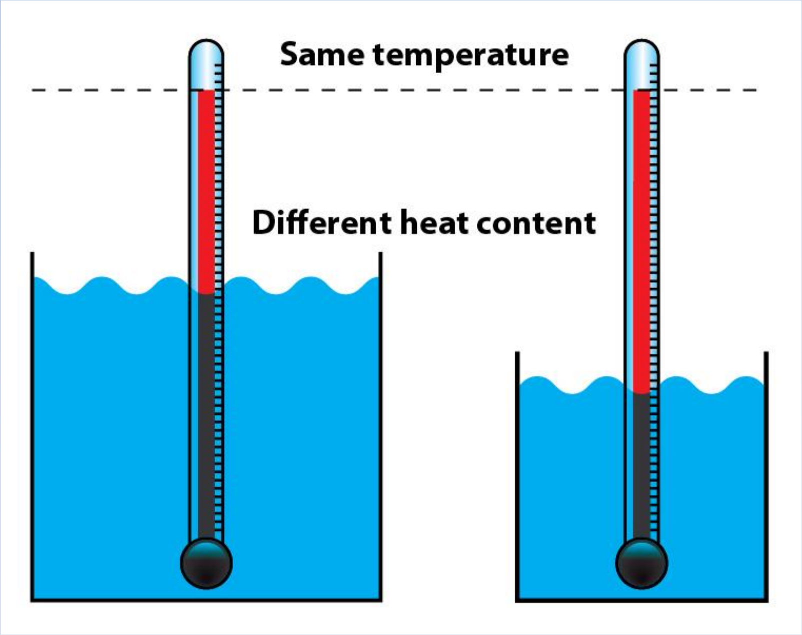
Example: Boiling water

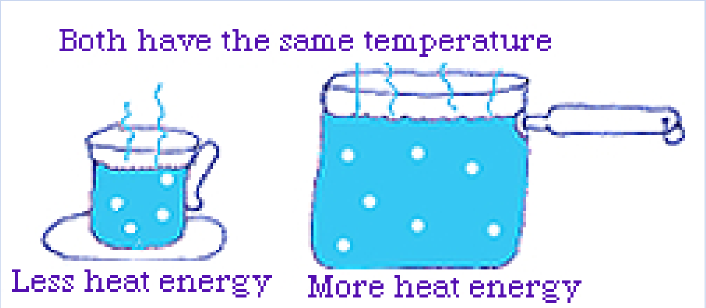
Radiation is the emission of energy as waves or particles or rays. Radiation does not require a medium to transfer energy.

# Temperature vs heat

Do you think temperature is the same thing as heat?

- No, heat and temperature are different.
- Temperature is a measure of how fast the atoms or molecules of a substance are moving.




Joules

Kelvin, Celsius or Fahrenheit

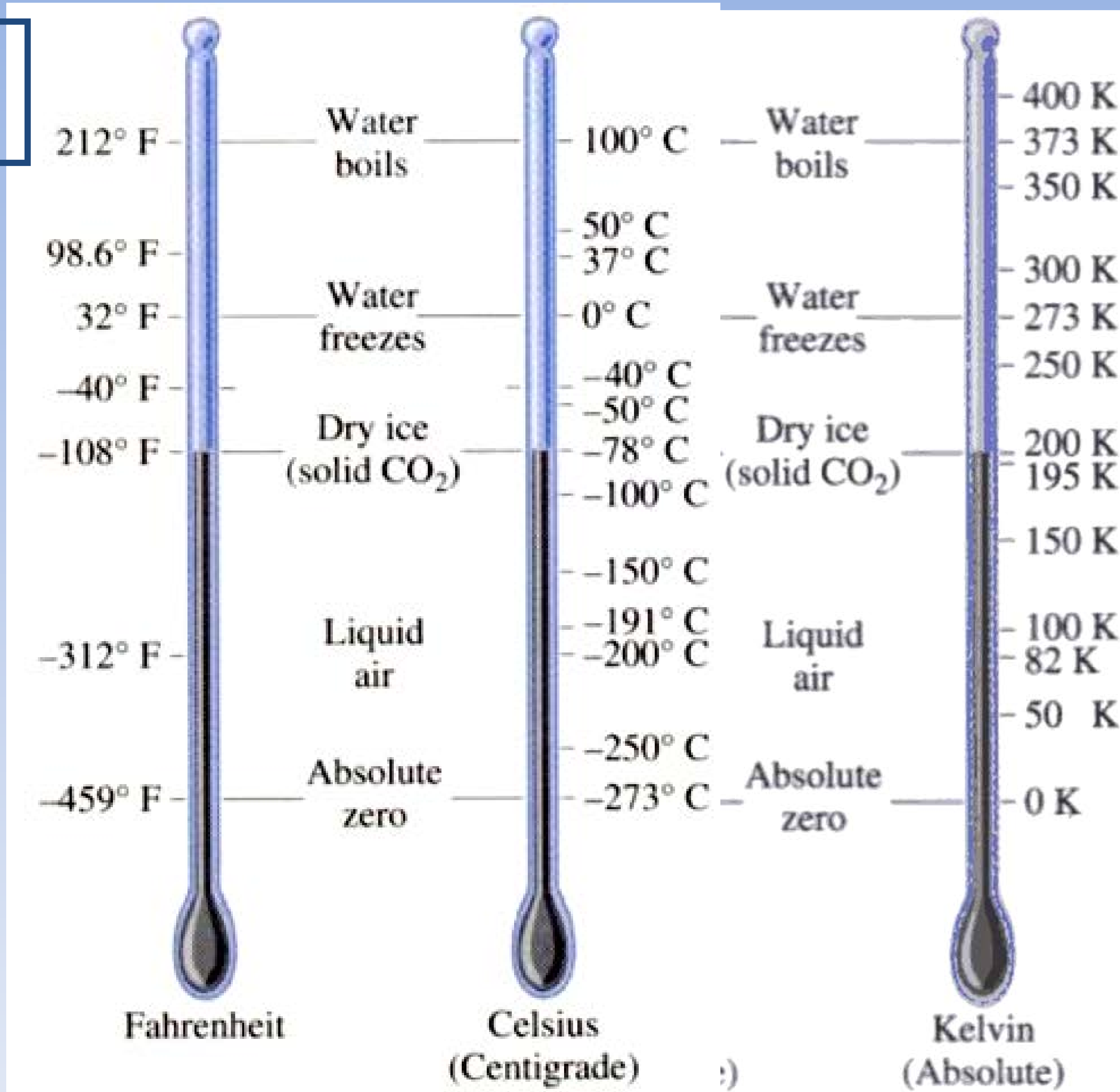
## Temperature and substance

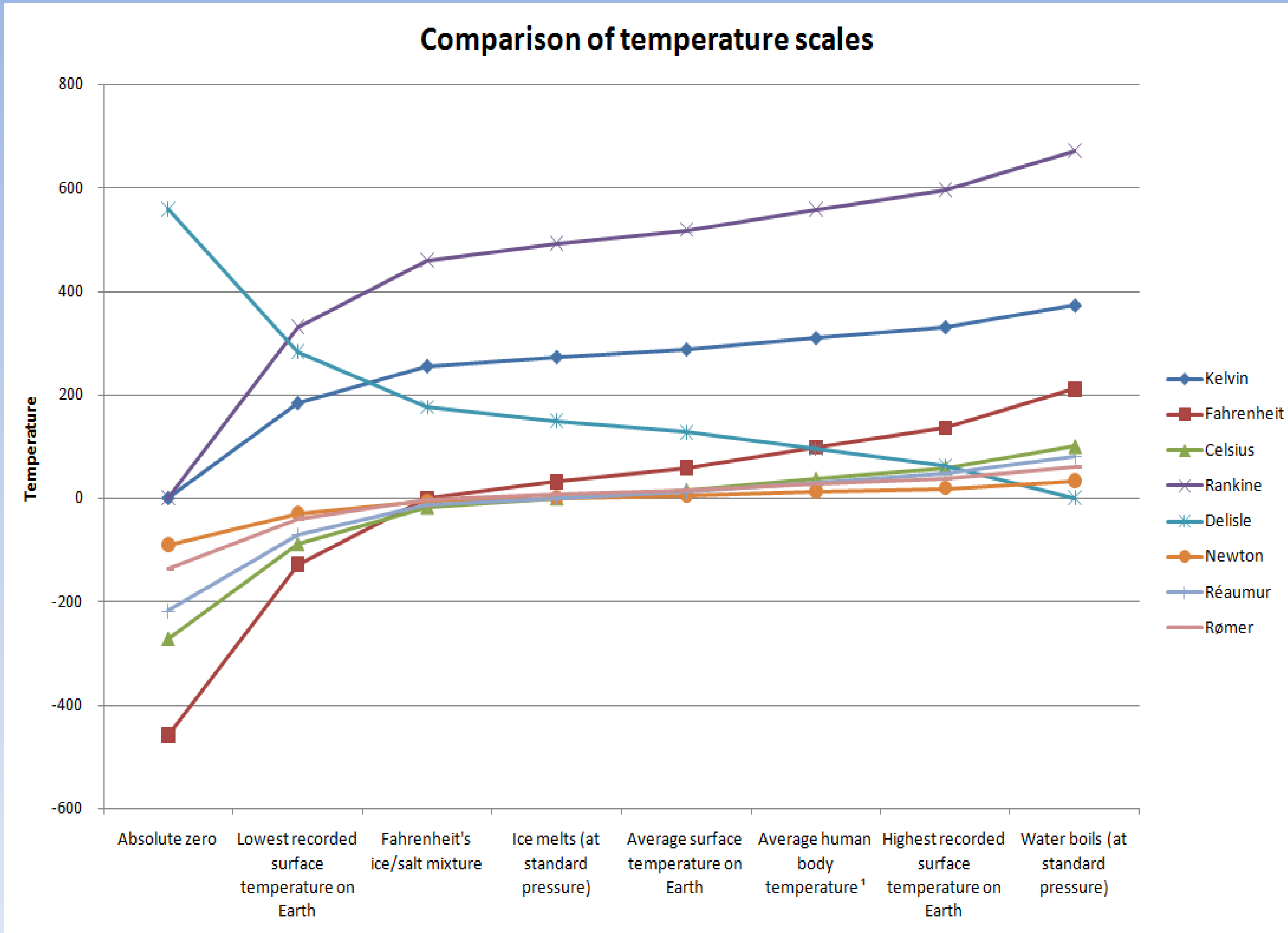
- Particles are always moving.
- When you heat water, the water molecules move faster.
- When molecules move faster, the substance gets hotter.
- When a substance gets hotter, its temperature goes up.

# Temperature Conversions

**Temperature Scales:**

Reliable and quantifiable way of measuring how “hot” an object is.





Comparison of temperature scales
800
600
400
200
0
-200
-400
-600
Temperature
Absolute zero
Lowest recorded surface temperature on Earth
Fahrenheit's ice/salt mixture
Ice melts (at standard pressure)
Average surface temperature on Earth
Average human body temperature 1
Highest recorded surface temperature on Earth
Water boils (at standard pressure)
Kelvin
Fahrenheit
Celsius
Rankine
Delisle
Newton
Réaumur
Rømer

# Kelvin Scale

- The Kelvin scale is based on absolute zero.
- Physically the lowest possible temperature is $-273.13^0$ C referred to as absolute zero.
- This is $0^0$ Kelvin, where there is no kinetic energy left in matter.
- There are no negative temperatures in the Kelvin scale.

Any guess temp on moon during day and night?

The temperature on the Moon varies from **-387 Fahrenheit** (**-233 Celsius**), at night, to **253 Fahrenheit** (**123 Celsius**) during the day.

# Units of Temperature between Boiling and Freezing

| | Fahrenheit | Celsius | Kelvin |
|---|---|---|---|
| Water boils | 212° F | 100° C | 373 K |
| | 180° | 100° C | 100K |
| Water freezes | 32° F | 0° C | 273 K |

# Learning Check

**A. Temperature of freezing water**

1) 0° F    2) 0° C    3) 0 K

**B. Temperature of boiling water**

1) 100° F    2) 32° F    3) 373K

**C. Number of Celsius units between the boiling and freezing points of water**

1) 100    2) 180    3) 273

# Solution

A. Temperature of freezing water

2) $0^\circ$ C

B. Temperature of boiling water

3) 373K

C. Number of Celsius units between the boiling and freezing points of water

1) 100

# Common temperature comparisons

| Temperature | Degree Celsius | Degree Fahrenheit |
|---|---|---|
| **Symbol** | **°C** | **°F** |
| Boiling point of water | 100. | 212. |
| Average human body temperature | 37. | 98.6 |
| Average room temperature | 20. to 25. | 68. to 77. |
| Melting point of ice | 0. | 32. |

What is formula to convert

**Fahrenheit to Celsius?**

# Fahrenheit Formula

$$\frac{180^\circ\ F}{100^\circ\ C} = \frac{9^\circ\ F}{5^\circ\ C} = \frac{1.8^\circ\ F}{1^\circ\ C}$$

Zero point: $0^\circ\ C = 32^\circ\ F$

$$^\circ F = 9/5\ T^\circ\ C + 32$$

or

$$^\circ F = 1.8\ T^\circ\ C + 32$$

# Celsius Formula

Rearrange to find T° C

$$°F = 1.8\,T°C + 32$$

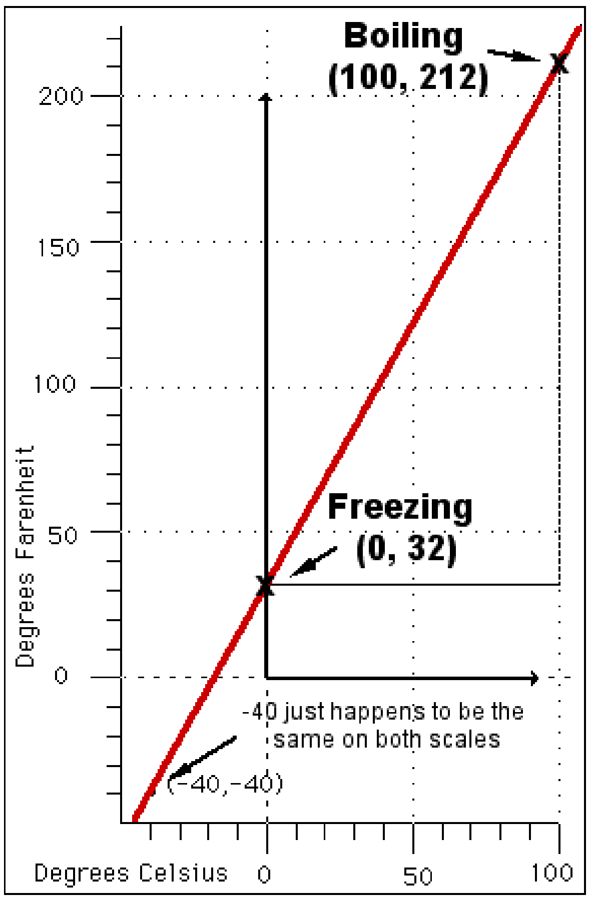
$$°F - 32 = 1.8T°C\ (+32 - 32)$$

$$\frac{°F - 32}{1.8} = \frac{\cancel{1.8}\,T°C}{\cancel{1.8}}$$

$$\frac{°F - 32}{1.8} = T°C$$

# Celsius/Fahrenheit Conversion

**Since both scales are linear it is easy to construct and analyze a graph that shows the relationship between the two**




**equation of line**

$$y = mx + b$$

**slope of line**

$$m = \frac{\Delta y}{\Delta x}$$

**slope of F vs. C line**

$$m = \frac{(212 - 32)}{(100\ -\ 0)}$$

$$m = \frac{180}{100} = 1.8$$

**intercept b = 32° F**

**equation of F vs. C line**

$$F = 1.8C + 32$$

A person with hypothermia has a body temperature of 29.1° C. What is the body temperature in ° F?

$$°F = 1.8\,(29.1°C) + 32$$

*exact* *tenth's* *exact*

$$= 52.4 + 32$$

$$= 84.4°F$$

*tenth's*

# Learning Check

**On a cold winter day, the temperature falls to -15° C. What is that temperature in ° F?**

1) 19° F
2) 59° F
3) 5° F

# Solution

3) $5^\circ$ F

**Solution:**

$$
\begin{aligned}
^\circ F &= 1.8(-15^\circ C) + 32 \\
&= -27 + 32 \\
&= 5^\circ F
\end{aligned}
$$

# Temperature Measurement

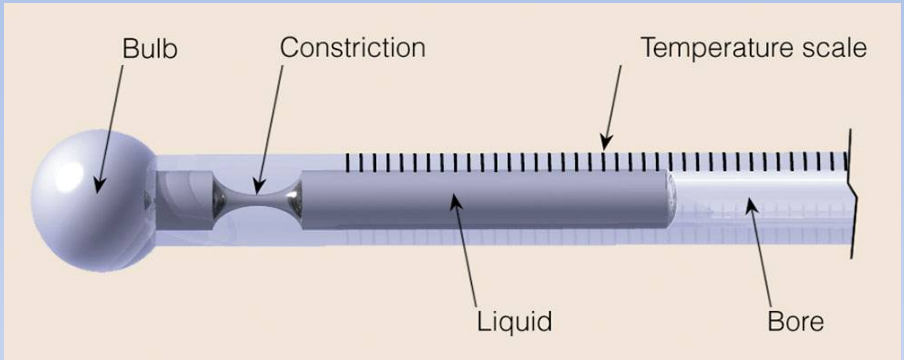
# Principle of Operation Temperature Devices

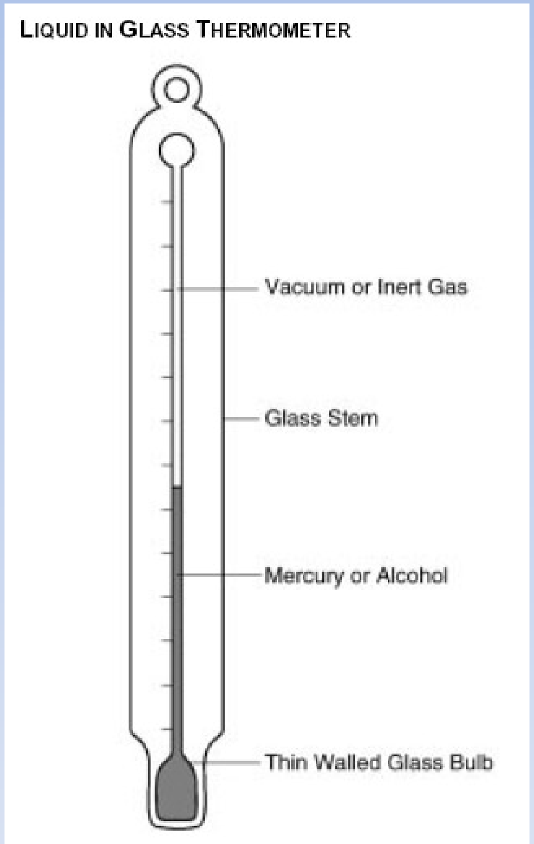
- **Expansion Thermometers**
  - Liquid in glass
  - Bimetallic
  - Filled system/distant reading

- **Pyrometers**
  - Thermocouple
  - Resistance
  - Radiation and optical pyrometers

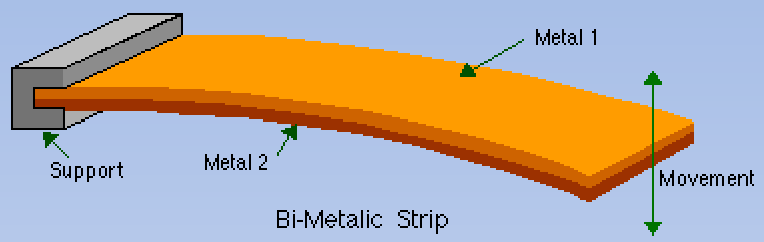
# Temperature: Liquid glass

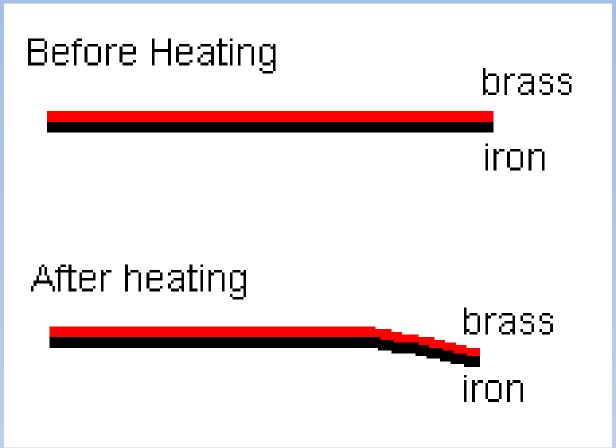
Determined by using a thermometer that contains a liquid that expands with heat and contracts with cooling.

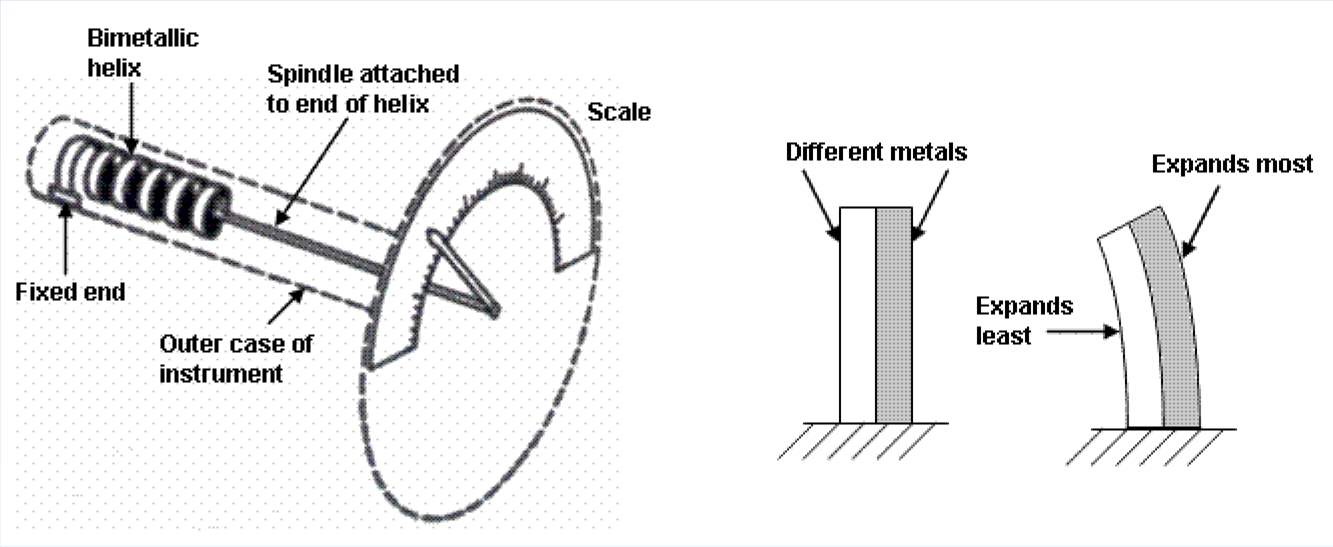


# Temperature: Bimetallic



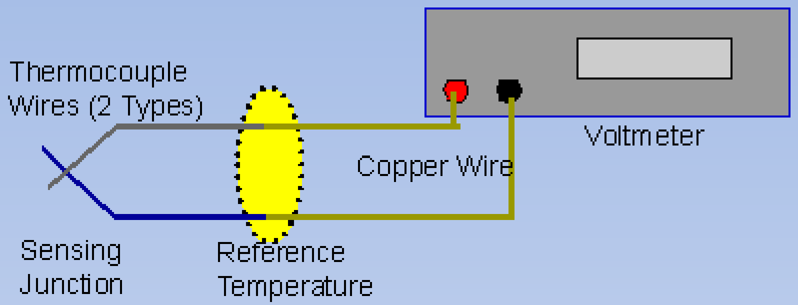



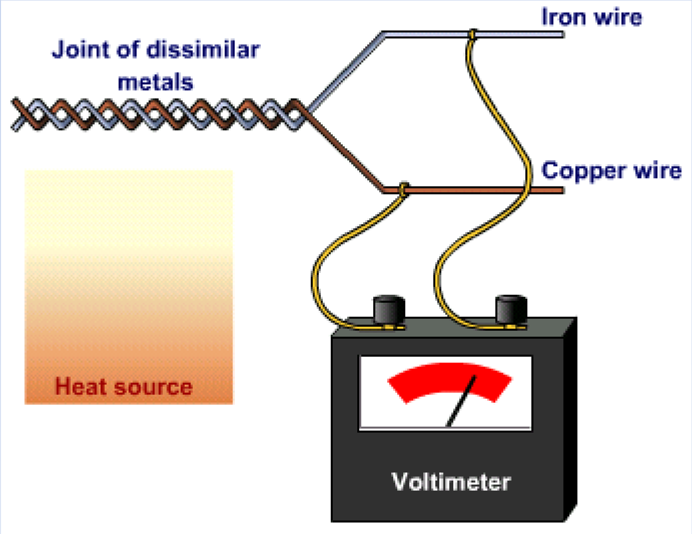
# Filled system/distant reading

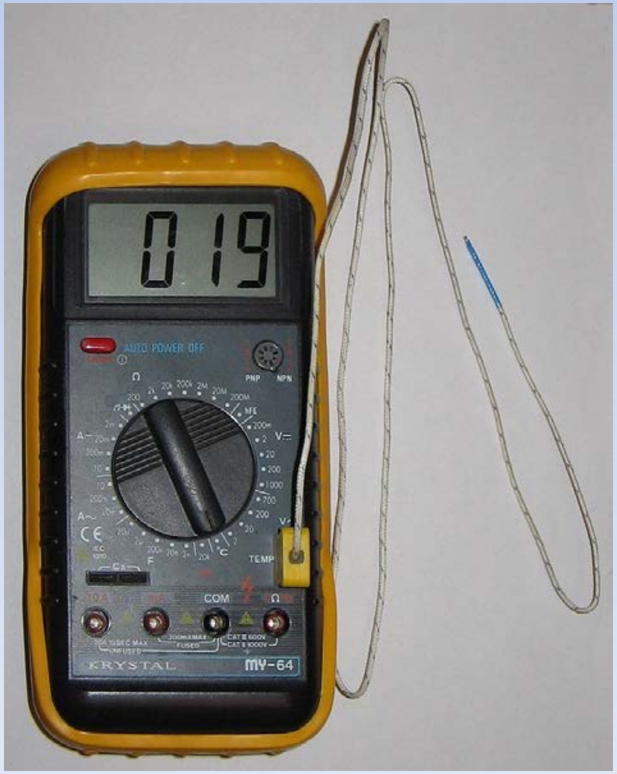
The filling or transmitting medium is a vapor, a gas, mercury, or another liquid.
The liquid-filled system is the most common because it requires a bulb with the smallest volume or permits a smaller instrument to be used.

# Thermocouple

**Thermocouple** is a temperature-measuring device consisting of two dissimilar conductors that contact each other at one or more spots, where a temperature differential is experienced by the different conductors (or semiconductors).

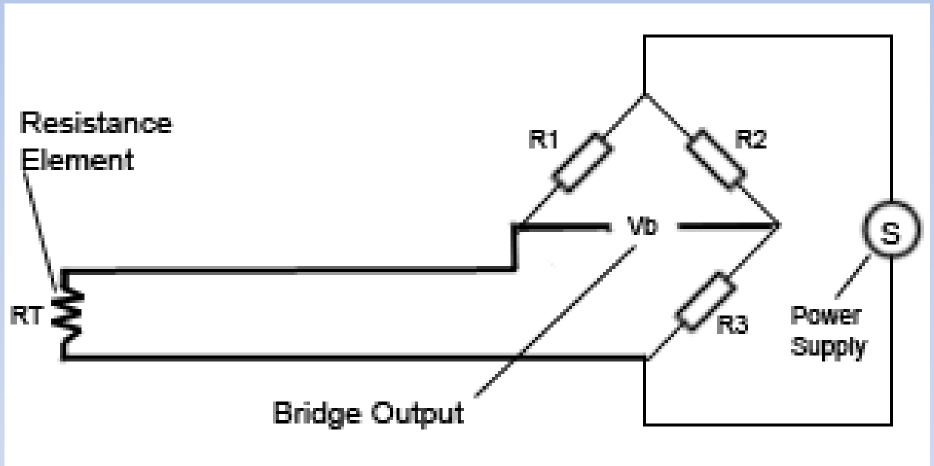


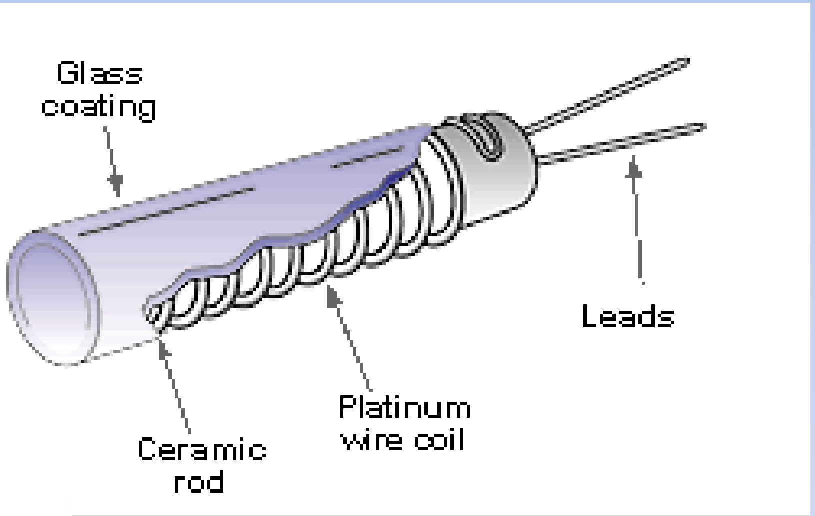



# Resistance thermometers

- Resistance thermometers, also called resistance temperature detectors (RTDs), are sensors used to measure temperature by correlating the resistance of the RTD element with temperature.
- Most RTD elements consist of a length of fine coiled wire wrapped around a ceramic or glass core.




# Optical pyrometer temperature sensor

- Optical pyrometer temperature sensor for non contact high temperature measurement is a disappearing filament pyrometer for precision high temperature measurements on small targets to 0.0005".

Extended Temperature Range:
1300°F - 8100° (700°C - 4500°C)

Standard Temperature Ranges:
1300°F - 5800° (700°C - 3200°C)

# Other methods

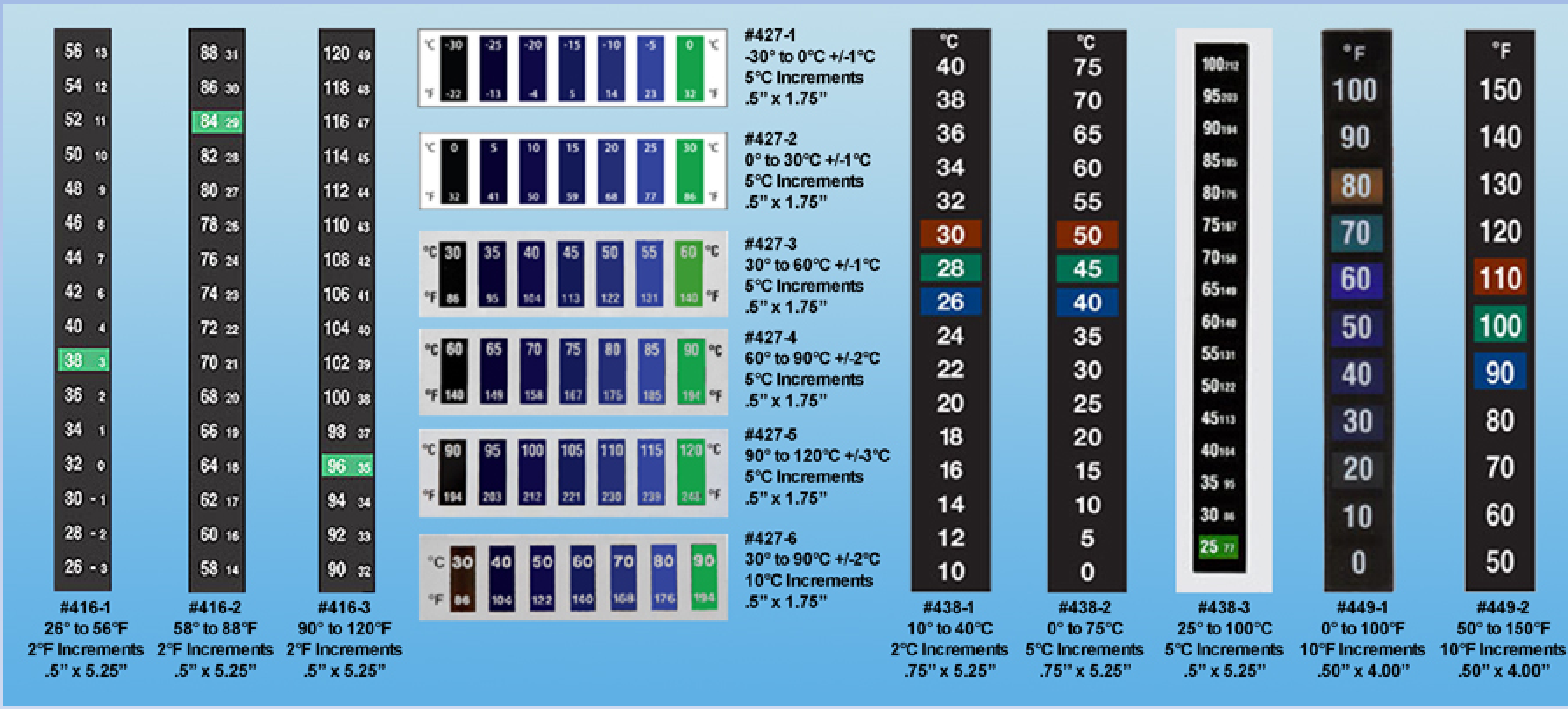
# Non-Electronic Temperature Gages

- Crayons – You can buy crayons with specified melting temperatures. Mark the surface, and when the mark melts, you know the temperature at that time.
- Lacquers – Special lacquers are available that change from dull to glossy and transparent at a specified temperature. This is a type of phase change.
- Pellets – These change phase like crayons and lacquers but are larger. If the heating time is long, oxidation may obscure crayon marks. Pellets are also used as thermal fuses; they can be placed so that when they melt, they release a circuit breaker.
- Temperature sensitive labels – These are nice because you can peel them off when finished and place them in a log book.

# Non-Electronic Temperature Gages, cont.

- Liquid crystals – They change color with temperature. If the calibration is know, color can be determined very accurately using a digital camera and appropriate image analysis software. This is used a fair amount for research.
- Naphthalene sublimation (to find h, not T)– Make samples out of naphthalene and measure their mass change over a specified time period. Use the heat and mass transfer analogy to back out h.

# Liquid crystals



# Frothing Thermometer

# Calibration

# Why Devices Need Calibration?

- Every device used for process-critical measurements should be checked periodically to verify it continues to deliver the required accuracy.
- Where adjustment is possible, a device measuring outside of expected limits should be brought back to an acceptable performance level.
- But in the case of non-adjustable equipment the deviation or measurement performance should be recorded and a decision made on whether it remains fit for purpose.

# Simplified Uncertainty Analysis

- Random (precision) error
  - For temperature measurements, this typically includes fluctuations in the electronics of the data acquisition units as well as fluctuations in the quantities measured.
- Systematic (Bias/fixed) error
  - Systematic errors which change during an experiment (drift) are easier to detect. Measurements indicate trends with time rather than varying randomly about a mean.
- Total uncertainty is found using the root mean square of these two errors

$$U = \sqrt{\text{random error}^2 + \text{bias error}^2}$$


Portable IR calibrator (blackbody target)

# Methods for Studying Past Temperature

# Past temperature

To reconstruct climate history, scientists use **proxy data** – records used to infer atmospheric properties such as temperature and precipitation.

This subfield of climate science is referred to as **paleoclimatology.**

Historical documents, such as personal diaries, mariner's logs, records of harvests and quality of wines, can provide indirect indications of past climate. These written documents, however, are not as reliable as the other proxy data sources described below.

**Methods of Studying Past Climates**

| Method | Measurement | Indicator | Time Span |
|---|---|---|---|
| Thermometers | Temperature | Temperature records at specific locations | Past 150 years |
| Tree rings | Ring width | Wider tree rings indicates warm weather and more precipitation | Hundreds to thousands of years. |
| Ice cores | Concentration of gases in ice and ocean water | Higher $^{16}O$ levels indicate a colder climate. | Hundreds of thousands of years |
| Ocean sediments | Concentration of oxygen isotope ($^{18}O$) in shells of microorganisms | Higher $^{18}O$ levels indicate a colder climate | Hundreds of thousands to millions of years. |

# Tree Rings and Coral Reefs

Tree rings and coral reefs indicate past growth rates.

Each **tree ring** indicates a year of growth. Trees tend to grow faster in warm and moist years.

**The Lost Colony**

Analyses of tree ring growth data also help scientists reconstruct past drought records. In the 1580s, the first English colony, known as the Roanoke colony or the Lost Colony, disappeared from the North Carolina coast. Persistent drought in late 16th and early 17th centuries may have contributed to colonists' disappearance.

*Image Credit: [Wikipedia]*

Scientists can extract cores from coral, and the coral growth rings can be used to reconstruct past climate in the tropical and subtropical regions.

Corals grow faster in warmer waters.

# Ice Cores

**Ice cores** are cores about 10 cm (4 inches) in diameter that are drilled through kilometers (miles) of **ice sheets** – a large thick mass of glacial ice that forms from the accumulation of annual layers of snow.

> The air between the original snowflakes is trapped as the snow begins to accumulate. As more snow falls, the buried snow is compressed and eventually freezes. The trapped "air bubbles" provide a historical record of the gases and even dust particles in the atmosphere at the time the snow fell. The deepest core samples contain the oldest air.

By the 1990s, the United States and Europe had drilled through the summit of Greenland's ice sheet to the bedrock to obtain about 200,000 years of climate data. And by 2008, the **European Project for Ice Coring in Antarctica (EPICA)** was able to reconstruct about 800,000 years of climate data.

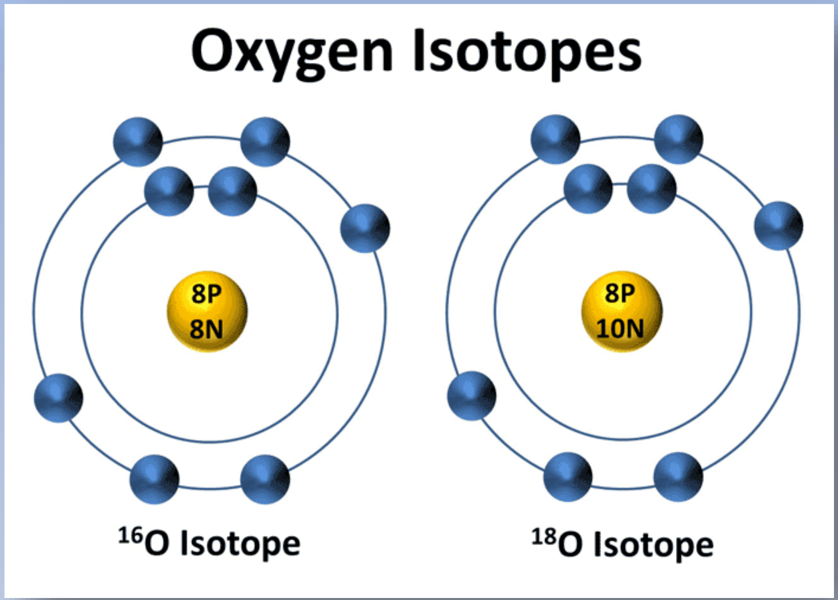
To reconstruct the air temperature from an ice core, scientists analyze the air trapped in the ice using either of two methods – the **oxygen isotope ratio** or the **deuterium to hydrogen ratio.**

# Isotope Ratios

The oxygen isotope ratio is one way used to determine past temperatures from the ice cores.

**Isotopes** are atoms of the same element that have a different number of neutrons.
All isotopes of an element have the same number of protons and electrons, but a different number of neutrons in the nucleus.

Depending on the climate, the two types of oxygen ($^{16}O$ and $^{18}O$) vary in water.



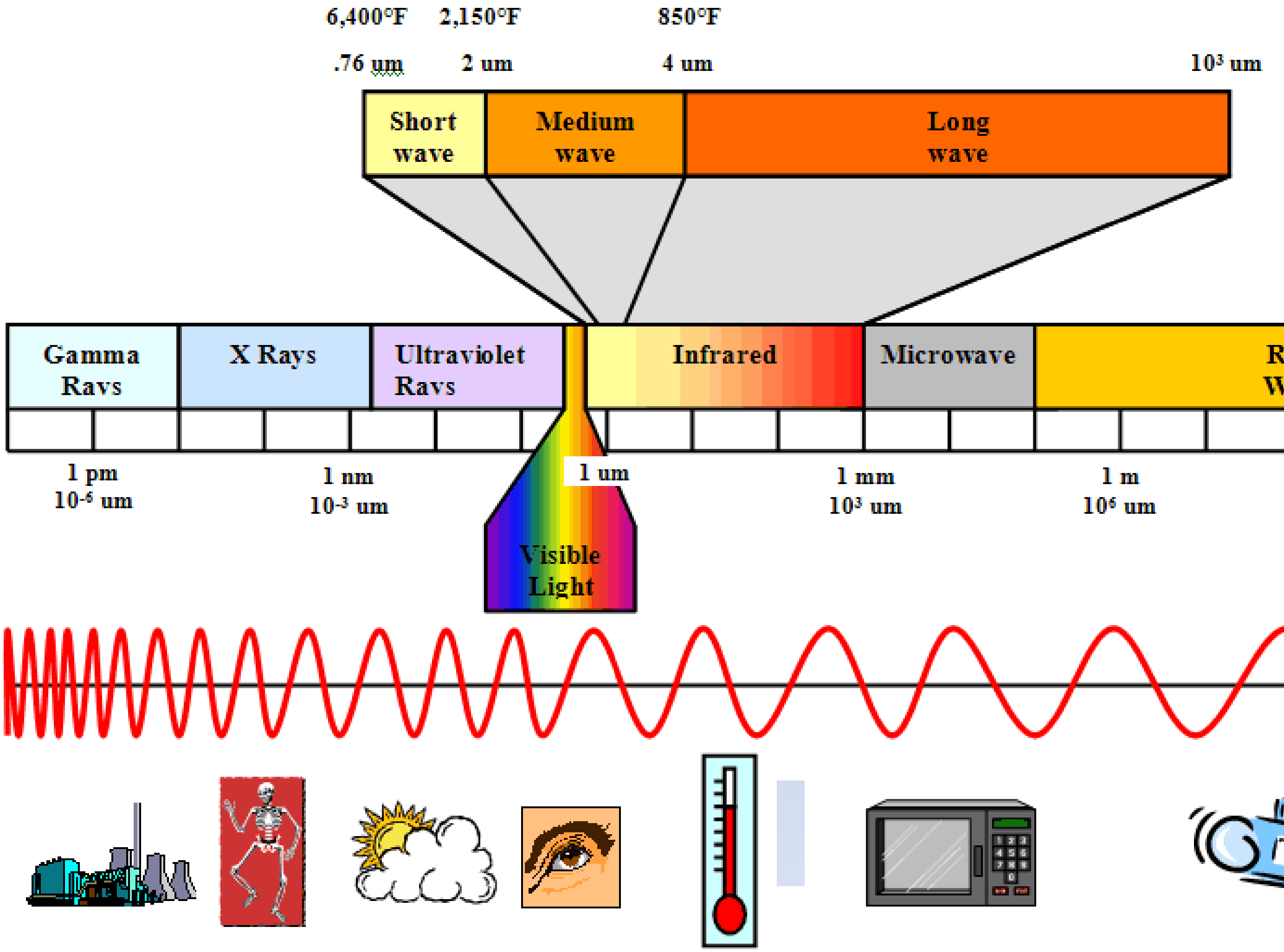

More evaporation occurs in warmer regions of the ocean, and water containing the lighter $^{16}O$ isotope evaporates more quickly than water containing the heavier $^{18}O$.

Water vapor containing the heavier $^{18}O$, however, will condense and precipitate more quickly than water vapor containing the lighter $^{16}O$.

# Infrared Thermometer

These sensors work based on the infrared emissions from the object being measured.

# Electromagnetic Spectrum




In general, discussions on infrared wavelengths are categorized as either short, medium, and long. A more precise description of these wavelengths is in Microns, a unit of measure that is 1000th of a millimeter.

# Infrared Thermometry

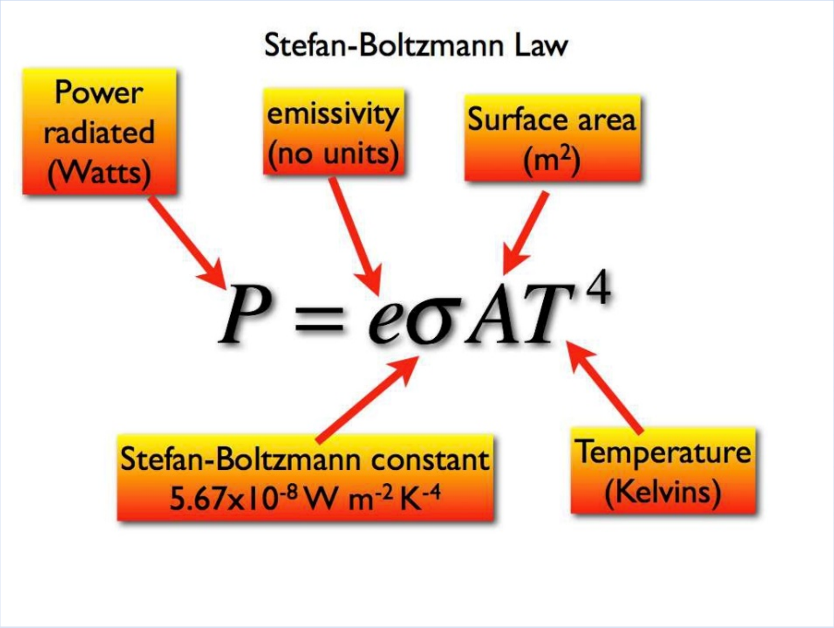
- Infrared thermometers measure the amount of radiation emitted by an object.
- Peak magnitude is often in the infrared region.
- Surface emissivity must be known. This can add a lot of error.
- Reflection from other objects can introduce error as well.
- Surface whose temp you're measuring must fill the field of view of your camera.

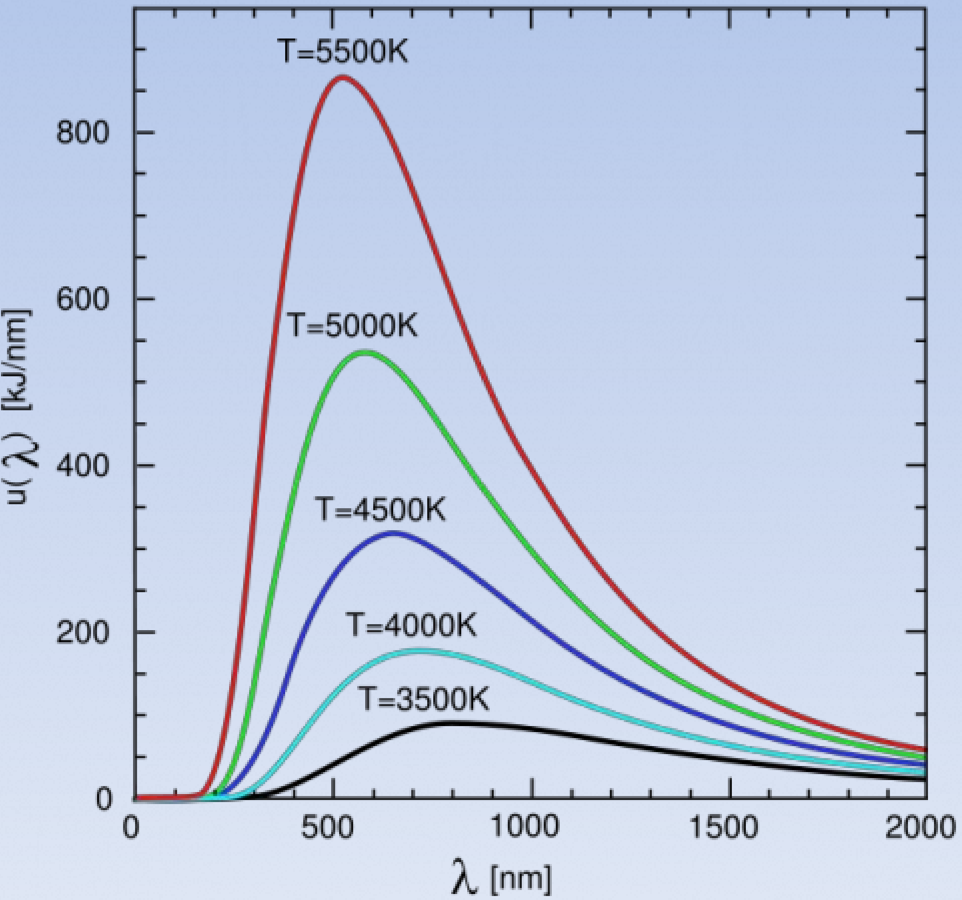
# Major applications

- Medical applications:
  - Skin temperature measurement.
  - Body temperature measurement.
- Detecting clouds for remote telescope operation.
- Checking mechanical equipment or electrical circuit breaker boxes or outlets for hot spots.
- Checking heater or oven temperature, for calibration and control purposes
- Detecting hot spots / performing diagnostics in electrical circuit board manufacturing
- Checking for hot spots in fire fighting situations
- Monitoring materials in process of heating and cooling, for research and development or manufacturing quality control situations

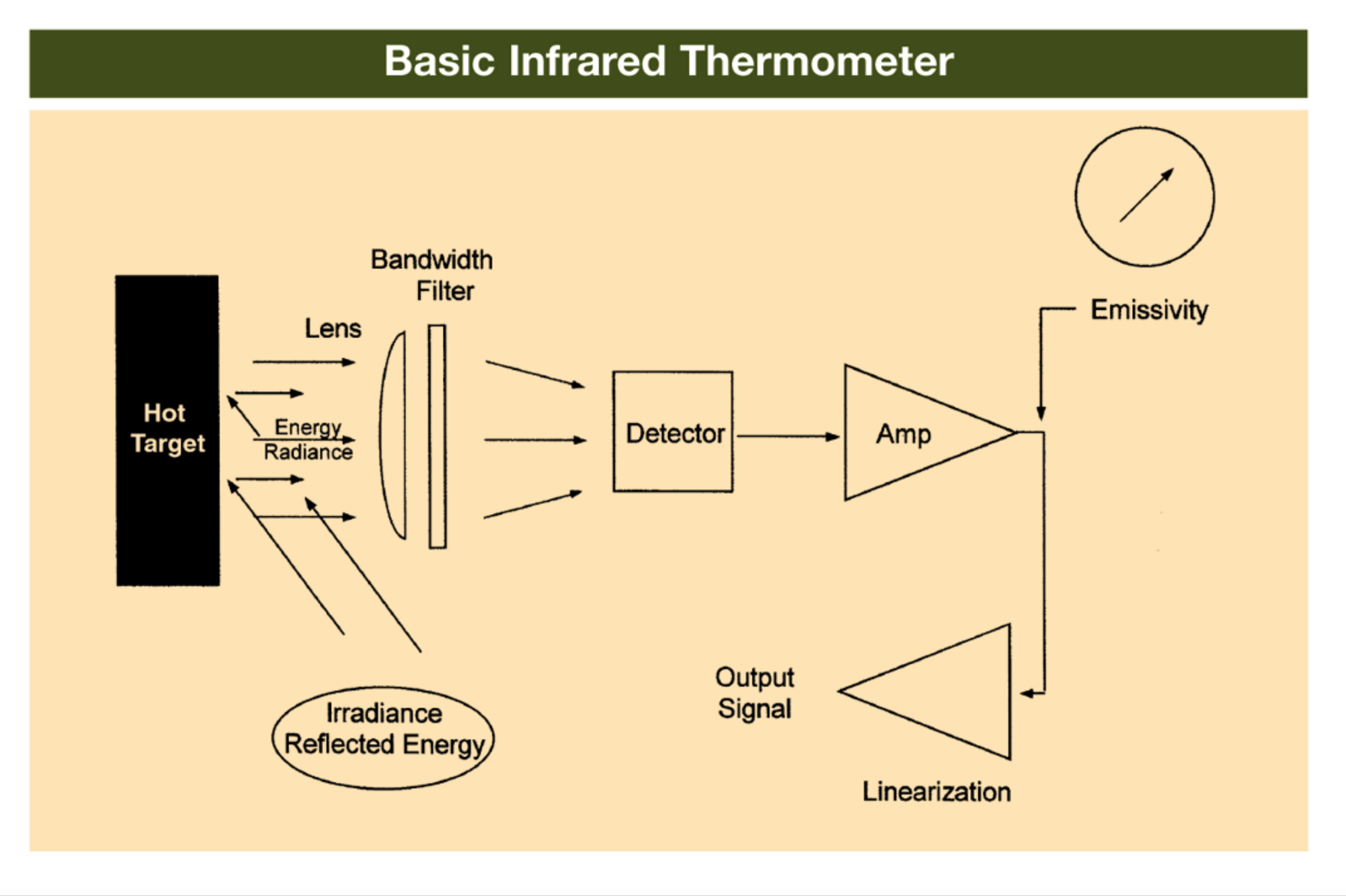
# Basic Working Principle

IR Emission Thermometers work based on the principle that all objects whose temperature is above the absolute zero radiate electromagnetic waves whose spectrum is associated to its surface temperature.



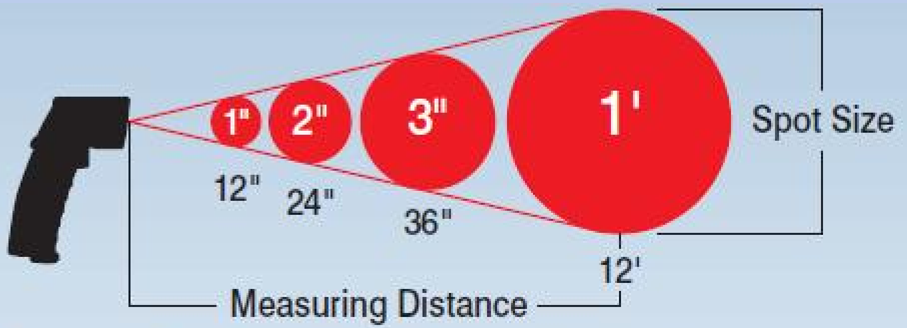



# Basic Working Principle



# Major Specifications

- Response time:
  - IR thermometers' response time is around one second, which is relatively fast. However, their warm up time is relatively large.

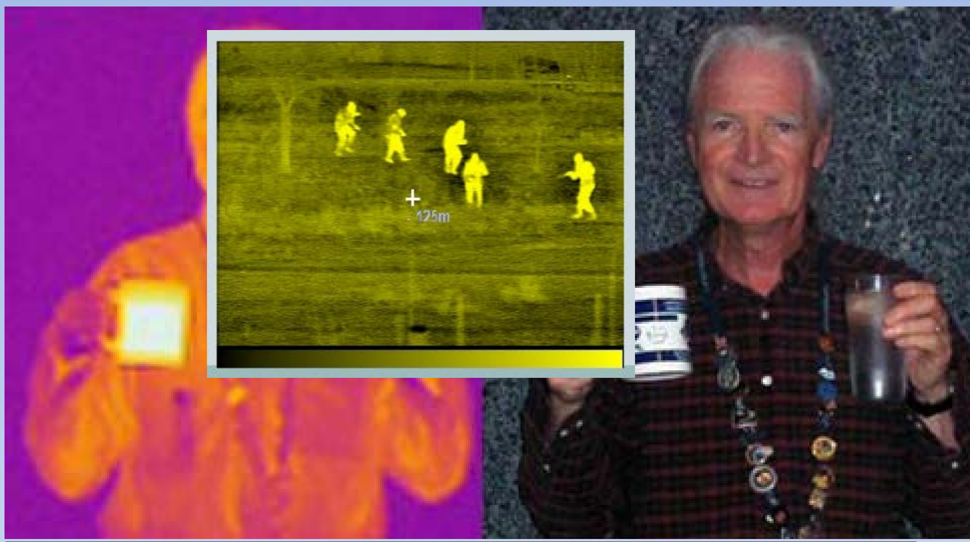


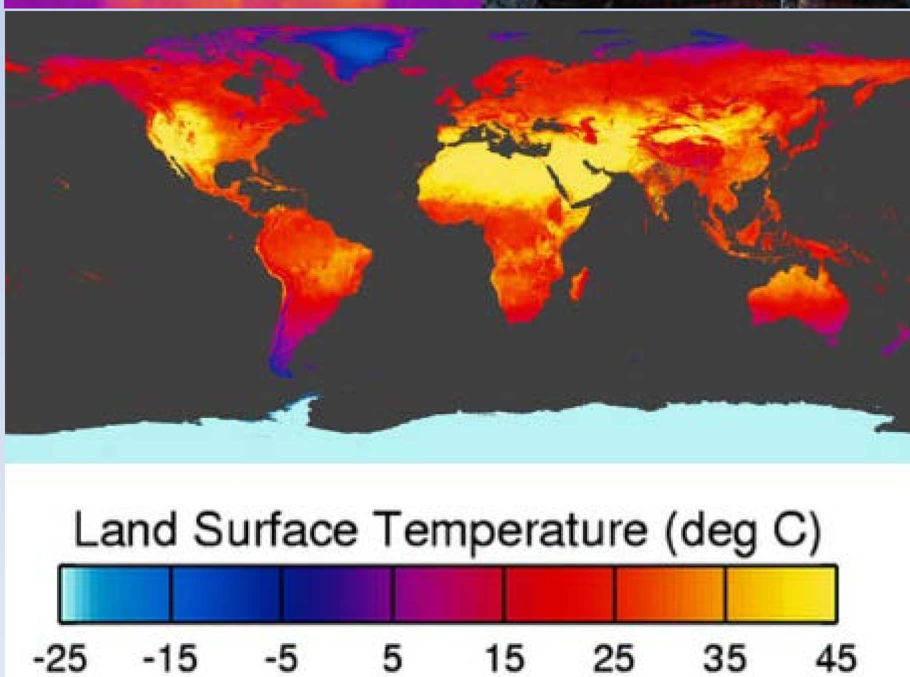

The Distance-to-Spot Ratio (D:S) indicates the size of the measurement field that a noncontact infrared thermometer uses to provide a temperature reading. The larger the ratio, the better the resolution and the smaller the area that can be measured.

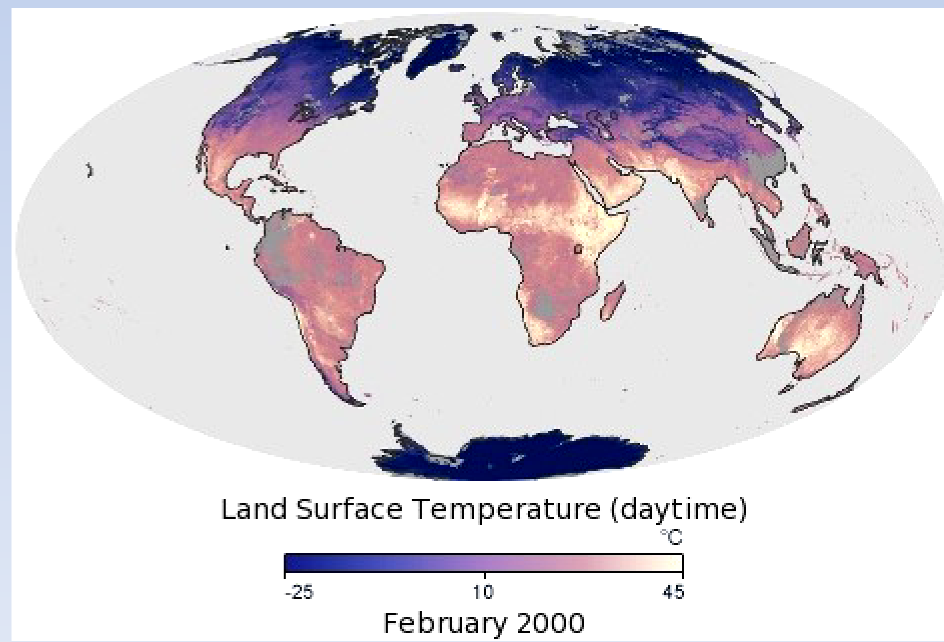
For example, a D:S ratio of 8:1 means that the measurement field is approximately 1" in diameter when the target is approximately 8" away. Likewise, a device that has a 12:1 D:S ratio measures a 1" spot when it's 12" away from the target; at 2' it's measuring a 2" spot; at 3' a 3" spot and so on.

# Satellite Remote Sensing

# Comparison of VIS and IR

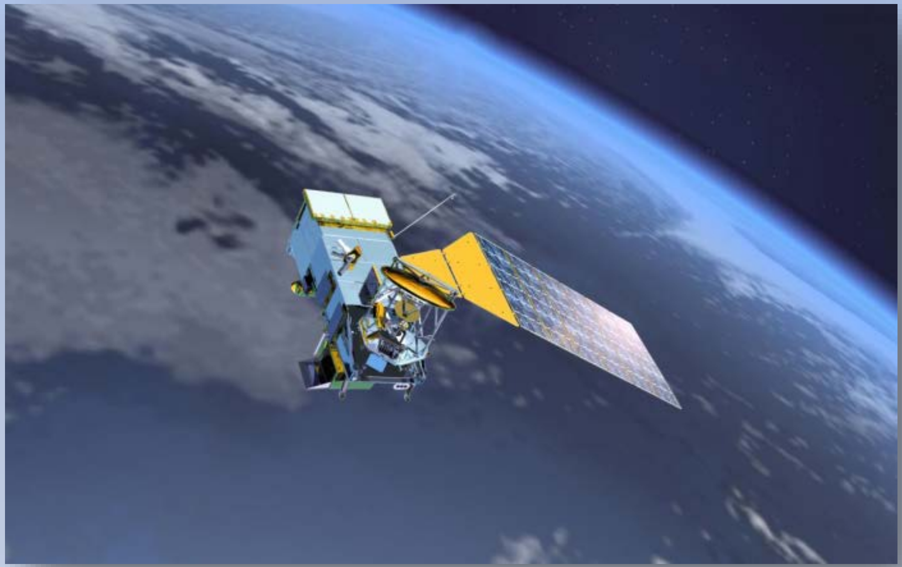




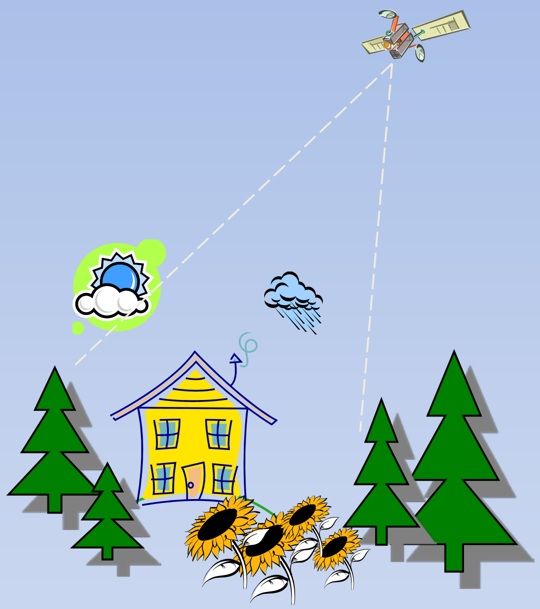



# Methods for measuring recent temperatures

- Earth's **global mean temperature (GMT)** is determined by averaging measurements of air temperatures over land ocean surface temperatures.
- Surface temperature is measured not only by thermometers at ground-based weather stations and on ships, but also by satellites and weather balloons
- Thousands of weather stations spread over land surface worldwide measure the local air temperatures while thousands of ships and buoys measure the local sea surface temperatures.
- These measurements are combined so that every square kilometer counts equally toward global mean temperature.



# Land Surface Temperature (LST)



## What is LST?

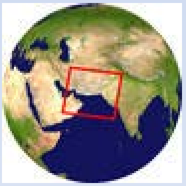
- The effective kinetic temperature of the earth surface "skin".
- For thermal infrared measurements: thermal emission from the ~10-13 microns depth.

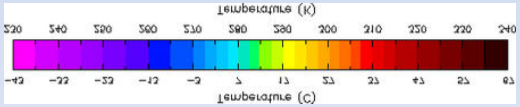
## Why is it important?

- Key climatological variable
- Contributes to the magnitude and partitioning of energy fluxes at the earth's surface.
- Applications: quantify surface's heat and water fluxes, monitor drought conditions and crop health, assess soil moisture content, map geological features, assess water quality, volcanology, etc.
- *Climate Data Record (CCSP, NASA, GCOS…).*

# MODIS RR LST Product

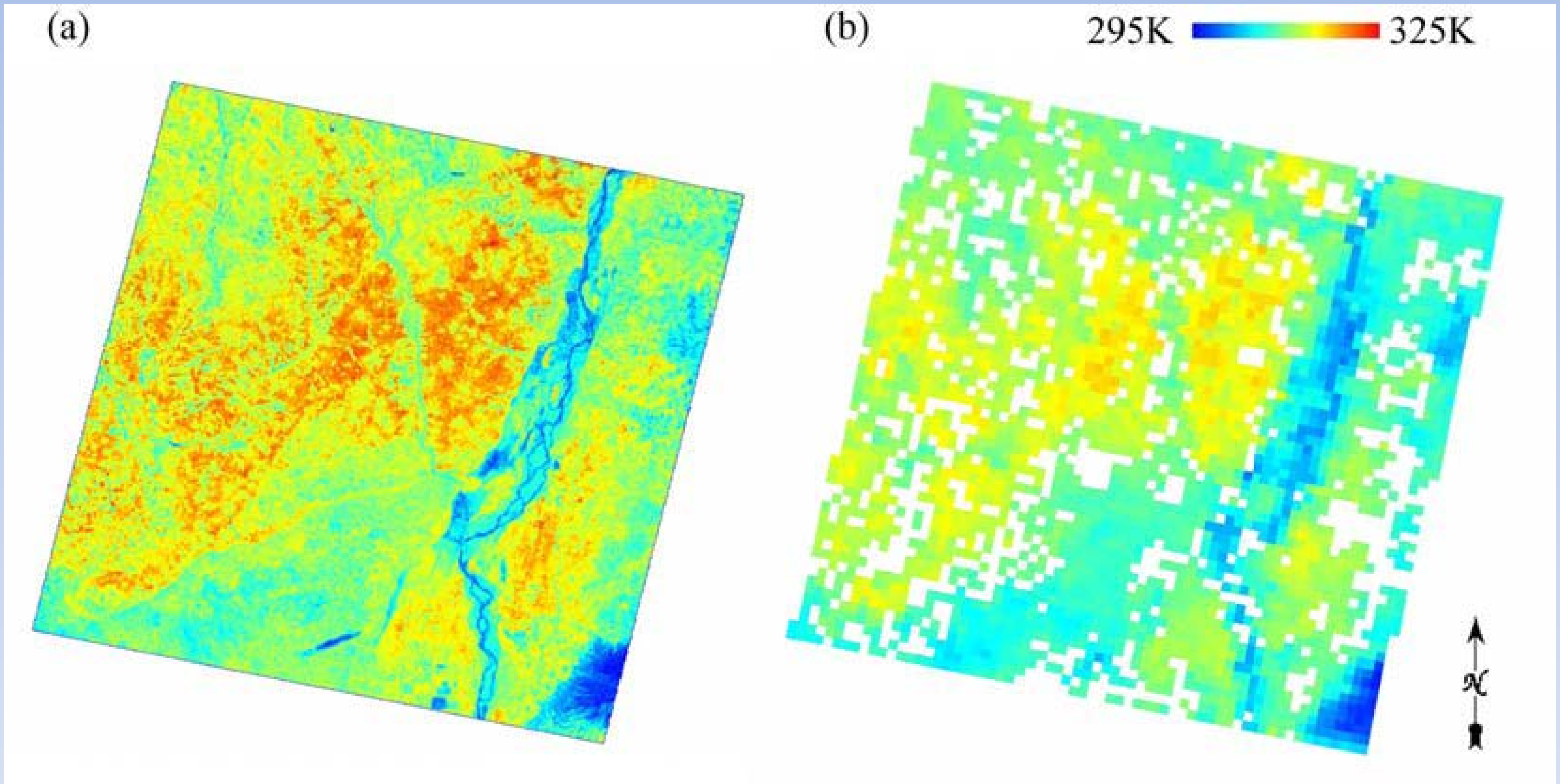
- RR LST product is generated for each granule acquired by MODIS Terra and MODIS Aqua.
- Provides day and night products at 1 km spatial resolution,  globally and in swath format.





# Land Surface Temperature

Example of ASTER LST compared to MODIS LST for the same area of study




(From Liu et al., 2009)

# Detection of Forest Fire

On February 18, 2015, the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard NASA's Aqua satellite captured an image of wildfires burning across both Chile and Argentina.

# Anybody remember this?

# MODIS standard LST swath algorithm

- Generated using a general split-window algorithm by Wan and Dozier (1996).

$$T_s = C + \left(A_1 + A_2\frac{1-\varepsilon}{\varepsilon} + A_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{31}+T_{32}}{2} + \left(B_1 + B_2\frac{1-\varepsilon}{\varepsilon} + B_3\frac{\Delta\varepsilon}{\varepsilon^2}\right)\frac{T_{31}-T_{32}}{2}$$

T31 and T32 are the brightness temperatures for MODIS bands 31 and 32, respectively;
and A1, A2, A3, B1, B2, B3 and C are regression coefficients.

- Coefficients (available in a LUT) :
  - are determined through regression analysis of radiative transfer simulations for a wide range of surfaces and atmospheric conditions.
  - are stratified by subranges of near surface air temperature and total column water vapor. These input fields are obtained at 5 km × 5 km resolution from the MOD07_L2 product.

- Estimates of the surface emissivity are required for each pixel to retrieve land surface temperature.

# Emissivity

- To back out temperature, surface emissivity must be known.
- You can look up emissivities, but it's not easy to get an accurate number, esp. if surface condition is uncertain (for example, degree of oxidation).
- Highly reflective surfaces introduce a lot of error.
- Narrow-band spectral filtering results in a more accurate emissivity value.

# Emissivity determination

- Based on a landcover classification approach. The algorithm determines each pixel's land cover class from MODIS gridded land cover product (MOD12Q1).

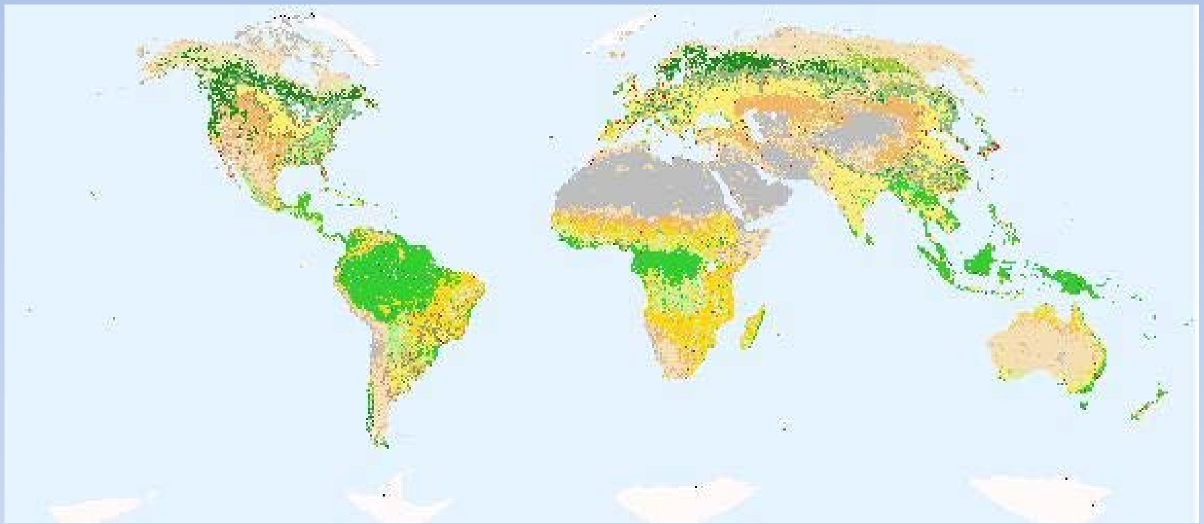


Fig.: MODIS Land cover map (MOD12Q1).

- Once the landcover type for a given pixel is identified, the emissivities ε31 and ε32 are retrieved from a LUT.

- For pixels in which MODIS angle of observation is above 42.3° an adjustment to the emissivity is used to account for directional emissivity variation.

# What is role of temperature measurement in my research?

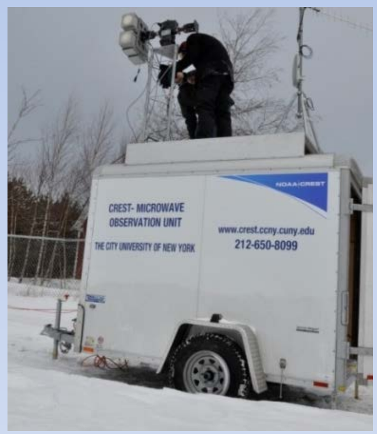
# CREST-SAFE - Snow Analysis and Field Experiment

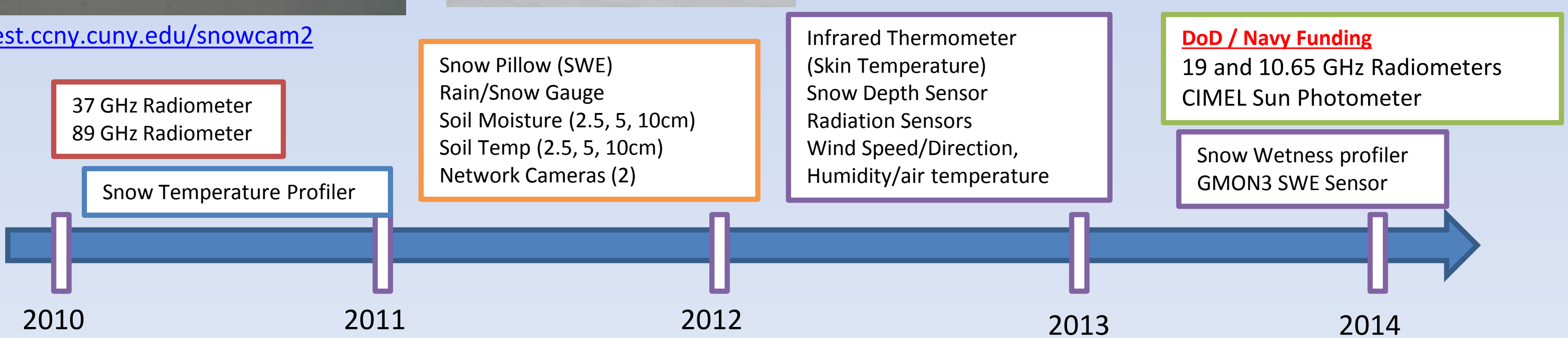
- This Field Experiment is setup near the National Weather Service office at Caribou, ME in 2010. Funded by (CUNY, NOAA, DoD/NAVY)
- This project is motivated to (a) develop, improve and validate the NASA/NOAA's Snow Retrieval Algorithms (b) develop real time and forecasted gridded snowpack data by objectively merging in-situ stationed with satellite based VIS/NIR and microwave observation.

http://crest.ccny.cuny.edu/snow


Real time Web-cam monitoring of site (11 Feb 2013)

http://crest.ccny.cuny.edu/snowcam2



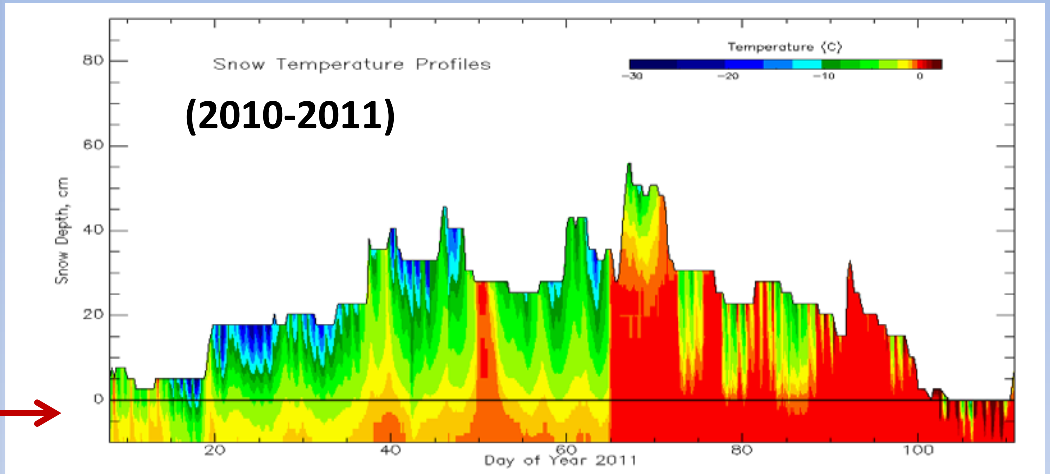

Timeline of Snow Experiment Development


CREST- MICROWAVE
OBSERVATION UNIT

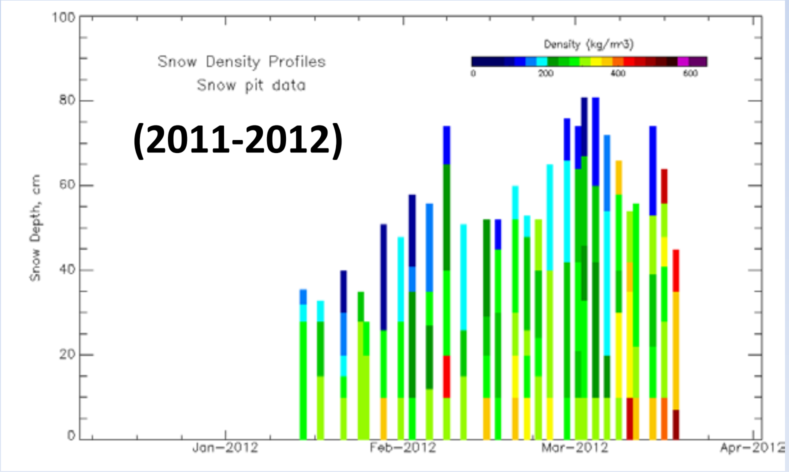
# CREST-SAFE: Observations

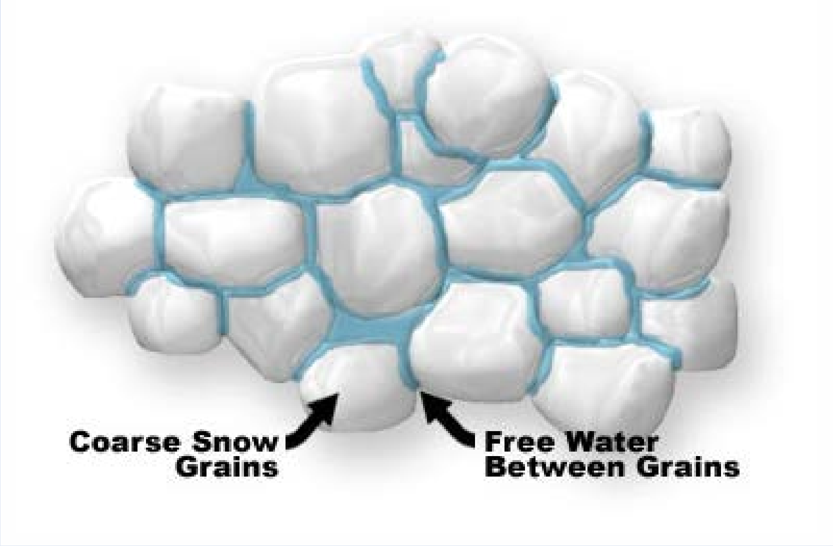


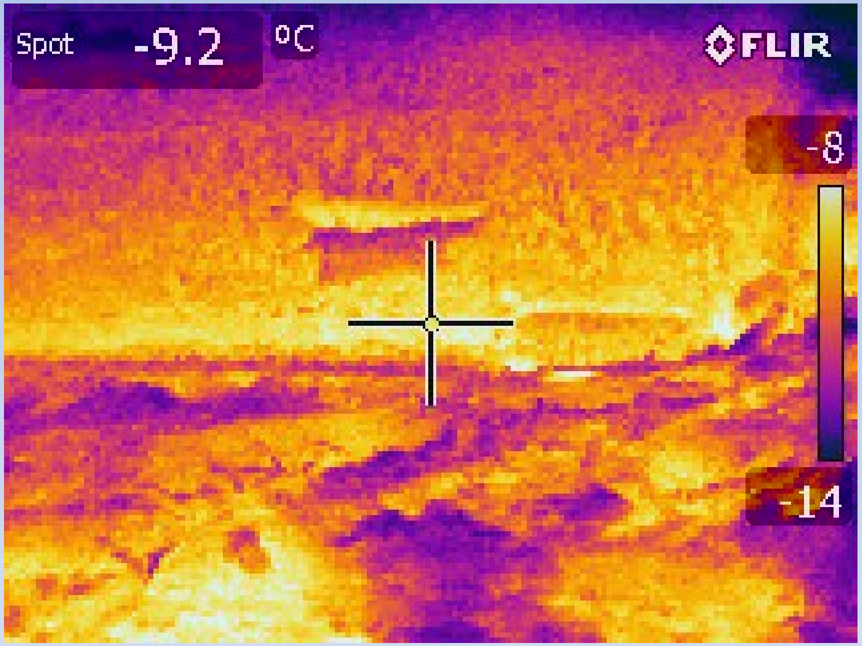
## Snow temperature profiler time series



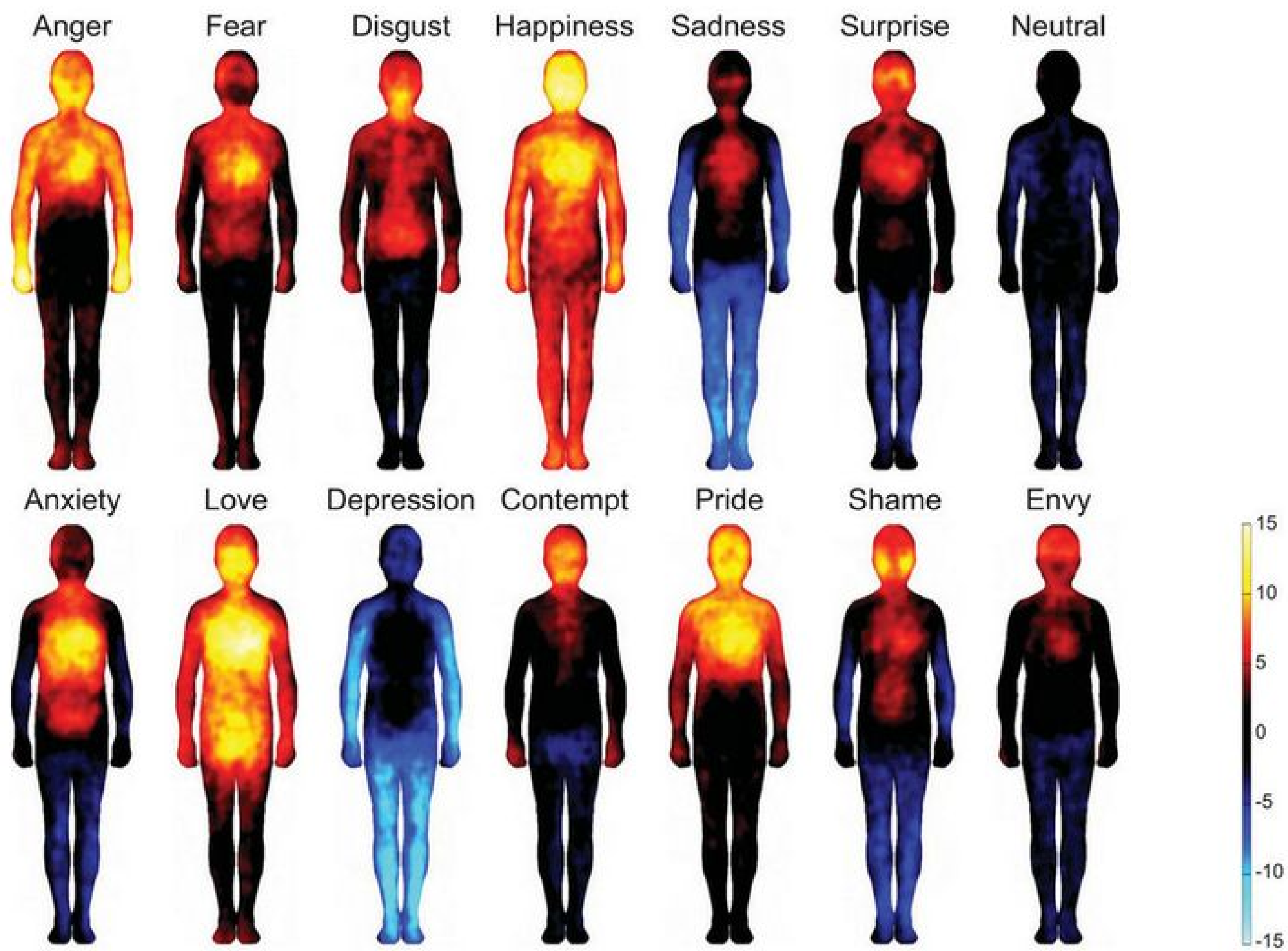

## Manual Measurements:



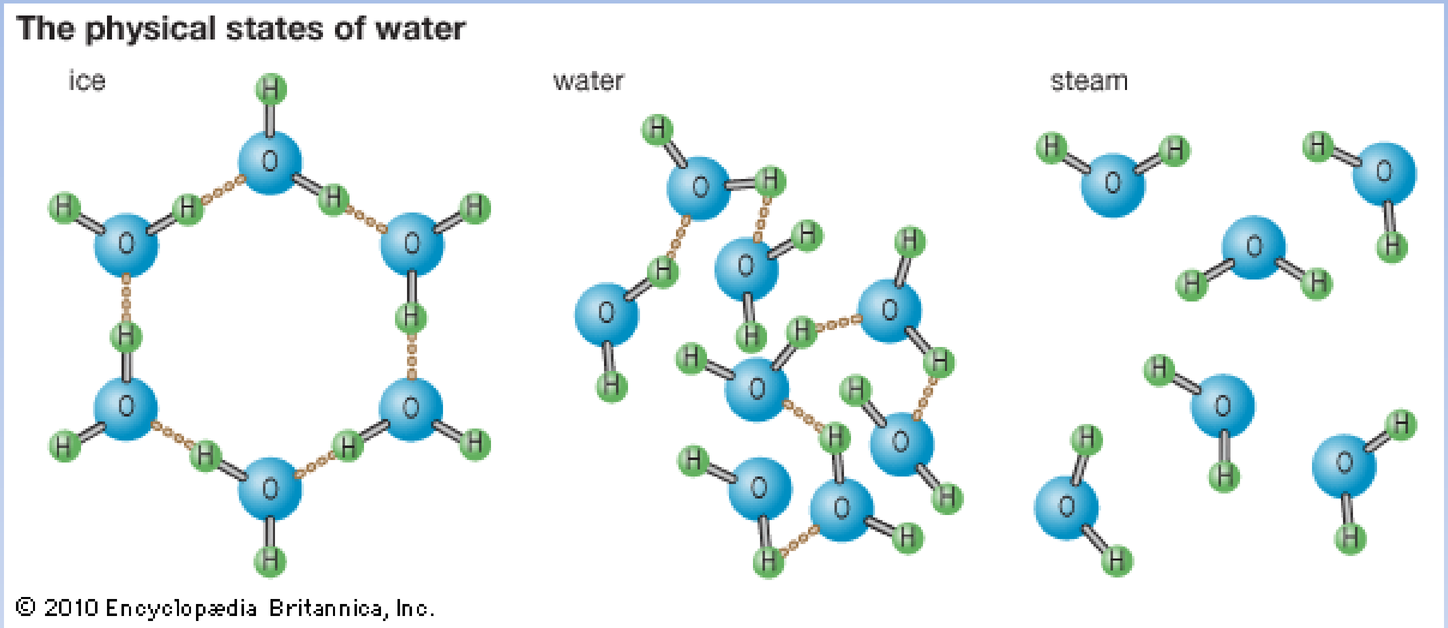

Spot -9.2 °C
FLIR
-8
-14

# Human body temperature varying




People drew maps of body locations where they feel basic emotions (top row) and more complex ones (bottom row). Hot colors show regions that people say are stimulated during the emotion. Cool colors indicate deactivated areas.

Image courtesy of Lauri Nummenmaa, Enrico Glerean, Riitta Hari, and Jari Hietanen.


The physical states of water
ice
water
steam
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