



SCIENCE OVERVIEW

One of the easiest ways to keep materials cool in sunlight is to put them in shade. People in warm climates are very familiar with the idea, as it is a simple and inexpensive way to keep items in a cool environment when active refrigeration is not possible. Similar ideas based on observing the properties of light, heat, and shadows can be used in developing space missions exploring environments with different temperatures. On a planetary scale, we are familiar with being shaded from the Sun at night in our daily cycle. On Earth, our dense atmosphere keeps the variations between daytime and night-time temperatures moderate, but on planets and moons that have no atmosphere, or only a very tenuous atmosphere, the variations may be extreme.

Temperature and Heat

An object's temperature is a measurement that describes the level of motion and vibration in the atoms and molecules of which it is composed (that is, the internal energy of the atoms and molecules). The higher the temperature of the object, the more vigorously its atoms and molecules move around and bounce off each other, and the more disorderly is their motion. This means that heat flowing into an object increases the internal energy and disorder in that object, while heat flowing out of it decreases its internal energy and disorder. For example, the water molecules in a snowflake are arranged in an orderly pattern. If you hold a snowflake in your hand, it will

melt and become a drop of water. While it melts, the orderly pattern of the snowflake is changed into the more disorderly form of liquid water.

Thermodynamics

The science of thermodynamics studies the relationships between various forms of energy, such as heat and mechanical work. There are three basic laws of thermodynamics:

- 1) Energy may change form, but it is never created or destroyed ("conservation of energy"). For example, heat and chemical energy can be changed into mechanical energy by steam turbines and by automobile gasoline engines.
- 2) Heat energy flows from hotter to colder substances unless work is done.
- 3) There is a theoretical temperature at which matter would have the least possible internal energy and no disorder. However, it is impossible to reduce the temperature of any system to this absolute zero, 0 K (-273°C, -459°F).

Transmitting Heat

If you hold a snowflake in your hand, it will melt because the heat from your hand travels to the snowflake and causes its temperature to rise. In general, heat passes from one substance or object to another by:





1) Conduction

- Heat moves through material without any of the material moving.
- E.g., the tip of a metal pitchfork placed in a fire: vibration of atoms is transmitted from the tip throughout the pitchfork, but none of the atoms move from the tip to other parts of the pitchfork.

2) Convection

- Heated material moves and carries heat with it.
- E.g., heating water in a pot on a stove: hot liquid from the bottom of the pot rises up, while cold water sinks down to be heated.

3) Radiation

- Heat is transmitted via electromagnetic radiation, either through a medium (such as air) or without need for material (e.g., through space).
- E.g., infrared rays, visible sunlight.

What Is Electromagnetic Radiation?

Weather forecasters often show temperature maps of the United States based on the temperature measurements in different parts of the country that day. The maps are created by assigning each temperature a color, and then filling the map with colors corresponding to the temperatures measured at each location. A map created this way shows the temperature field of the United States on that particular day. The temperature field covering the United States, in this sense, is a description of the temperatures at every location across the country.

In a similar fashion, the universe can be thought of as being permeated by an electric field. All electrically charged particles (such as electrons) have a region of space around them where they influence the behavior of other charged particles wandering there. This region can be described as an electric field around the particle. Just as temperatures in different parts of the country create the temperature field of the United States, the electric charges in the universe can be thought of as creating an electric field permeating the whole universe. Magnetic objects behave in a similar fashion: every magnetic object creates a magnetic field around it, and their collective magnetic field permeates the universe.

Most things in the universe tend to move around, and electric charges are rarely an exception. If the velocity of an electric charge changes (that is, it accelerates or decelerates), it creates a disturbance in the electric and magnetic fields permeating the universe. These disturbances move across the universe as waves in the "fabric" of the electric and magnetic fields. The waves also carry energy from the disturbance with them, in a similar way that the energy of the wind striking a flag is carried across the fabric by the waving of the flag. The waves carrying the energy of the disturbance across the universe are characterized by their wavelength, which measures the distance between two consecutive wave crests.

A familiar example of this kind of wave is visible light. Different colors of visible light have slightly different wavelengths, and there are waves which have





much higher and shorter wavelengths than the light that humans can see. Together, the waves of all different wavelengths are called electromagnetic radiation, and the whole array of different kinds of light, arranged according to their wavelength, is called the electromagnetic spectrum. Electromagnetic radiation travels at the speed of light (300,000 km/s or 186,000 miles/s in a vacuum such as space).

(See Figure 2.)

Electromagnetic radiation is not the same as "heat" – it is a way to transmit energy from a heat source as radiation. The energy can then be felt as heat when it interacts with matter (e.g., feeling warm sunlight on our skin). Energy transmitted this way can travel

through a medium (e.g., sunlight traveling through the Earth’s atmosphere) but it can also travel through a vacuum in space. In both cases, the transferred energy creates heat in objects that absorb the radiation. We usually associate heat with infrared radiation, since our bodies are warm and therefore emit radiation in infrared wavelengths. (Remember that our bodies do not emit visible light; we see each other because of light reflected by our bodies, but originally emitted by the Sun or another light source.) Hot objects (such as the Sun) emit energy also in other wavelengths, including visible light. The energy of sunlight is carried through space by electromagnetic radiation of all kinds.

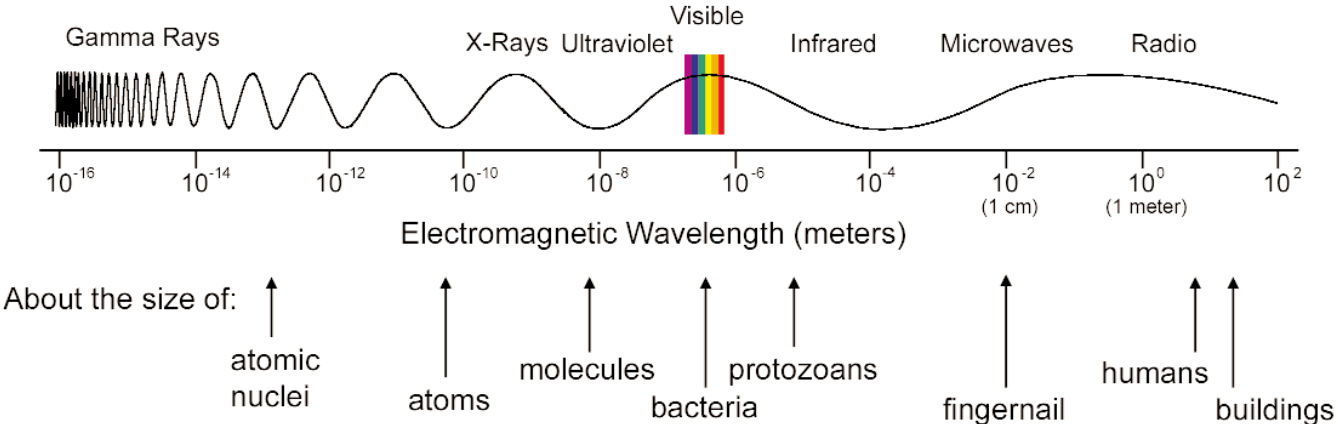


Figure 2: The electromagnetic spectrum. In the picture, different parts of the spectrum are shown as one continuous wave. In reality, a given electromagnetic wave has one particular wavelength. The continuous wave in the picture above is used to better illustrate the difference between wavelengths from one part of the spectrum to another.





How Heat Changes a Substance

There are three basic ways in which heat can change materials:

1) Change in temperature

- The internal energy of the atoms and molecules of the material increases.
- This is the most common result of heat interacting with matter.
- The amount of heat needed to raise the temperature of one gram of a substance one degree Celsius is called the specific heat capacity (or just specific heat) of the substance.

2) Change in size

- Since the motion of the atoms and molecules in the substance increases when heat flows into it, the atoms and molecules need more space and the substance expands in most cases.
- In contrast, when heat flows out of a substance, the atoms and molecules move more slowly and require less space; the substance contracts in most cases.
- All gases and most liquids and solids expand when heated. An important exception is water, which contracts when its temperature rises from 0°C (32°F) to 4°C (39°F), and only then starts expanding as it is heated. The same is also true when water changes phase from solid to liquid: water contracts when heated from ice to liquid.

This property is due to water's rigid crystal structure in the solid state (ice).

- The change in size is the basis for bulb-type thermometers, among other things.
- This effect must be taken into account when building bridges, buildings, and other structures, so that the materials will be able to expand and contract without causing severe problems.

3) Changes in the physical state (phase)

- Melting: heat causes a substance to change from solid to liquid.
- Freezing: loss of heat causes a substance to change from liquid to solid.
- Boiling: heat causes a substance to change from liquid to gas.
- Condensation: loss of heat causes a substance to change from gas to liquid.
- Sublimation: absorbing heat causes a solid to change directly into gas.
- Deposition: loss of heat causes gas to change directly into solid.
- Melting and freezing occur at the same temperature: melting and freezing point.
- Boiling and condensation occur at the same temperature: condensation and boiling point.
- The amount of energy that needs to be added or removed to change the state of a material is called latent heat.





When energy is added to a substance that is changing its state (for example, heating water that is boiling already), its temperature remains the same until all of the substance has changed state. If one draws a graph of the temperature of a substance as a function of the amount of heat given to it (see Figure 3), the phase changes show up as plateaus in the graph. The temperatures at which the phase changes occur vary greatly between different materials and depend on the type of substance.

Phases of Water

Water is one of the most important substances on Earth. It is a major component in the interaction between the Earth systems (hydrosphere, atmosphere, geosphere, and biosphere). It is also essential for life; liquid water is necessary in every environment on Earth that supports life forms, and may be necessary to any possible life forms elsewhere.

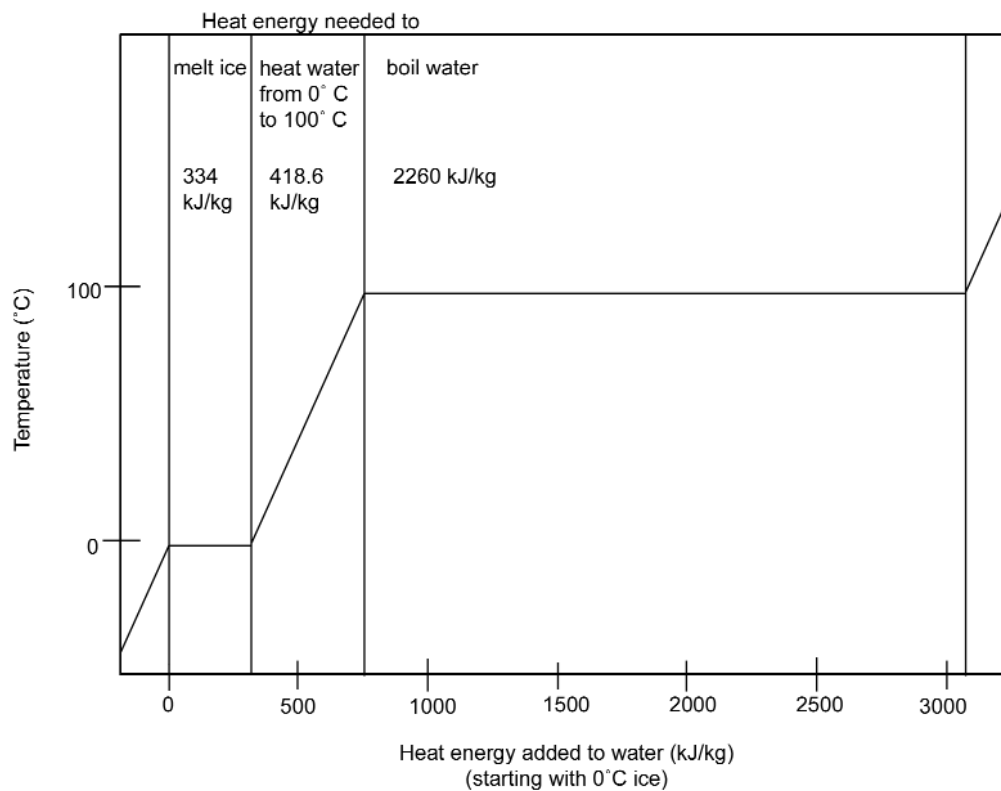


Figure 3. The heating curve of water shows the amount of energy needed to convert water from ice to liquid water and then to water vapor. Before ice reaches its melting point (0°C; 32°F), adding energy to it results in the increase of its temperature. While the ice is melting, its temperature stays at 0°C (32°F) until all the ice has melted, resulting in the first plateau in the curve. When more energy is added to the liquid water, its temperature increases, until the boiling point of 100°C (212°F) is reached. At this point, another plateau in the curve is created, as the temperature stays the same until all the water has turned into vapor. When more energy is added into water vapor, its temperature rises again. The curve can be read also right-to-left; in this case it describes the amount of energy removed from water when water vapor is turned to liquid and then to ice.





The three phases of water are ice or snow (solid water), liquid water, and water vapor or steam (gaseous water). All the phases of water have important roles in the Earth system: for example, liquid water from the oceans evaporates, forms into clouds, and later rains down on land, and may freeze into snow or ice deposits in cold areas. At normal atmospheric pressure, the melting (and freezing) point of water is 0°C (32°F), and the boiling (and condensation) point is 100°C (212°F).

The graph for the temperature change of water as a function of energy added to it (Figure 3) can be explained in the following manner. The temperature of ice, the solid form of water, is 0°C or less. When ice is heated, its temperature rises as the heat energy is converted into the increased internal energy of the water molecules. This continues until the temperature of the ice reaches the melting point. At this point (also the zero point of the heat energy added to the ice in Figure 3), the heat energy given to the ice goes toward changing the phase of the water from ice to liquid – effectively breaking the solid bonds between water molecules - and does not show up as temperature change. This can be seen as the first plateau in the curve in Figure 3. Only when all the ice in the ice-water mixture has melted does the temperature in the (now liquid) water begin to rise again. The amount of energy required to melt the ice (the latent heat, sometimes also called "the heat of fusion") is 334 kJ per kg of ice. Additional energy given to the water after all the ice has melted results in a rise in the water tem-

perature until the temperature reaches the boiling point, 100°C . At this point, the energy given to the water goes into changing its phase from liquid into gas. During this process, the internal energy of the water molecules becomes so high that they overcome the forces keeping the water molecules together (such as attraction between molecules and the vapor pressure of gaseous water above the liquid), disassociate themselves from neighboring molecules, and become vapor. The amount of energy required to vaporize the water ("heat of vaporization") is 2260 kJ per kg of water. This creates the second plateau in the curve in Figure 3. As Figure 3 indicates, boiling 1 kg of water requires much more energy than melting the same amount of ice (or raising the temperature of the same amount of liquid water from 0°C to 100°C); this is because overcoming the forces keeping the liquid molecules together requires a lot more energy than breaking the solid bonds of ice.

The existence of the phase change plateaus is a source of misconceptions. People may think that the temperature of an ice-water mixture will rise when more heat is applied, even before all the ice has melted. When boiling water on the stove, if you turn up the burner, you will get a more vigorous boil, and people sometimes think that this means that the temperature of the water is rising. As explained above, this is not what happens in either case. The temperature of ice water will remain at 0°C until all the ice has melted. When the water is boiling harder, it means that more water is being vaporized in a given time (the water in





the pot boils faster), but not that the temperature is any higher. The additional energy given by the higher setting of the burner just goes into changing the phase of a larger amount of the water in a given time.

The total amount of energy required to cause a phase change can be written as an equation:

$$Q = m \times L,$$

where Q = heat energy (kJ),

m = mass (kg),

L = latent heat (kJ/kg).

Using the values given in Figure 2, the amount of energy needed to melt a given amount of ice or boil a given amount of liquid water can be calculated easily.

Keeping Heat at Bay

In order to keep items cool, we need to try and keep heat from interacting with them. The movement of heat from one place to another can be restricted by insulation: by keeping heat from entering or flowing out of an object. The word "insulation" can also be used to describe electric or acoustic insulation – keeping electric currents or sound from a certain place or within a certain place – but in this discussion, thermal insulation is the basic topic.

To combat the three ways in which heat can travel, there are three basic methods of insulation:

- 1) To fight conduction, some materials are used as insulators.
 - E.g., many pots and pans have plastic or wood handles.

- 2) To fight convection, the space between hot and cold areas can be filled with "dead air."

- E.g., double-pane window: the layer of air between the outer and the inner windows stops the convection from transferring heat between them; narrow dead air space is better than wide since it makes the formation of convective air circulation currents more difficult.

- 3) To fight radiation, reflective or blocking materials can be used.

- E.g., reflective car sunshades placed against a windshield to prevent the inside of the car from heating up; sunscreen spread on skin to prevent sunburn.

Oftentimes, insulators are designed to combine different ways with which they can act to make them as efficient insulators as possible. For example, insulating material may be composed of poorly conducting material, have cell-like spaces to reduce the motion of cold or hot air, and be coated with reflective material. Insulation is used in homes and in various industrial applications, from steel furnaces to spacecraft.

Sunlight –The Principal Source of Energy on Earth

The Sun provides most of the energy on Earth. Some heat is generated inside the Earth, but it is a very small effect compared with sunlight. Without the Sun, the Earth would be cold and lifeless. The amount of solar radiation arriving on Earth at the top





of the atmosphere is known as the solar constant, and is 1370 W/m^2 . Much of the solar radiation arriving at Earth is reflected away or absorbed by the atmosphere, and typically only about half of it reaches the surface.

On Earth, the Sun's radiation is absorbed by the ground, the seas, and the atmosphere. It drives air flows in the atmosphere, currents in the oceans, and greatly influences climate and weather. It is the most important source of energy for life on Earth: it provides energy for photosynthesis and, in this manner, supports the first link in most food chains on Earth. It is possible for life to exist in places without sunlight (such as at the bottom of the oceans), but most of the life with which we are familiar uses the energy provided by sunlight in one way or another.

Shadows on Planets

The amount of solar radiation arriving at a point on the surface of the Earth varies between daytime and night-time. Roughly half of our planet is in sunlight at any given time (day), while the other half is shaded from the Sun by the Earth's own shadow (night). During the night, the energy of the sunlight no longer reaches the shadowed areas directly, and the surface is able to cool off by emitting infrared radiation into space. [Note that the surface emits infrared radiation also during the day, but the cooling effect is then countered by the arriving sunlight.] As a result, temperatures in a given place are usually lower during the night than during the day. Earth's dense atmos-

phere moderates the temperature variations and, under some weather patterns, the temperatures can actually be warmer at night than during the day.

The largest daily temperature differences on Earth occur in deserts. Deserts are hot because they are at low latitudes and, therefore, the Sun is almost directly overhead at noon for most of the year and, unlike rainforests at similar latitudes, they do not have the benefit of the cooling effect of substantial vegetation. Water vapor in the air can prevent infrared radiation from escaping into space, and the lack of it at desert areas means that they can cool efficiently at night. Under these conditions, the temperature difference between the day and the night can be about 40°C (75°F) (changing from 66°C to 24°C ; 150°F to 75°F). The desert also provides a good example of the effectiveness of cooling by staying in the shadows: the temperature in the shadow of a desert rock can be more than 22°C (40°F) cooler than on top of it.

If we consider planets with no atmosphere or only a very tenuous atmosphere, the fluctuations in temperatures between the sunlit and shadowed sides of the planet can vary wildly. This is because the surface can heat up fast when it receives sunlight and also cool off quickly at night. For example, Mercury's atmosphere is very tenuous (virtually a vacuum) and cannot produce a similar moderating effect to Earth's. As a result, the daytime temperatures can be as high as 450°C (850°F), while at night, the temperatures can drop down to -180°C (-300°F).





MESSENGER and Shadows

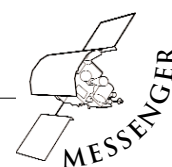
The MESSENGER mission to Mercury is a great engineering challenge because of the high-temperature environment in which the spacecraft will operate. At Mercury's distance from the Sun, the solar radiation will reach levels 5-11 times as high as they are in space near Earth, depending on where Mercury is on its orbit around the Sun. Since the Earth's atmosphere allows only about half of solar radiation to pass through, the MESSENGER spacecraft will be exposed to as much as 22 times the amount of solar radiation as it would on the surface of Earth. Combined with the infrared radiation emitted from Mercury, this creates an environment for the spacecraft where temperatures can reach well over 400°C (750°F).

MESSENGER mission designers have developed several solutions to overcome this problem, such as using heat-resistant materials, and employing radiator panels to radiate the generated excess heat effectively into space. The spacecraft's orbit around Mercury has been designed so that its closest approach to the planet is away from the most sun-baked region of the surface and so that it flies quickly over the sunlit areas. This is achieved by an orbit where the periapsis (the closest point to the surface of Mercury and also the part of the orbit where the spacecraft's speed is at its highest; the distance from the surface is 200 km or 124 miles) is at a high latitude and the apoapsis (the farthest point of the orbit and also the part of the orbit where the spacecraft's speed is at its lowest; the distance from the surface is 15,193 km or 9443 miles) is

far away from the surface of Mercury. This orbital design keeps the amount of infrared radiation received from the planet's surface at safe levels.

The central solution to the heating problem is the use of a sunshade made of cutting-edge thermal materials and designs. While the spacecraft is operating in orbit around Mercury, the sunshade will be pointed toward the Sun at all times, allowing the instruments to remain in its shadow. The temperature difference between the side of the sunshade facing the Sun and the shaded parts of the spacecraft can be as high as 400°C (720°F). As a result, MESSENGER's instruments will be in a thermal environment comparable to room temperature; during Mercury's orbit around the Sun, the temperature on the instrument deck of MESSENGER is expected to vary from a few degrees below 0°C (32°F) to 33°C (91°F).

The use of passive cooling methods is essential for the success of the MESSENGER mission. Using an active cooling system with refrigerants would be prohibitively expensive and probably not even technically feasible for a mission designed to study Mercury from orbit for one Earth year. The cost for the sunshade is about \$130,000, which is very reasonable when considering its importance for the mission and that the total cost for the whole MESSENGER project (mission design, spacecraft construction, launch, mission operations, etc.) is about \$300 million. An important consideration for minimizing the cost of the mission is to keep the spacecraft as lightweight as possible – each





kilogram of mass increases the cost of launching the spacecraft significantly. Again, an active cooling system with refrigerants would increase the weight considerably, while the sunshade adds only 19 kg to the total spacecraft mass of 1100 kg. The total cost for the launch (including the launch vehicle as well as the services by the launch personnel) is about \$65 million. Even though not all costs of the launch (such as the launch services) are directly proportional to the spacecraft mass, a rough estimate of the amount of money it costs to launch the spacecraft is \$59,000 per kilogram, based on these numbers.

Another important aspect of shadows for the MESSENGER mission is the amount of sunlight reaching the polar regions of Mercury. Since Mercury's rotation axis is not tilted (as the Earth's is – that is why Earth has the kind of seasons that it does), the highest apparent position of the Sun in Mercury's sky at a given latitude on the surface does not change during

Mercury's year. (But remember: the Sun does not actually revolve around Mercury; the rotation of the planet just creates the appearance that the Sun moves in the sky during the day.) For example, near Mercury's poles, the Sun appears very low near the horizon each day. In fact, right at the pole, the Sun appears to just crawl around the horizon every day, all year round, as the planet rotates. This means that the sunlight arriving at Mercury's polar regions arrives at a very low angle. Therefore, there probably are craters in the polar regions, whose bottoms have never seen sunlight, and it is possible for water ice to exist in these craters. (We say "water ice" to distinguish it from other kinds of ice made of different frozen materials.) Earth-based radar observations of Mercury have suggested that water ice might, indeed, exist in the polar regions, and confirming or rejecting this idea is one of the principal scientific goals of the MESSENGER mission.

