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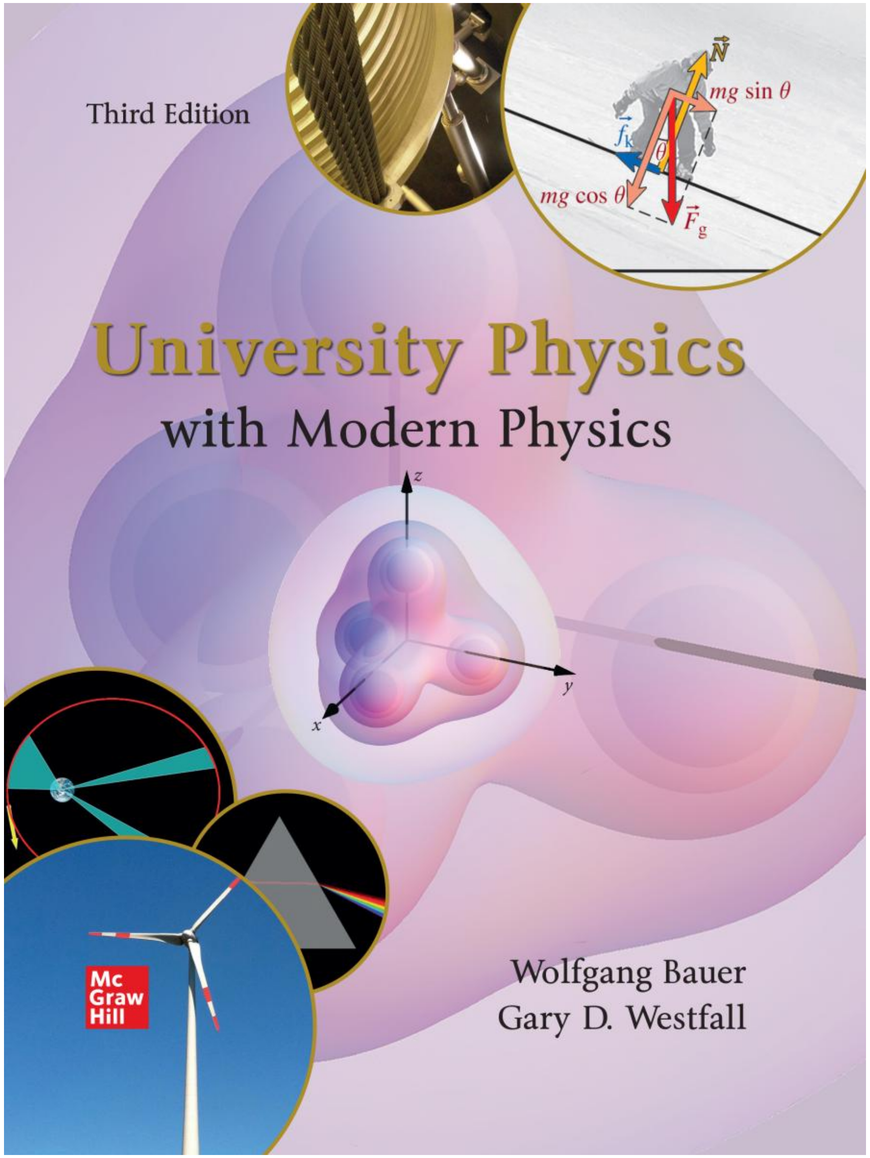
Chapter 17

Temperature

University Physics with Modern Physics
Third Edition

Wolfgang Bauer Gary D. Westfall



Temperature

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Temperature 1

- The Pleiades star cluster in the previous slide can be seen with the naked eye and was known to the ancient Greeks.
- What they could not know is that these stars exhibit some of the highest temperatures that occur in nature.
- Their surface temperatures range from 4,000 °C to 10,000 °C, depending on size and other factors.
- However, their interior temperatures can reach over 10 million °C, hot enough to vaporize any substance.
- On the other end of the temperature range, space itself, far from any stars, registers a temperature of roughly −270 °C.
- This chapter begins our study of thermodynamics.

Temperature 2

- Temperature is a concept we all understand from experience.
- We hear weather forecasters tell us that the temperature will be 72 °F today.
- We hear doctors tell us that our body temperature is 98.6 °F.
- When we touch an object, we can tell whether it is hot or cold.
- If we put a hot object in contact with a cold object, the hot object will cool off and the cold object will warm up.
- If we measure the temperatures of the two objects after some time has passed, they will be equal.
- The two objects are then in **thermal equilibrium**.

Heat

- Heat is the transfer between a system and its environment of thermal energy, which is energy in the form of random motion of the atoms and molecules making up the matter.
- Chapter 18 will quantify the concept of heat as thermal energy that is transferred because of a temperature difference.
- The temperature of an object is related to the tendency of the object to transfer heat to or from its surroundings.
- Heat will transfer from the object to its surroundings if the object’s temperature is higher than that of its surroundings.
- Heat will transfer to the object if its temperature is less than its surroundings.

Thermometer

- Measuring temperature relies on the fact that if two objects are in thermal equilibrium with a third object, they are in thermal equilibrium with each other.
- This third object could be a **thermometer,** which measures temperature.
- This idea, often called the **Zeroth Law of Thermodynamics**, defines the concept of temperature and underlies the ability to measure temperature.
- In order to find out if two objects have the same temperature, you do not need to bring them into thermal contact and monitor whether thermal energy transfers.
- Instead, you can use a thermometer and measure each object's temperature separately.

Concept Check 1

- The Zeroth Law of Thermodynamics tells us that

A. there is a temperature of absolute zero.

B. the freezing point of water is 0 °C.

C. two systems cannot be in thermal equilibrium with a third system.

D. thermal energy is conserved.

E. it is possible to construct a thermometer to measure the temperature of any system.

Solution Concept Check 1

- The Zeroth Law of Thermodynamics tells us that

A. there is a temperature of absolute zero.

B. the freezing point of water is 0 °C.

C. two systems cannot be in thermal equilibrium with a third system.

D. thermal energy is conserved.

E. it is possible to construct a thermometer to measure the temperature of any system.

Temperature Scales 1

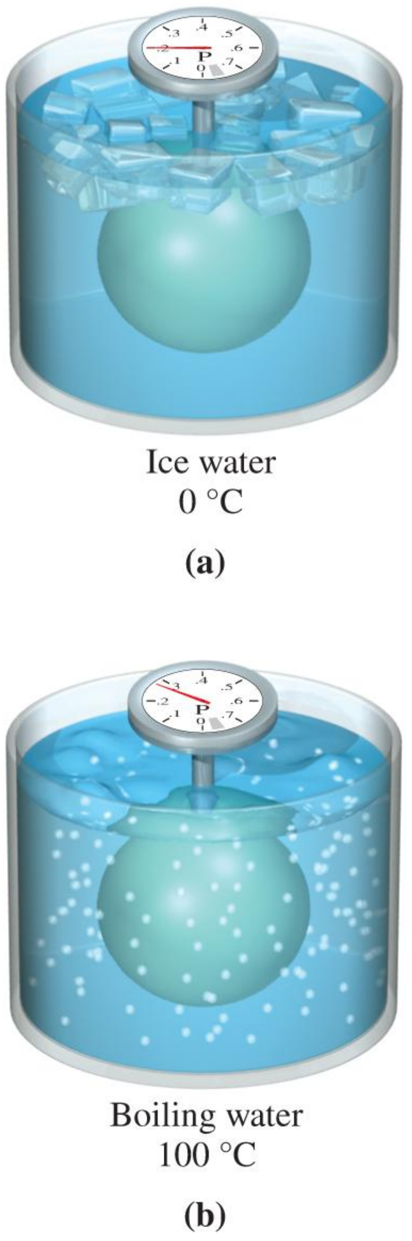
- Several systems have been proposed and used to quantify temperature; the most widely used are the Fahrenheit, Celsius, and Kelvin scales.
- The **Fahrenheit temperature scale** was proposed in 1724 by Gabriel Fahrenheit, a German-born scientist living in Amsterdam.
- Fahrenheit finally defined the unit of the Fahrenheit scale (°F) by fixing 32 °F for the freezing point of water and 96 °F for the temperature of the human body, as measured under the arm.
- Later, other scientists refined the scale by defining the freezing point of water as 32 °F and the boiling point of water as 212 °F.
- This temperature scale is used widely in the United States.

Temperature Scales 2

- Anders Celsius, a Swedish astronomer, proposed the **Celsius temperature scale** in 1742.
- Several iterations of this scale resulted in its unit (°C) being determined by setting the freezing point of water at 0 °C and the boiling point of water at 100 °C.
- This temperature scale is used worldwide, except in the U.S.
- In 1848, William Thomson (Lord Kelvin), a British physicist, proposed another temperature scale, which is now called the **Kelvin temperature scale**.
- This scale is based on the existence of absolute zero, the minimum possible temperature.

Absolute Zero 1

- The value of absolute zero was established by studying the pressure of gases as a function of temperature.
- Suppose we have a fixed volume of nitrogen gas in a hollow spherical aluminum container connected to a pressure gauge that reads 0.200 atm when placed in ice water.
- If we then place the container in boiling water, the gauge reads 0.273 atm.
- We can repeat this process with different starting pressures.



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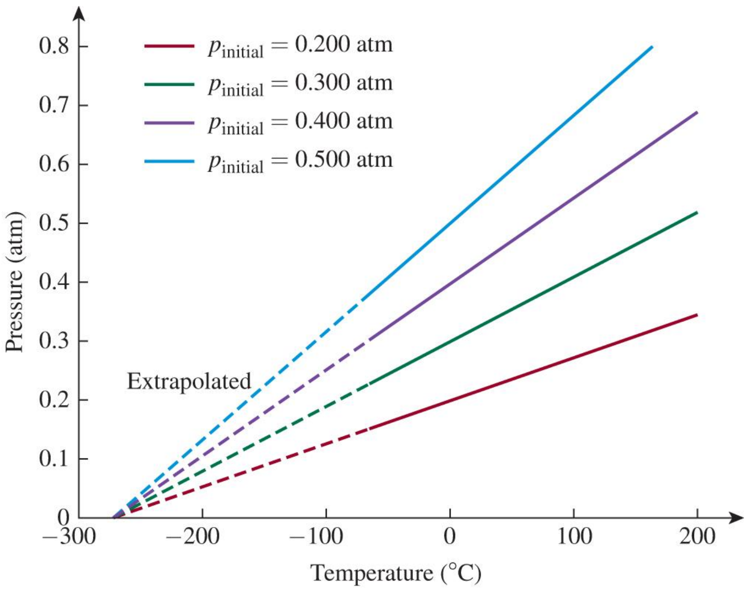
Absolute Zero 2

- What we find is that the pressure of the gas goes down as the temperature decreases.
- We can extrapolate the behavior of the gas until the pressure becomes zero.



- Note that we cannot make a direct measurement at low temperatures because the gas will liquefy.
- We find that all the extrapolated curves intersect at the same temperature at zero pressure.
- We call this temperature *absolute zero* (−273.15 °C).

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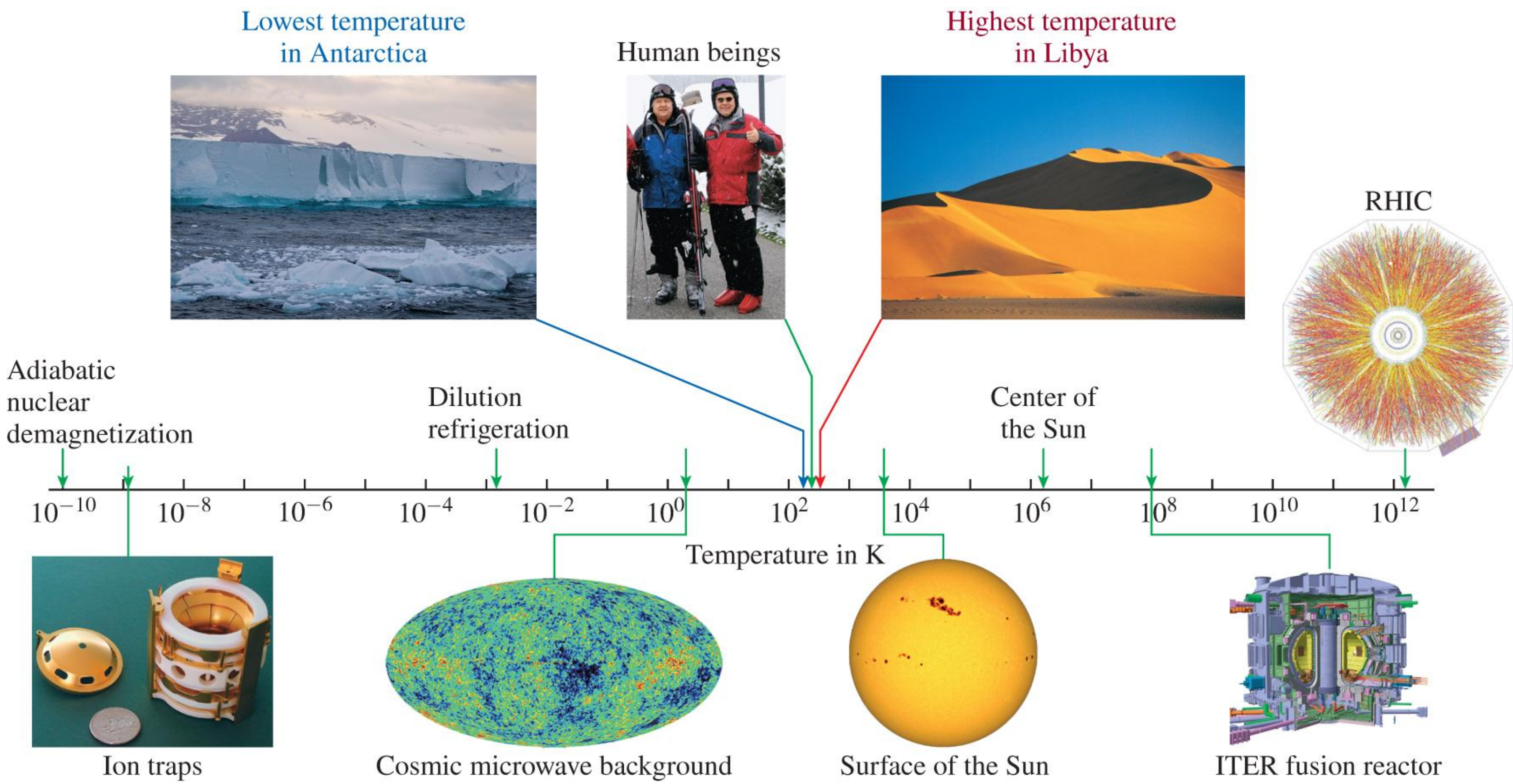
Kelvin Temperature Scale

- Kelvin used the size of the Celsius degree (°C) as the size of the unit of his temperature scale, now called the **kelvin** (K).
- On the Kelvin scale, the freezing point of water is 273.15 K and the boiling point of water is 373.15 K.
- This temperature scale is used in many scientific calculations, as we'll see in the next few chapters.
- Because of these considerations, the kelvin is the standard SI unit for temperature.
- To achieve greater consistency, scientists have proposed defining the kelvin in terms of other fundamental constants, rather than in terms of the properties of water.
- These new definitions went into effect in 2019.

Temperature Ranges

- Temperature measurements span a huge range.



(Ocean): Richard McManus/Getty Images; (Skiers): W. Bauer and G. D. Westfall; (Namib Desert): Digital Vision/Getty Images; (RHIC): The STAR Experiments, Brookhaven National Laboratory; (Ion Trap): MSU National Superconducting Cyclotron Laboratory; (Cosmic microwave): ESA and the Planck Collaboration/NASA; (Sun): NASA/Goddard Space Flight Center Scientific Visualization Studio; (Fusion Reactor): ITER

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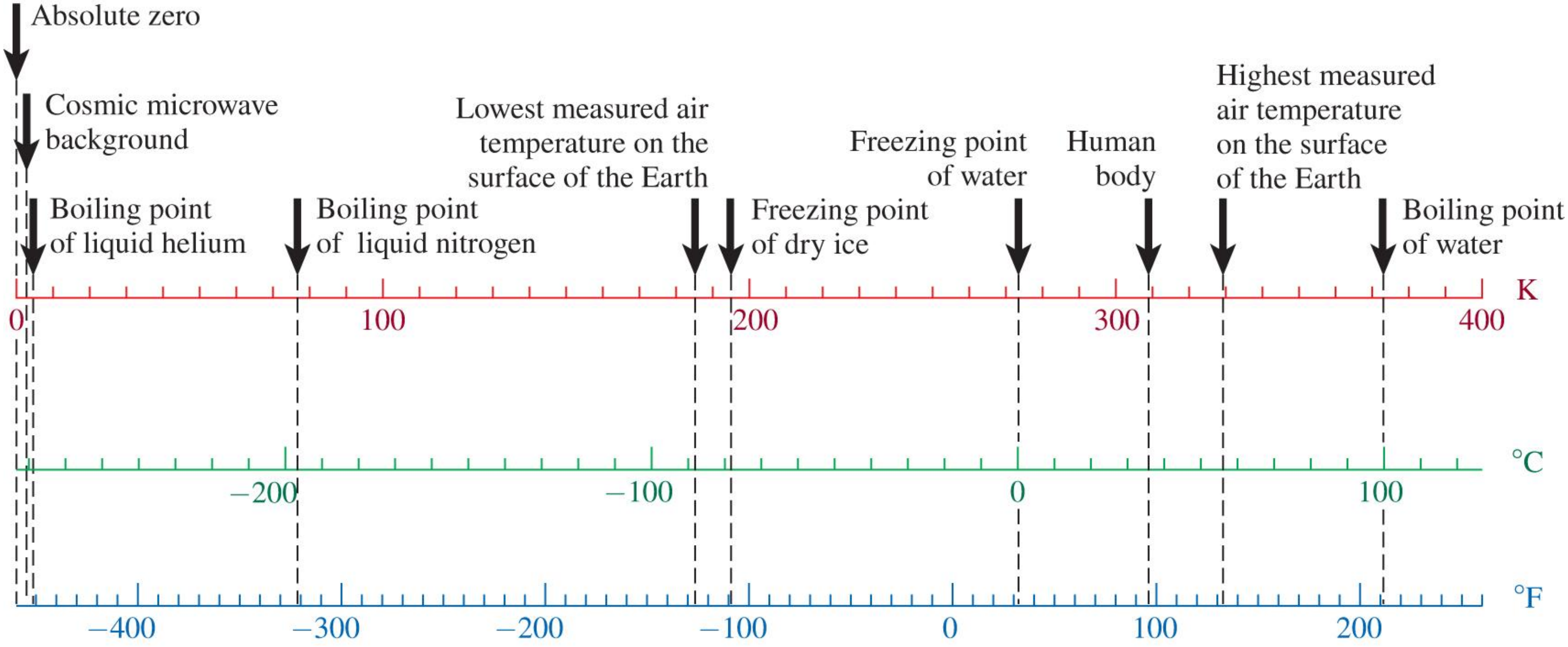
Representative Temperatures

- Here are some representative temperatures.



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Temperature Scales

- The formulas for converting between the various temperature scales are:
  - Fahrenheight to Celsius

$$T_{\mathrm{C}} = \frac{5}{9}(T_{\mathrm{F}} - 32°\mathrm{F})$$

  - Celsius to Fahrenheight

$$T_{\mathrm{F}} = \frac{9}{5}T_{\mathrm{C}} + 32\ °\mathrm{F}$$

  - Celsius to Kelvin

$$T_{\mathrm{K}} = T_{\mathrm{C}} + 273.15\ °\mathrm{C}$$

  - Kelvin to Celsius

$$T_{\mathrm{C}} = T_{\mathrm{K}} - 273.15\ °\mathrm{C}$$

Human Body Temperature

- The mean human body temperature taken orally is 36.8 °C, which corresponds to 98.2 °F.
- The often-quoted mean oral temperature of 98.6 °F corresponds to a 19th-century measurement of 37 °C.
- This temperature is highlighted on this oral mercury thermometer.

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- The difference between 98.6 °F and 98.2 °F thus corresponds to the error due to rounding the Celsius scale measurement of human body temperature to two digits.

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Concept Check 2

- Which of the following temperatures is the coldest?

A. 10 °C

B. 10 °F

C. 10 K

Solution Concept Check 2

- Which of the following temperatures is the coldest?

A. 10 °C

B. 10 °F

C. 10 K

Concept Check 3

- Which of the following temperatures is the warmest?

A. 300 °C

B. 300 °F

C. 300 K

Solution Concept Check 3

- Which of the following temperatures is the warmest?

A. 300 °C

B. 300 °F

C. 300 K

Concept Check 4

- At what temperature do the Celsius and Fahrenheit temperature scales have the same numeric value?

A. −40 degrees

B. 0 degrees

C. 40 degrees

D. 100 degrees

Solution Concept Check 4

- At what temperature do the Celsius and Fahrenheit temperature scales have the same numeric value?

A. −40 degrees

B. 0 degrees

C. 40 degrees

D. 100 degrees

Room Temperature

- Room temperature is often taken to be 72.0 °F.

PROBLEM:

- What is room temperature in the Celsius and Kelvin scales?

SOLUTION:

- Convert Fahrenheit to Celsius:

$$T_{\mathrm{C}} = \frac{5}{9}(72.0\ °\mathrm{F} - 32\ °\mathrm{F}) = 22.2\ °\mathrm{C}$$

- Convert Celsius to Kelvin:

$$T_{\mathrm{K}} = 22.2\ °\mathrm{C} + 273.15\ °\mathrm{C} = 295\ \mathrm{K}$$

Temperature Conversion 1

PROBLEM:

- On a cold winter day, you notice that the temperature reading in Fahrenheit degrees is 10.0 degrees higher than that in Celsius degrees.
- By how many Celsius degrees does the temperature need to change for the Fahrenheit reading to be 10.0 degrees lower than the Celsius reading?

SOLUTION:

Think

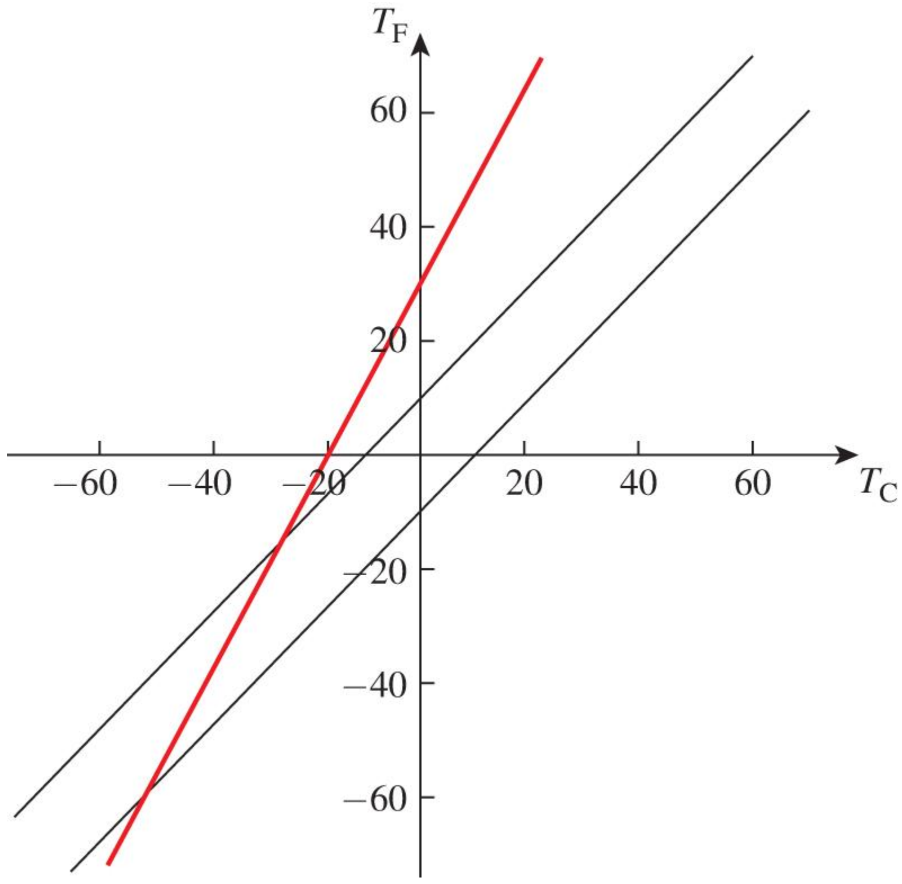
- This appears to be a straightforward temperature conversion problem.
- The easiest way to solve this problem is to first figure out the temperature that meets the 10-degree-higher condition and then find the temperature that fulfills the 10-degree-lower condition.

Temperature Conversion 2

- Our final answer is then the difference of those two temperatures.

Sketch

- We can graph the conversion line for Celsius and Fahrenheit temperatures and the two boundary conditions specified in the problem.



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Temperature Conversion 3

Research

- The formula for converting from Celsius to Fahrenheit is:

$$T_{\mathrm{F}} = \frac{9}{5} T_{\mathrm{C}} + 32\ ^\circ\mathrm{F}$$

- For the first set of temperature readings, we have:

$$T_{\mathrm{F}} = T_{\mathrm{C}} + 10$$

- For the second set of temperature readings, we have:

$$T_{\mathrm{F}} = T_{\mathrm{C}} - 10$$

Simplify

- The temperature that meets the 10-degrees-higher condition can be obtained from:

$$T_{\mathrm{C}} + 10 = \frac{9}{5} T_{\mathrm{C}} + 32 \quad \Rightarrow \quad -22 = \frac{4}{5} T_{\mathrm{C}} \quad \Rightarrow \quad T_{\mathrm{C}} = -27.5\ ^\circ\mathrm{C}$$

Temperature Conversion 4

- The temperature that meets the 10-degrees-lower condition can be obtained from:

$$T_\text{C} - 10 = \frac{9}{5}T_\text{C} + 32 \quad \Rightarrow \quad -42 = \frac{4}{5}T_\text{C} \quad \Rightarrow \quad T_\text{C} = -52.5\ ^\circ\text{C}$$

Calculate

- Now take the difference between the two temperatures:

$$\Delta T_\text{C} = -52.5\ ^\circ\text{C} - (-27.5\ ^\circ\text{C}) = -25.0\ ^\circ\text{C}$$

Round

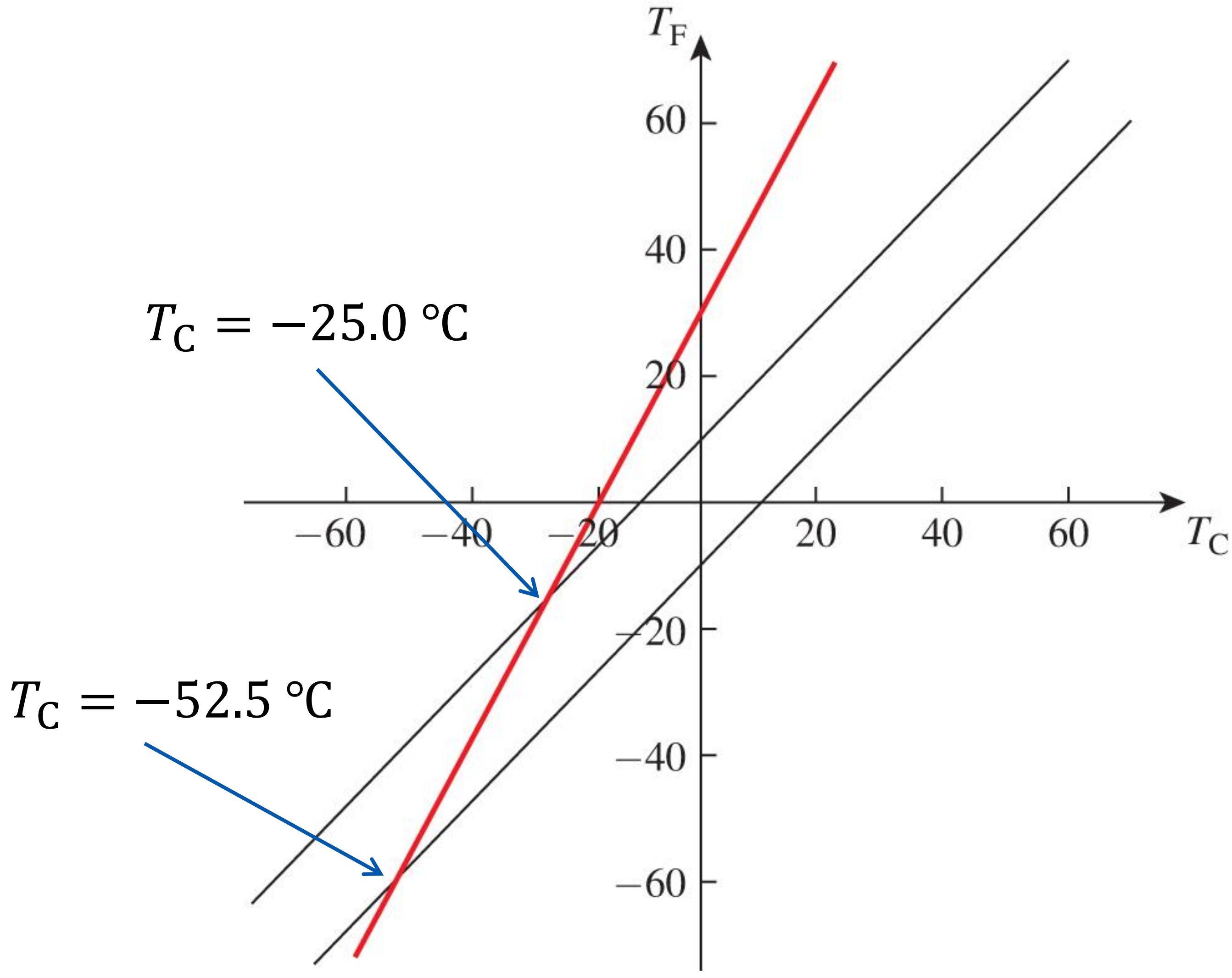
- We report our answer to three significant figures:

$$\Delta T_\text{C} = -25.0\ ^\circ\text{C}$$

Double-check

- We do our double-check using our sketch.

Temperature Conversion 5



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Measuring Temperature 1

- A device that measures temperature is called a *thermometer*.
- Any thermometer that can be calibrated directly by using a physical property is called a *primary thermometer*.
- A primary thermometer does not need calibration to external standard temperatures.
- An example of a primary thermometer is one based on the speed of sound in a gas.
- A *secondary thermometer* is one that requires external calibration to standard temperature references.
- Often, secondary thermometers are more sensitive than primary thermometers.

Measuring Temperature 2

- A common thermometer is the mercury-expansion thermometer, which is a secondary thermometer.
- Other types of thermometers include bimetallic, thermocouple, chemoluminescence, and thermistor thermometers.
- It is also possible to measure the temperature of a material by studying the distribution of the speeds of the molecules inside that material.
- To measure the temperature of an object or a system using a thermometer, the thermometer must be placed in thermal contact with the object or system.
- Heat will then transfer between the object or system and the thermometer, until they have the same temperature.

Measuring Temperature 3

- The thermometer should also be easily calibrated, so that anyone making the same measurement will get the same temperature.
- Calibrating a thermometer requires reproducible conditions.
- It is difficult to reproduce the freezing point of water, so scientists use a condition called the *triple point of water*.
- Solid ice, liquid water, and gaseous water vapor can coexist at only one temperature and pressure.
- By international agreement, the temperature of the triple point of water has been assigned the temperature 273.16 K (and a pressure of 611.73 Pa) for the calibration of thermometers.

Thermal Expansion 1

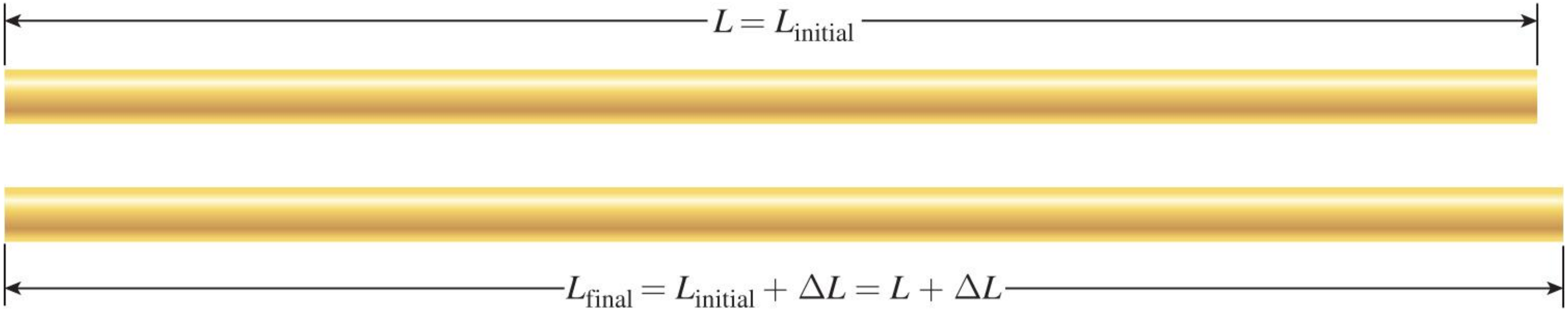
- Most of us are familiar with thermal expansion.
- You may have seen that bridge spans contain gaps in the roadway to allow for the expansion of sections of the bridge in warm weather.
- Why do materials expand due to a change in temperature?
- In Chapter 13, we saw that all matter is made of atoms.
- The atoms vibrate, and the amplitude of their vibrations is a function of the temperature of the matter.
- The larger the amplitude of this vibrational motion, the greater the spaces between the atoms in solids and liquids.
- As a rule, a higher temperature means larger vibrations and thus greater atomic spacing.
- Therefore, solids and liquids expand with increasing temperature.

Thermal Expansion 2

- The thermal expansion of liquids and solids can be put to practical use.
- Bimetallic strips, which are often used in room thermostats, meat thermometers, and thermal protection devices in electrical equipment, take advantage of linear thermal expansion. (A bimetallic strip consists of two thin, long strips of different metals, which are welded together.)
- A mercury thermometer uses volume expansion to provide precise measurements of temperature.
- Thermal expansion can occur as linear expansion, area expansion, or volume expansion;
  - all three classifications describe the same phenomenon.

Linear Expansion 1

- Let's consider a rod of length L.



- We raise the temperature of the rod by:

$$\Delta T = T_{\text{final}} - T_{\text{initial}}$$

- The length of the rod increases by:

$$\Delta L = L_{\text{final}} - L_{\text{initial}}$$

- The increase in length is given by:

$$\Delta L = \alpha L_{\text{initial}} \Delta T$$

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Linear Expansion 2

- The quantity α is the **linear expansion coefficient**.
- The linear expansion coefficient is a constant for a given material within normal temperature ranges.
- Some typical linear expansion coefficients are:

Table 17.2 Linear Expansion Coefficients of Some Common Materials

Material	$\alpha(10^{-6}\ {}^\circ C^{-1})$
Aluminum	22
Brass	19
Concrete	15
Copper	17
Diamond	1
Gold	14
Lead	29
Plate glass	9
Rubber	77
Steel	13
Tungsten	4.5

Thermal Expansion of the Mackinac Bridge

- The center span of the Mackinac Bridge has a length of 1158 m.
- The bridge is built of steel.
- Assume that the lowest possible temperature is −50. °C and the highest possible temperature is 50. °C.

JamesBrey/iStock/Getty Images

PROBLEM:

- How much room must be made available for thermal expansion of the center span of the Mackinac Bridge?

Thermal Expansion of the Mackinac Bridge 2

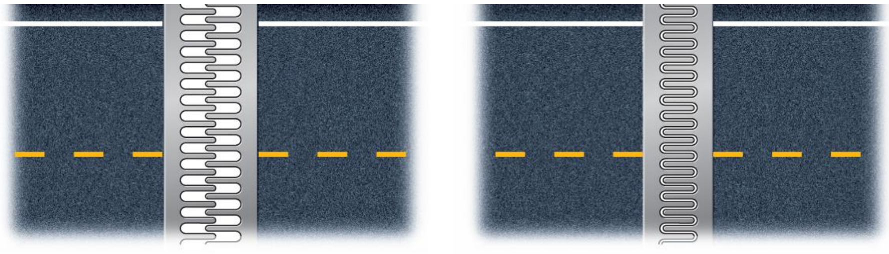
SOLUTION:

- The linear expansion coefficient of steel is $\alpha = 13 \cdot 10^{-6}\ ^{\circ}\text{C}^{-1}$
- The linear expansion of the center span of the bridge that must be allowed for is given by:

$$\Delta L = \alpha L \Delta T = (13 \cdot 10^{-6}\ ^{\circ}\text{C}^{-1})(1158\ \text{m})\big(50.\ ^{\circ}\text{C} - (-50.\ ^{\circ}\text{C})\big) = 1.5\ \text{m}$$

DISCUSSION:

- How is this length change accommodated in practice?
- The answer lies in expansion joints.
- A popular type of expansion joint is the finger joint:



(a) (b)

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Concept Check 5

- Modern train tracks have no expansion gaps.
- Which one of the following statements explains why this is possible?

A. The tracks are made of a new type of steel with a very low linear expansion coefficient.

B. Electrical current is run through the tracks to keep them at a constant temperature.

C. The tracks are laid in circular sections to accommodate expansion and contraction.

D. The tracks are laid when the temperature is moderate and fixed to nonmovable supports that prevent expansion or contraction.

Solution Concept Check 5

- Modern train tracks have no expansion gaps.
- Which one of the following statements explains why this is possible?

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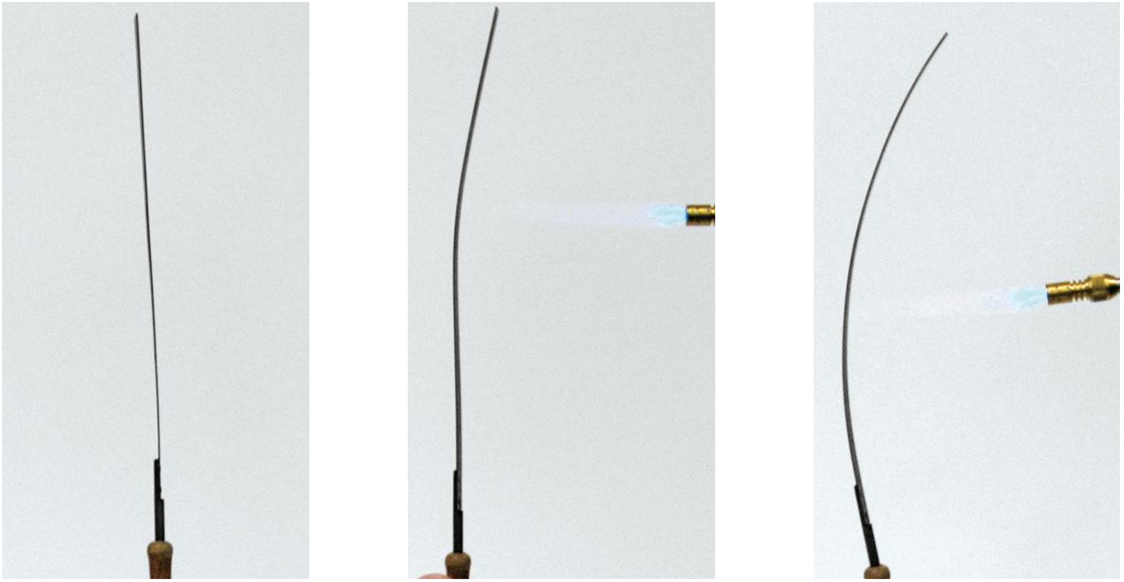
Bimetallic Strip 1

- A straight bimetallic strip consists of a steel strip and a brass strip, each 1.25 cm wide and 30.5 cm long, welded together.



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- Each strip is $t = 0.500$ mm thick.
- The bimetallic strip is heated uniformly along its length.
- The strip curves with a radius of curvature of $R = 36.9$ cm.

Bimetallic Strip 2

PROBLEM:

- What is the temperature of the bimetallic strip after it is heated?

SOLUTION:

Think

- The bimetallic strip is constructed from two metals, steel and brass, that have different linear expansion coefficients.
- As the temperature of bimetallic strip increases, the brass expands more than the steel does, so the strip curves toward the steel side.
- When the bimetallic strip is heated uniformly, both the steel and brass strips lie along the arc of a circle, with the brass strip on the outside and the steel strip on the inside.

Bimetallic Strip 3

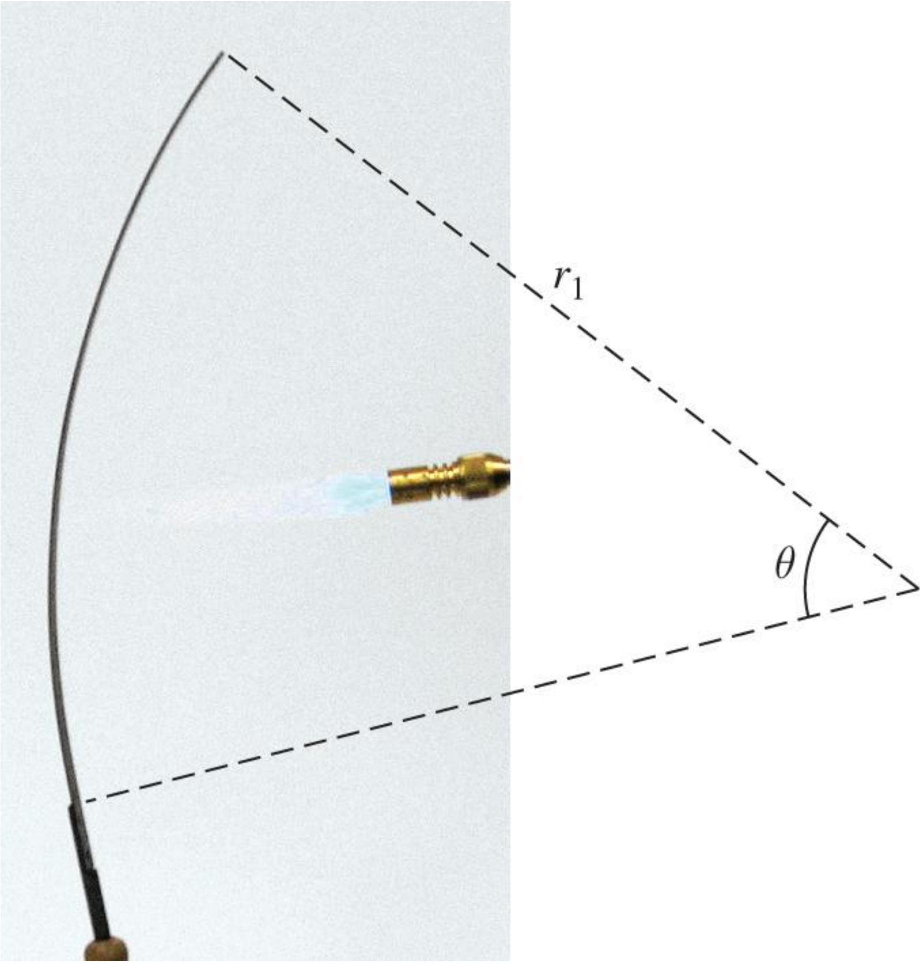
- The ends of the bimetallic strip subtend the same angle, measured from the center of the circle.
- The arc length of each metal strip then equals the length of the bimetallic strip at room temperature, plus the length due to linear thermal expansion.
- Equating the angle subtended by the steel strip to the angle subtended by the brass strip allows the temperature to be calculated.

Sketch

- The sketch shows the bimetallic strip after it is heated.

Bimetallic Strip 4

- The angle subtended by the two ends of the strip is θ and the radius of the inner strip is r_1.
- The inner strip lies along a circle with radius r_1 = 36.9 cm.



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Bimetallic Strip 5

Research

- The arc length, s_1, of the heated steel strip is $s_1 = r_1\theta$, where r_1 is the radius of the circle along which the steel strip lies, and θ is the angle subtended by the steel strip.
- The arc length, s_2, of the heated brass strip is $s_2 = r_1\theta$, where r_2 is the radius of the circle along which the brass strip lies and θ is the *same angle* as that subtended by the steel strip.
- The two radii differ by the thickness, t, of the steel strip:

$$r_2 = r_1 + t \quad \Rightarrow \quad t = r_2 - r_1$$

- We can equate the expressions that are equal to the angle subtended by the two strips:

$$\theta = \frac{s_1}{r_1} = \frac{s_2}{r_2}$$

Bimetallic Strip 6

- The arc length, s_1, of the steel strip after it is heated is:

$$s_1 = s + \Delta s_1 = s + \alpha_1 s \Delta T = s(1 + \alpha_1 \Delta T)$$

- α_1 is the linear expansion coefficient of steel and ΔT is the difference between the final and initial temperatures.
- The arc length, s_2, of the brass strip after being heated is:

$$s_2 = s + \Delta s_2 = s + \alpha_2 s \Delta T = s(1 + \alpha_2 \Delta T)$$

- α_2 is the linear expansion coefficient of brass.

Simplify

- We combine our last three equations:

$$\frac{s(1 + \alpha_1 \Delta T)}{r_1} = \frac{s(1 + \alpha_2 \Delta T)}{r_2}$$

Bimetallic Strip 7

- Dividing both sides of this equation by the common factor s and multiplying by $r_1 r_2$ gives:

$$r_2 + r_2 \alpha_1 \Delta T = r_1 + r_1 \alpha_2 \Delta T$$

- Rearranging and gathering common terms:

$$\Delta T = \frac{r_2 - r_1}{r_1 \alpha_2 - r_2 \alpha_1}$$

- Using the relation $t = r_2 - r_1$ leads to:

$$\Delta T = \frac{t}{r(\alpha_2 - \alpha_1) - t\alpha_1}$$

Calculate

- $\alpha_1 = \alpha_{\text{steel}} = 13 \cdot 10^{-6}\ ^\circ\text{C}^{-1}$
- $\alpha_2 = \alpha_{\text{brass}} = 19 \cdot 10^{-6}\ ^\circ\text{C}^{-1}$.

Bimetallic Strip 8

- Inserting our remaining numerical values gives us:

$$\Delta T = \frac{0.500 \cdot 10^{-3}\ \text{m}}{(0.369\ \text{m})(19 \cdot 10^{-6}\ {}^{\circ}\text{C}^{-1}) - (0.500 \cdot 10^{-3}\ \text{m})(13 \cdot 10^{-6}\ {}^{\circ}\text{C}^{-1})}$$

$$\Delta T = 226.5^{\circ}\text{C}$$

Round

- Taking room temperature to be 20 °C and reporting our result to two significant figures gives us the temperature of the bimetallic strip after heating:

$$T = 20\ {}^{\circ}\text{C} + \Delta T = 250\ {}^{\circ}\text{C}$$

Double-check

- This temperature is well below the melting point of steel and brass.

Bimetallic Strip 9

- The angle subtended by the steel strip is:

$$\theta_1 = \frac{s_1}{r_1} = \frac{30.5 \text{ cm} + (30.5 \text{ cm})(13 \cdot 10^{-6}\ {}^\circ\text{C}^{-1})(226.5\ {}^\circ\text{C})}{36.9 \text{ cm}} = 0.829 \text{ rad} = 47.5^\circ$$

- The angle subtended by the brass strip is:

$$\theta_2 = \frac{s_2}{r_2} = \frac{30.5 \text{ cm} + (30.5 \text{ cm})(19 \cdot 10^{-6}\ {}^\circ\text{C}^{-1})(226.5\ {}^\circ\text{C})}{36.9 \text{ cm} + 0.05 \text{ cm}} = 0.829 \text{ rad} = 47.5^\circ$$

- The angles agree.
- Note that because the thickness of the strips is small compared with the radius of the circle, we can write:

$$\Delta T \approx \frac{t}{r_1(\alpha_2 - \alpha_1)} = \frac{(0.500 \cdot 10^{-3} \text{ m})}{(0.369 \text{ m})(19 \cdot 10^{-6}\ {}^\circ\text{C}^{-1} - 13 \cdot 10^{-6}\ {}^\circ\text{C}^{-1})} = 226\ {}^\circ\text{C}$$

- All looks reasonable.

Concept Check 6

- Suppose the bimetallic strip was made of aluminum on the right side and copper on the left side.
- Which way would the strip bend if it were heated in the same way as in the example?

A. It would bend to the right.

B. It would stay straight.

C. It would bend to the left.

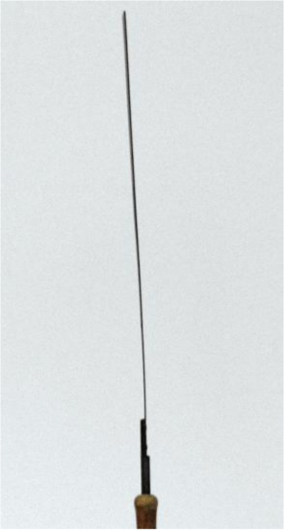

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Table 17.2 Linear Expansion Coefficients of Some Common Materials

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Aluminum	22
Brass	19
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Solution Concept Check 6

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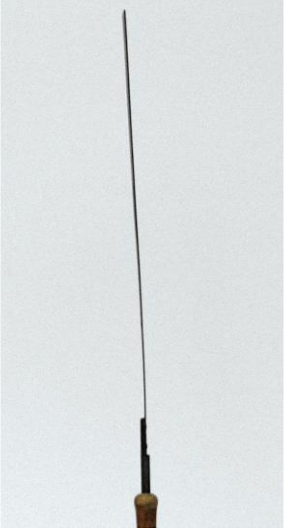

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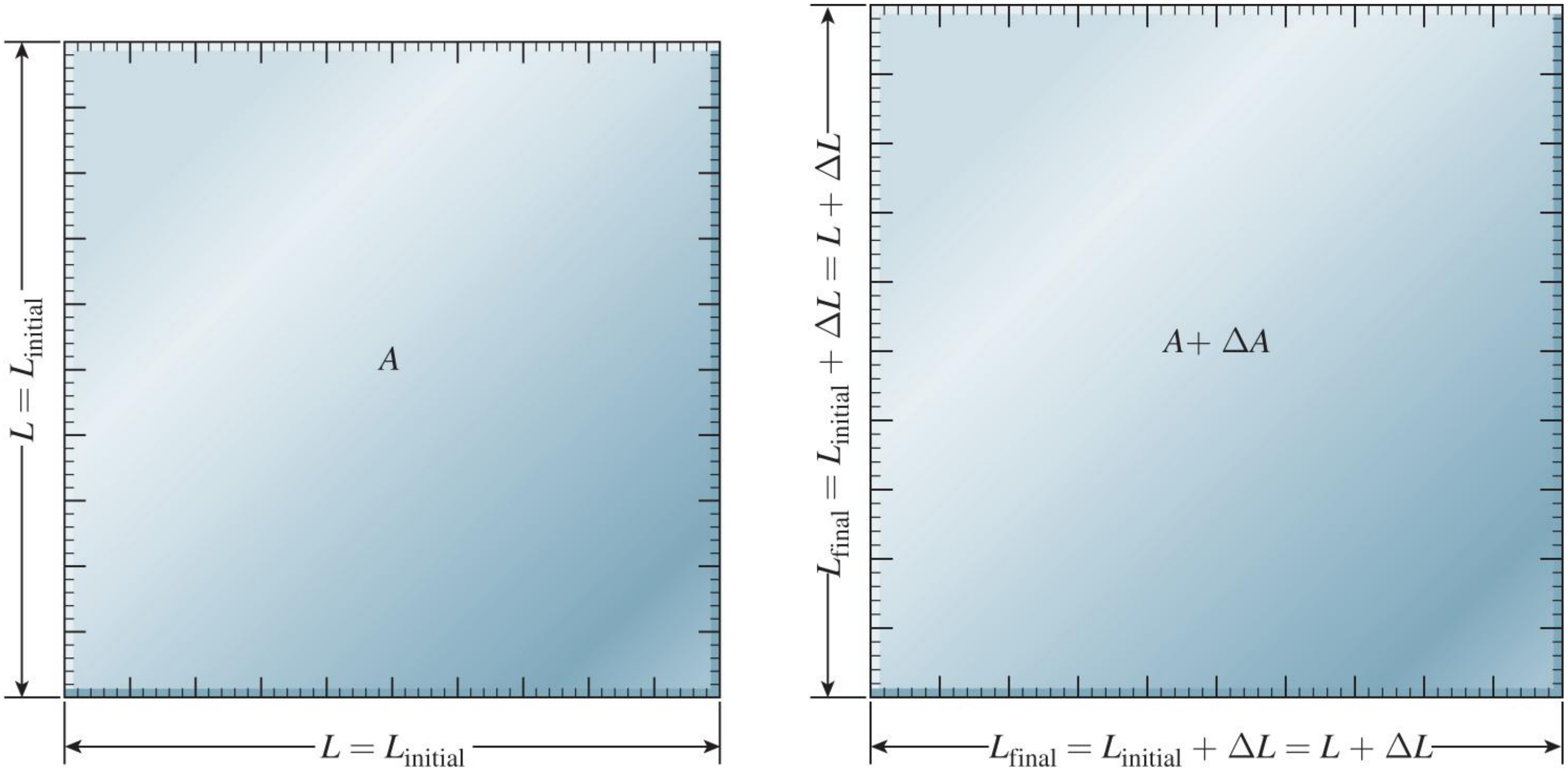
Area Expansion 1

- The effect of a change in temperature on the area of an object is analogous to using a copy machine to enlarge or reduce a picture.



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Area Expansion 2

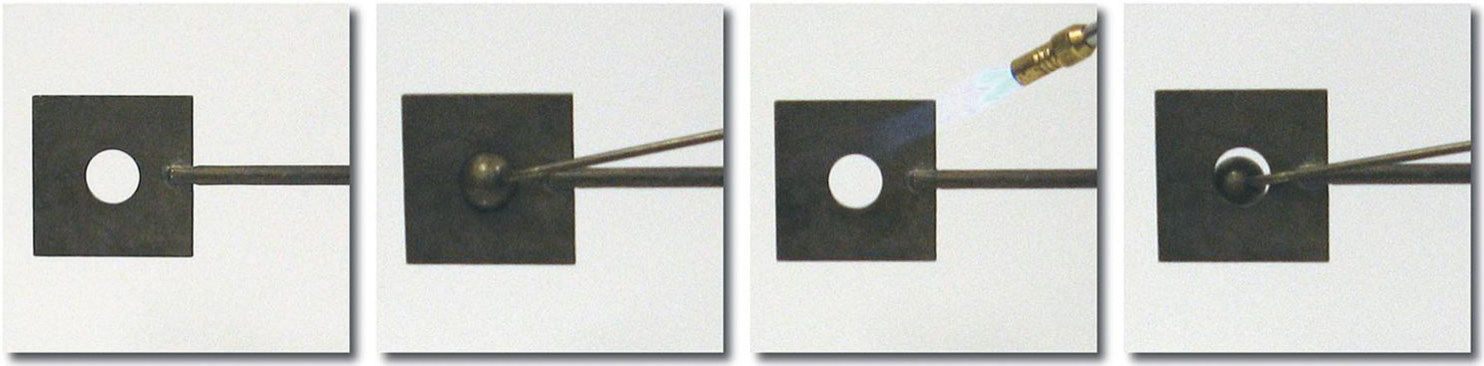
- Each dimension of the object will change linearly with the change in temperature.
- Quantitatively, for a square object with side L, the area is given by $A = L^2$.
- Taking the differential of both sides of this equation, we get $dA = 2L\, dL$.
- If we make the approximations $\Delta A = dA$ and $\Delta L = dL$, we can write $\Delta A = 2L\Delta L$.
- Using $\Delta L = \alpha L \Delta T$, we can write:

$$\Delta L = 2L(\alpha L \Delta T) = 2\alpha A \Delta T$$

- This was derived for a square, but it works for any shape.

Expansion of a Plate with a Hole in It 1

- A brass plate has a hole with diameter *d* = 2.54 cm.



(a) (b) (c) (d)

W. Bauer and G. D. Westfall

- The hole is too small to allow a brass sphere to pass.
- However, when the plate is heated from 20.0 °C to 220.0 °C, the brass sphere passes through the hole in the plate.

Access the text alternative for slide images.

Expansion of a Plate with a Hole in It 2

PROBLEM:

- How much does the area of the hole in the brass plate increase because of heating?

SOLUTION:

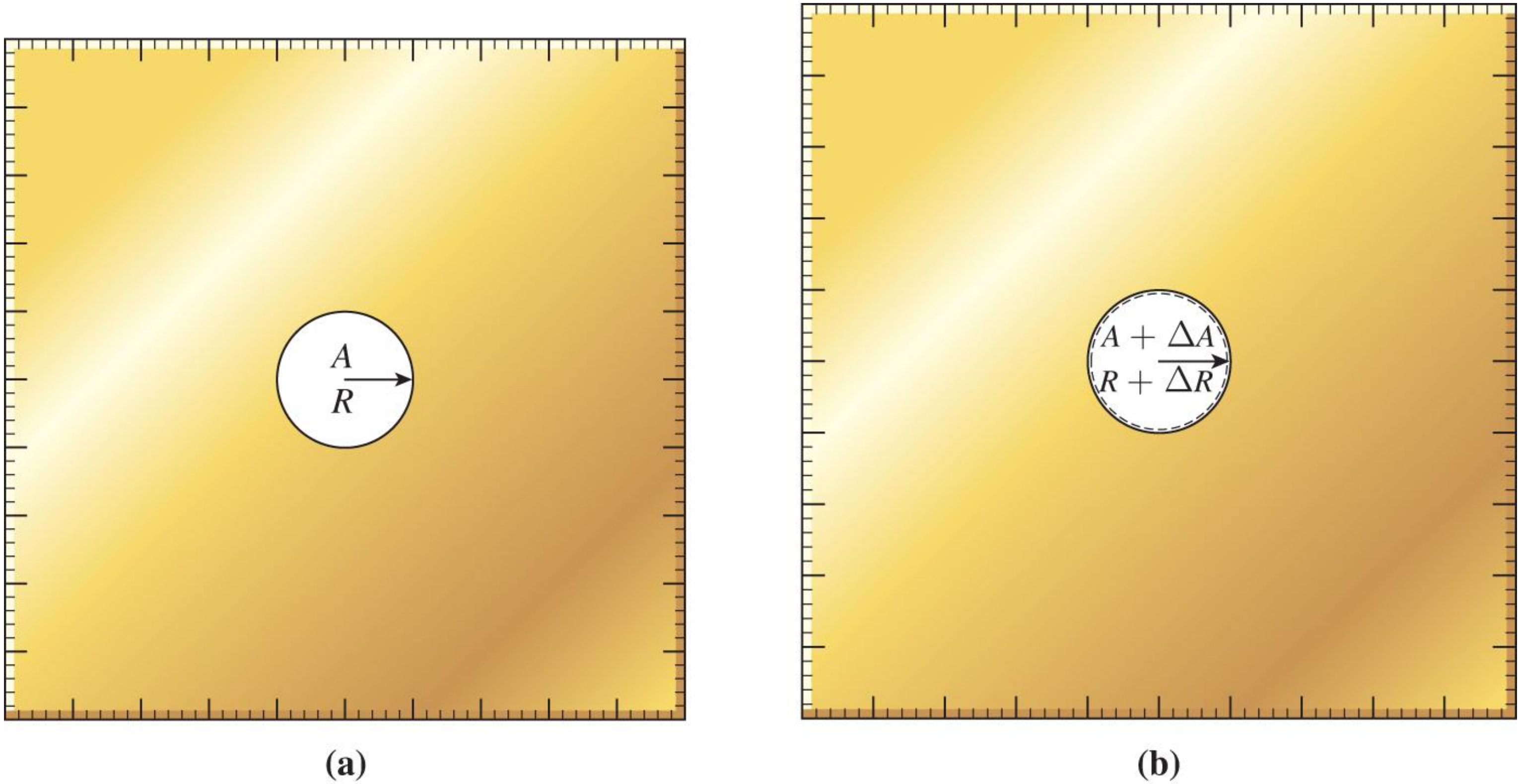
Think

- The area of the brass plate increases as the temperature of the plate increases.
- The area of the hole in the plate also increases.

Sketch

- The sketch shows the brass plate before and after it is heated.

Expansion of a Plate with a Hole in It 3



Research

- The area of the plate increases as the temperature increases and the area of the hole increases proportionally.

Access the text alternative for slide images.

Expansion of a Plate with a Hole in It 4

- The change in the area of the hole is:

$$\Delta A = 2\alpha A \Delta T$$

Simplify

- Using $A = \pi R^2$, the change in the area of the hole is:

$$\Delta A = 2\alpha(\pi R^2)\Delta T$$

- Remembering that $R = d/2$, we have:

$$\Delta A = 2\alpha\left(\pi\left(\frac{d}{2}\right)^2\right)\Delta T = \frac{\pi\alpha d^2 \Delta T}{2}$$

Calculate

- The change in the area of the hole is:

$$\Delta A = \frac{\pi(19 \cdot 10^{-6}\ {}^{\circ}\mathrm{C}^{-1})(0.0254\ \mathrm{m})^2(220.0\ {}^{\circ}\mathrm{C} - 20.0\ {}^{\circ}\mathrm{C})}{2} = 3.85098 \cdot 10^{-6}\ \mathrm{m}^2$$

Expansion of a Plate with a Hole in It 5

Round

- We report our results to two significant digits:

$$\Delta A = 3.9 \cdot 10^{-6}\ \text{m}^2$$

Double-check

- A small change in the area is reasonable.
- The change in the radius of the hole is:

$$\Delta R = \alpha R \Delta T = \left(19 \cdot 10^{-6}\ {}^\circ\text{C}^{-1}\right)\left(\frac{0.0254\ \text{m}}{2}\right)\left(200.\ {}^\circ\text{C}\right) = 4.83 \cdot 10^{-5}\ \text{m}$$

- For that change in the radius, the area of the hole increases:

$$\Delta A = \Delta\left(\pi R^2\right) = 2\pi R \Delta R = 2\pi\left(\frac{0.0254\ \text{m}}{2}\right)\left(4.83 \cdot 10^{-5}\ \text{m}\right) = 3.85 \cdot 10^{-6}\ \text{m}^2$$

- Our results are reasonable.

Volume Expansion 1

- Consider the change in volume of an object with a change in temperature.
- For a cube with side L, the volume is given by $V = L^3$.
- Taking the differential of this equation, we get $dV = 3L^2 dL$.
- Making the approximations $\Delta V = dV$ and $\Delta L = dL$, we can write $\Delta V = 3L^2 \Delta L$, which we can write as:

  $$\Delta V = 3L^2(\alpha L \Delta T) = 3\alpha V \Delta T$$

- Because the change in volume with a change in temperature is often of interest, it is convenient to define the **volume expansion coefficient**:

  $$\beta = 3\alpha$$

Volume Expansion 2

- So, we can write:

  $\Delta V = \beta V \Delta T$

- Although we used a cube to derive this equation, it can be applied to a change in the volume of any shape.
- Here are some typical volume expansion coefficients.
- This expression applies to most solids and liquids, but not to water.

Table 17.3 Volume Expansion Coefficients for Some Common Liquids

Material	$\boldsymbol{\beta (10^{-6}\ °C^{-1})}$
Mercury	181
Gasoline	950
Gasoline	990
Ethyl alcohol	750
Water (1 °C)	-47.8
Water (4 °C)	0
Water (7 °C)	45.3
Water (10 °C)	87.5
Water (15 °C)	151
Water (20 °C)	207

Concept Check 7

- Two mercury-expansion thermometers have identical reservoirs and cylindrical tubes made of the same glass but of different diameters.
- Which of the two thermometers can be calibrated to a better resolution?

A. The thermometer with the smaller-diameter tube will have better resolution.

B. The thermometer with the larger-diameter tube will have better resolution.

C. The diameter of the tube is irrelevant; it is only the volume expansion coefficient of mercury that matters.

D. Not enough information is given to tell.

Solution Concept Check 7

- Two mercury-expansion thermometers have identical reservoirs and cylindrical tubes made of the same glass but of different diameters.
- Which of the two thermometers can be calibrated to a better resolution?

A. The thermometer with the smaller-diameter tube will have better resolution.

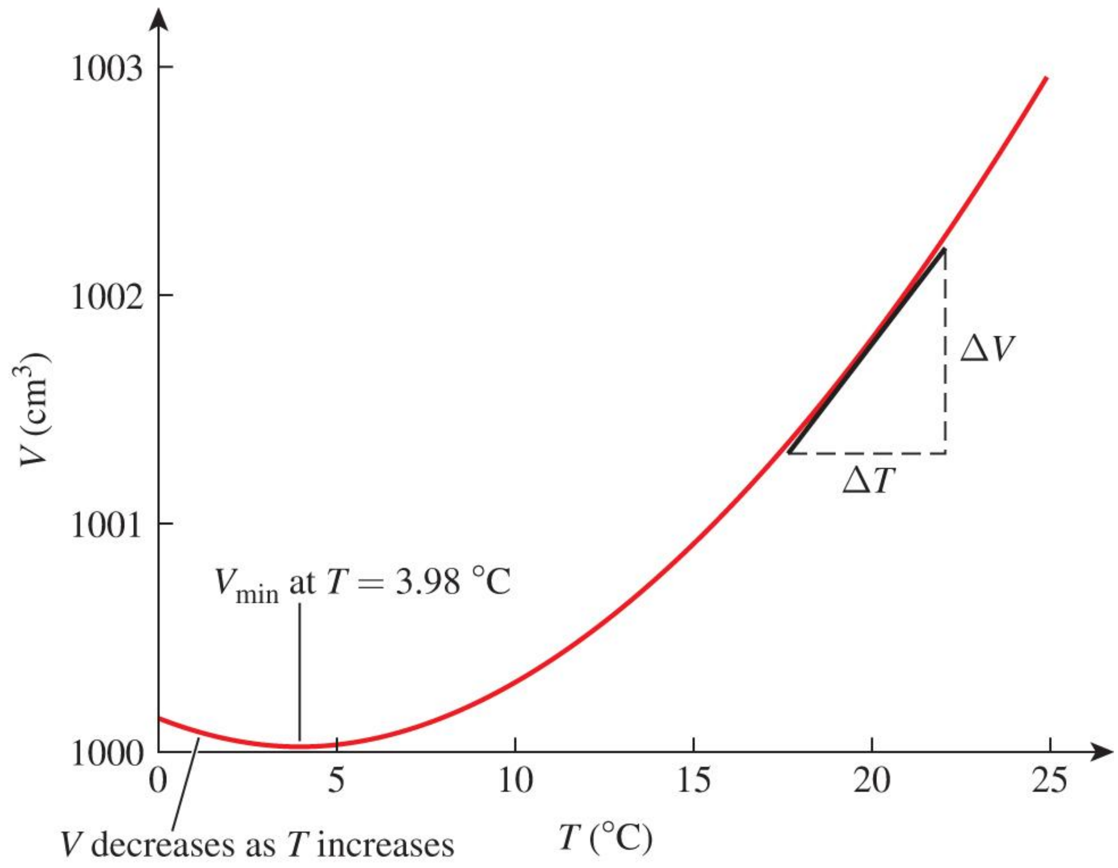
B. The thermometer with the larger-diameter tube will have better resolution.

C. The diameter of the tube is irrelevant; it is only the volume expansion coefficient of mercury that matters.

D. Not enough information is given to tell.

Volume Expansion of Water

- The change in volume with temperature is never linear for water.



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Thermal Expansion of Gasoline 1

- You pull your car into a gas station on a hot summer day, when the air temperature is 40. °C.
- You fill your empty 55-L gas tank with gasoline that comes from an underground storage tank where the temperature is 12 °C.
- After paying for the gas, you decide to walk to the restaurant next door and have lunch.
- Two hours later, you come back to your car, realize that you left the cap off the gas tank, and discover that gasoline has spilled out of the gas tank onto the ground.

PROBLEM:

- How much gas has spilled?

Thermal Expansion of Gasoline 2

SOLUTION:

- The temperature of the gasoline you put in the tank starts out at 12 °C.
- The gasoline warms up to 40. °C.
- The volume expansion coefficient of gasoline is: $950 \cdot 10^{-6}\ ^{\circ}\text{C}^{-1}$.
- The change in volume of the gasoline is:

$$\Delta V = \beta V \Delta T = (950 \cdot 10^{-6}\ ^{\circ}\text{C}^{-1})(55\ \text{L})(40.\ ^{\circ}\text{C} - 12\ ^{\circ}\text{C}) = 1.5\ \text{L}$$

- Because the tank was initially full at 12 °C, 1.5 L of gasoline overflows from the tank when it reaches 40 °C.

Concept Check 8

- You have a metal cube, which you heat.
- After heating, the area of one of the cube's surfaces has increased by 0.02%.
- Which statement about the volume of the cube after heating is correct?

A. It has decreased by 0.02%.

B. It has increased by 0.02%.

C. It has increased by 0.01%.

D. It has increased by 0.03%.

E. Not enough information is given to determine the volume change.

Solution Concept Check 8

- You have a metal cube, which you heat.
- After heating, the area of one of the cube's surfaces has increased by 0.02%.
- Which statement about the volume of the cube after heating is correct?

A. It has decreased by 0.02%.

B. It has increased by 0.02%.

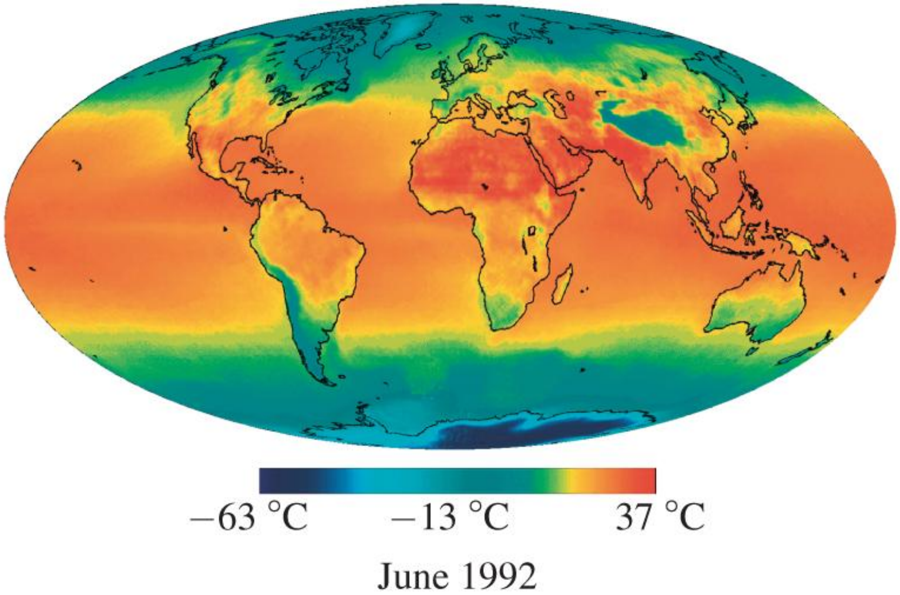
C. It has increased by 0.01%.

D. It has increased by 0.03%.

E. Not enough information is given to determine the volume change.

Surface Temperature of the Earth 1

- A current topic of intense discussion is whether the temperature of Earth is rising.
- A conclusive answer to this question requires data giving appropriate averages.
- The first average that is useful is over time.
- Here is a plot of the surface temperature of the Earth, time averaged over one month (June 1992).



WMAP Science Team/NASA

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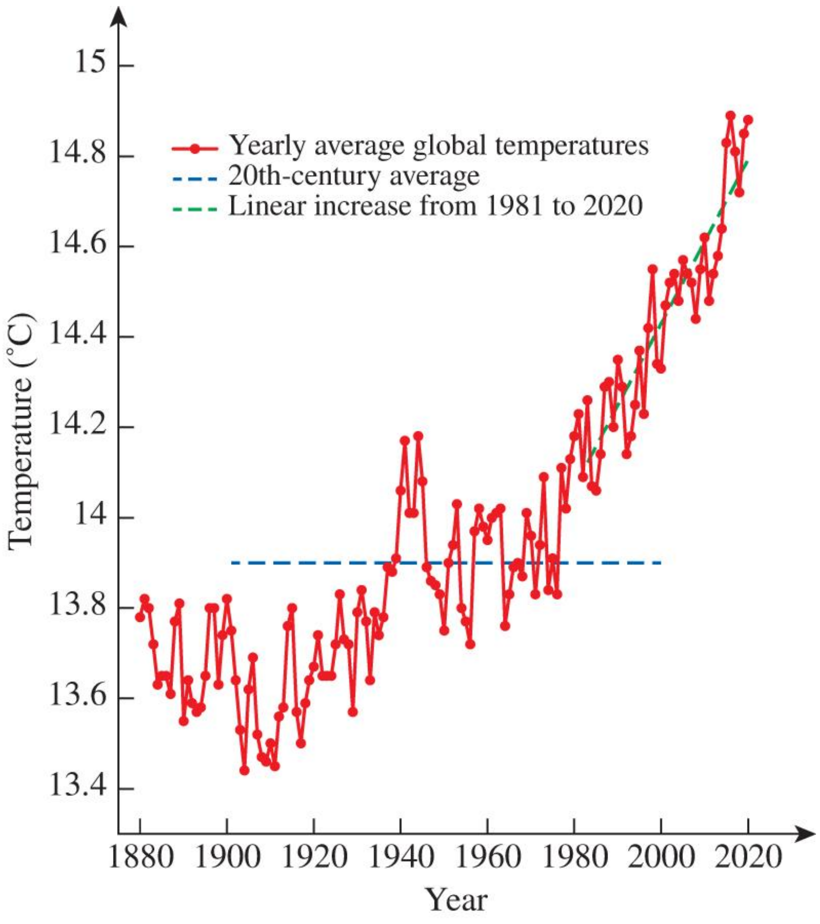
Surface Temperature of the Earth 2

- The time-averaged values of the temperature over the entire surface of Earth are obtained by systematically taking temperature measurements over the surface of the Earth, including the oceans.
- These measurements are then corrected for any systematic biases, such as the fact that many temperature measuring stations are in populated areas and many sparsely populated areas have few temperature measurements.
- After all the corrections are considered, the result is the average surface temperature of Earth each year.
- The current year-round average surface temperature of Earth is approximately 287.7 K (14.6 °C).

Surface Temperature of the Earth 3

- Here is the average global temperature plotted for the years 1880 to 2011.
- The blue horizontal line in the graph represents the average global temperature for the 20th century, 13.9 °C.
- For the past few decades, the Earth has been warming up at a rate of approximately 0.2 °C per decade.



(Source: Data compiled by the National Climatic Data Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.)

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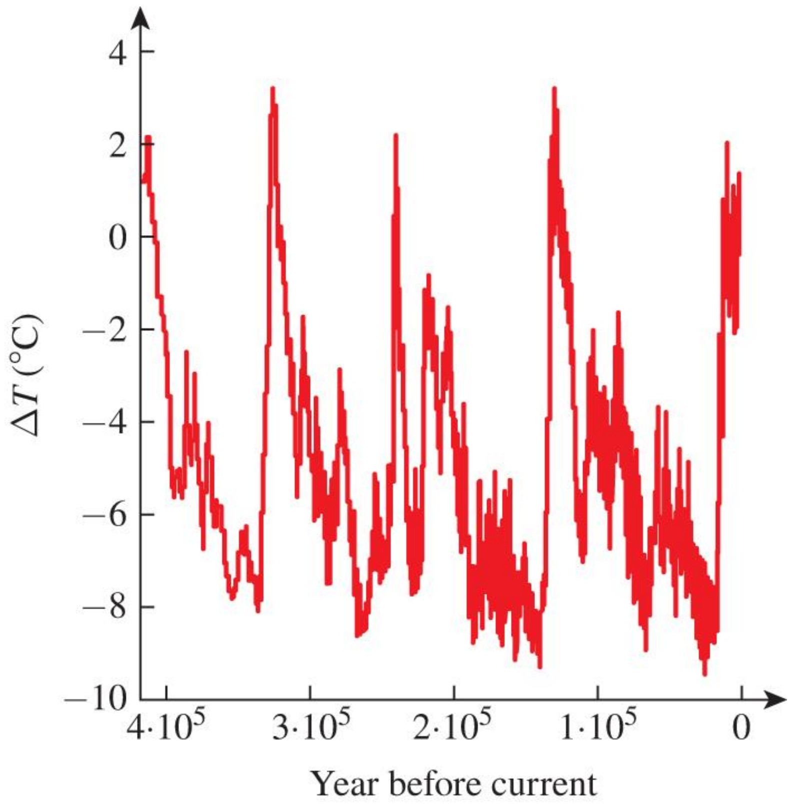
Surface Temperature of the Earth 4

- Several models predict that the average global surface temperature of Earth will continue to increase.
- The magnitude of the increase in average global temperature over the past 155 years is around 1 °C, which does not seem like a large increase.
- However, combined with predicted future increases, it is sufficient to cause observable effects, such as the raising of ocean water levels, the disappearance of the Arctic ice cover in summers, climate shifts, and increased severity of storms and droughts around the world.
- We can look back in time at the surface temperature of the Earth using ice core measurements.

Surface Temperature of the Earth 5

- The past temperatures were evaluated from measurements of carbon dioxide in the ice cores.
- Several distinct periods are visible.
- The warmer periods are called interglacial periods, and the colder periods are called glacial periods.
- The current warm, interglacial period began about 10,000 years ago.
- One effect of the warming of the Earth's surface is a rise in sea level.



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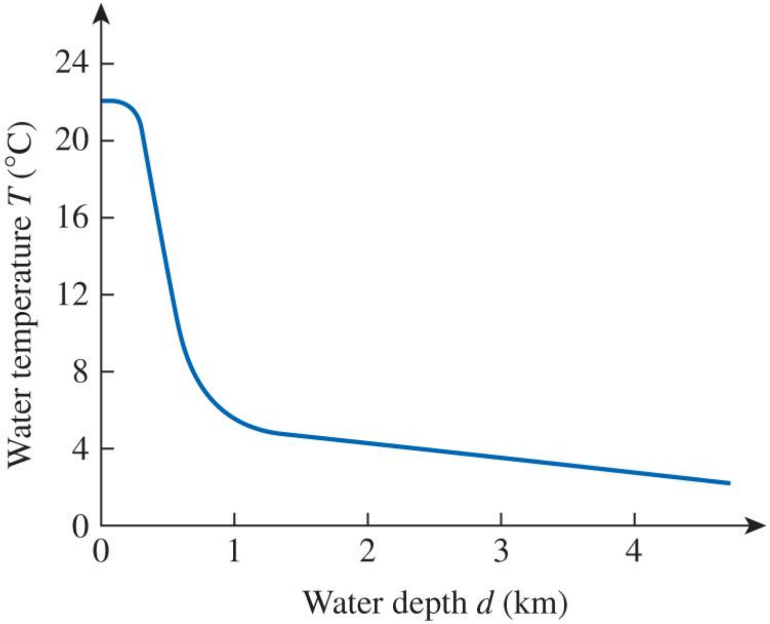
Surface Temperature of the Earth 6

- Sea level has risen 120 m since the last glacial period.
- The melting of ice resting on solid ground is the largest contributor to a further rise in sea level.
- If all the ice in Antarctica melted, sea level would rise 61 m.
- If all the ice in Greenland melted, sea level would rise 7 m.
- It would take several centuries for this to happen, even in the worst-case scenario.
- The current rate of the rise in sea level is 3.2 ± 0.4 mm/yr.
- By the end of the 21^{st} century, sea level is predicted to rise 1.0 ± 0.3 m.
- Let's calculate the rise in sea level due to thermal expansion.

Rise in Sea Level Due to Thermal Expansion [1]

- Oceans cover slightly more than 70% of Earth's surface area.
- The average ocean depth is 3790 m.
- The surface ocean temperature varies between 35 °C in the summer in the Persian Gulf and –2 °C in the polar regions.
- Even if the ocean surface temperature exceeds 20 °C, the water temperature rapidly falls off as a function of depth and approaches 4 °C at a depth of 1000 m.
- The average temperature of all seawater is 3 °C.



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Rise in Sea Level Due to Thermal Expansion 2

- The volume expansion coefficient of water is zero at 4 °C.
- It is safe to assume that the volume of ocean water changes little at a depth greater than 1000 m.
- For the top 1000 m of the ocean, assume a global average temperature of 10.0 °C.

PROBLEM:

- By how much would sea level change, solely because of the thermal expansion of water, if the water temperature of all the oceans increased by $\Delta T = 1.0$ °C?

SOLUTION:

- The volume expansion coefficient of water at 10.0 °C is

$$\beta = 87.5 \cdot 10^{-6}\ {}^{\circ}\mathrm{C}^{-1}$$

Rise in Sea Level Due to Thermal Expansion 3

- The volume change of the oceans is given by:

$$\frac{\Delta V}{V} = \beta \Delta T$$

- The total surface area of the oceans is:

$A = (0.7)4\pi R^2$ R is the radius of the Earth

- Assume that the surface area of the oceans will not change from the water moving up the shores.
- All the change in the volume of the oceans will result from a change in depth:

$$\frac{\Delta V}{V} = \frac{\Delta d \cdot A}{d \cdot A} = \frac{\Delta d}{d}$$

Rise in Sea Level Due to Thermal Expansion 4

- Combining our two equations gives us the change in depth:

$$\beta \Delta T = \frac{\Delta d}{d} \quad \Rightarrow \quad \Delta d = \beta d \Delta T$$

- Putting in our numerical values:

$$\Delta d = (87.5 \cdot 10^{-6}\ {}^{\circ}\mathrm{C}^{-1})(1000\ \mathrm{m})(1.0\ {}^{\circ}\mathrm{C}) = 9\ \mathrm{cm}\ (3.5\ \mathrm{in})$$

- This rise is smaller than the anticipated rise due to the melting of the ice cover on Greenland or Antarctica.

Temperature of the Universe 1

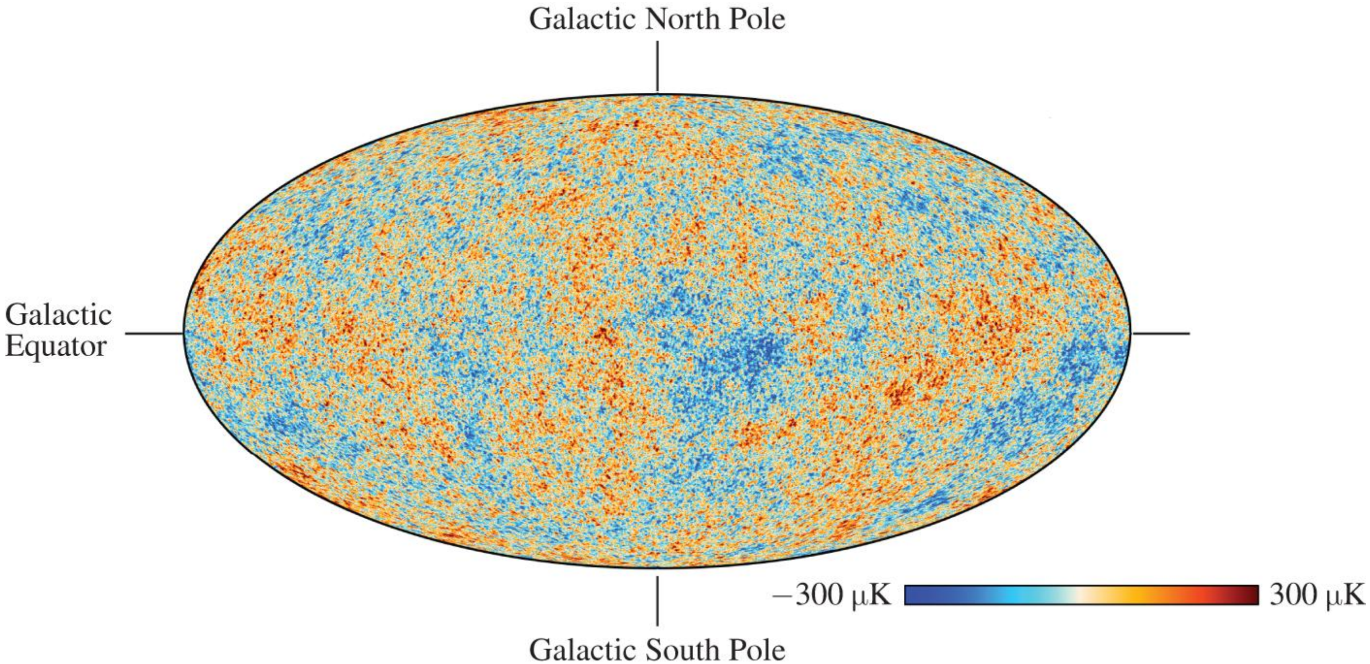
- In 1965, while working on an early radio telescope, Arno Penzias and Robert Wilson discovered the cosmic microwave background radiation.
- They detected "noise," or "static," that seemed to come from all directions in the sky.
- Penzias and Wilson figured out what was producing this noise (which earned them the 1978 Nobel Prize).
- It was electromagnetic radiation left over from the Big Bang, which occurred 13.8 billion years ago.
- It is amazing to realize that an "echo" of the Big Bang still reverberates in "empty" intergalactic space after such a long time.

Temperature of the Universe 2

- The wavelength of the cosmic background radiation is similar to the wavelength of the electromagnetic radiation used in a microwave oven.
- An analysis of the distribution of wavelengths of this radiation led to the deduction that the background temperature of the universe is 2.725 K.
- In 2001, the Wilkinson Microwave Anisotropy Probe (WMAP) satellite measured variations in the background temperature of the universe.
- This mission followed the successful Cosmic Background Explorer (COBE) satellite, launched in 1989, which resulted in the 2006 Nobel Prize for Physics being awarded to John Mather and George Smoot.
- The COBE and WMAP missions found that the cosmic microwave background radiation was very uniform in all directions, but small differences in the temperature were superimposed on the smooth background.

Temperature of the Universe 3

- Here are the WMAP results for the background temperature in all directions with the effects of the Milky Way galaxy subtracted out.



Planck Collaboration 2020, A&A, 641, A4.

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Temperature of the Universe 4

- Scientists from the PLANCK experiment have deduced that the age of the universe is 13.81 billion years with an accuracy of 0.3%.
- In addition, scientists have been able to deduce that the universe is composed of 5% ordinary matter, 27% dark matter, and 68% dark energy.
- Dark matter is matter that exerts an observable gravitational pull but seems to be invisible.
- Dark energy seems to be causing the expansion of the universe to speed up.

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