PHAS1000 – THERMAL PHYSICS

Lecture 4

Conduction, Convection and Radiation

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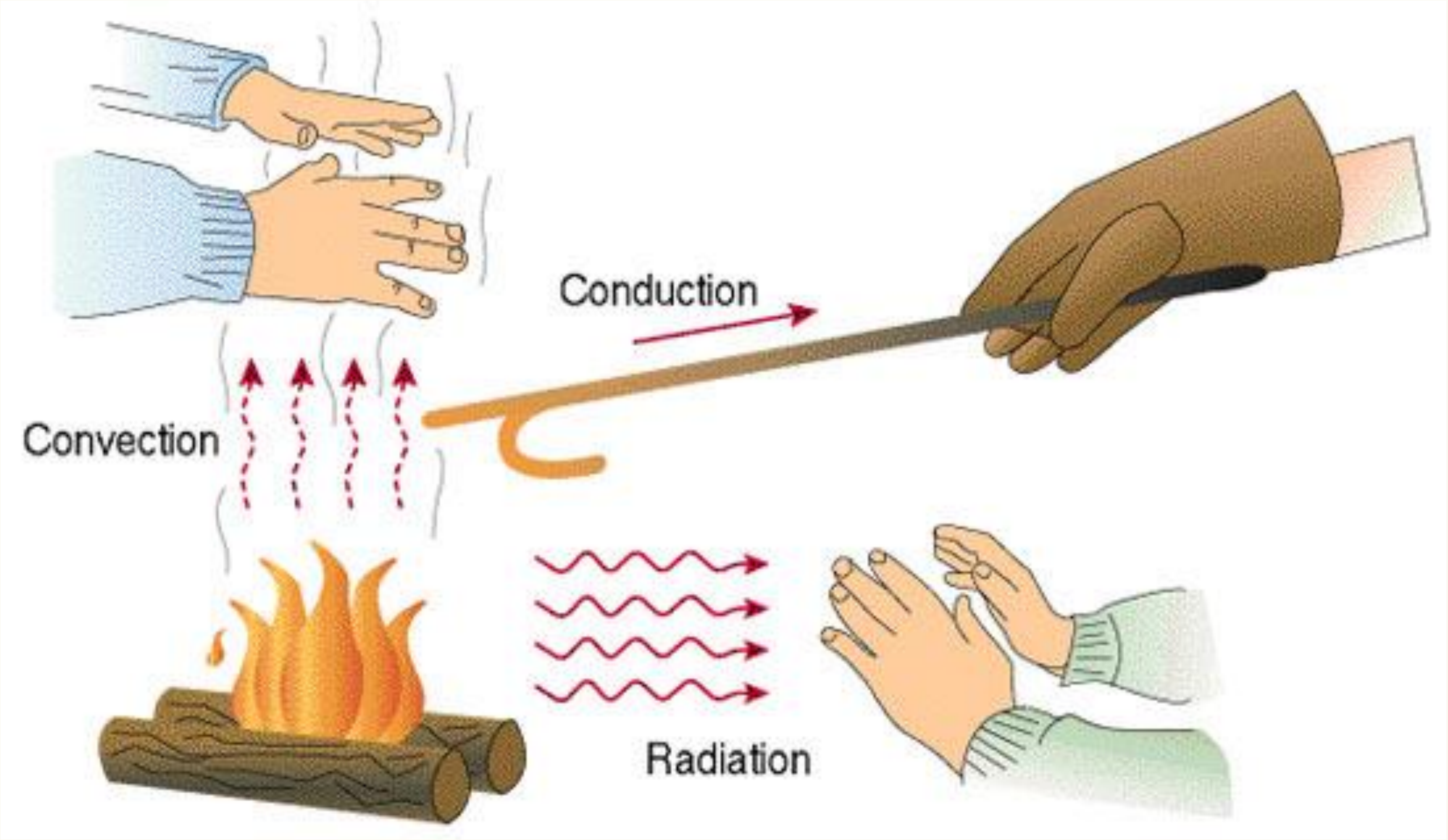
Heat Flow

We look at heat flow by the mechanisms of:

- conduction
- convection
- radiation



Conduction

Why do some materials feel cold (e.g. metal and glass) whereas others feel warm (e.g. wood and wool)?

Applications

Heated towel rail

Metal saucepan

Lagged pipes

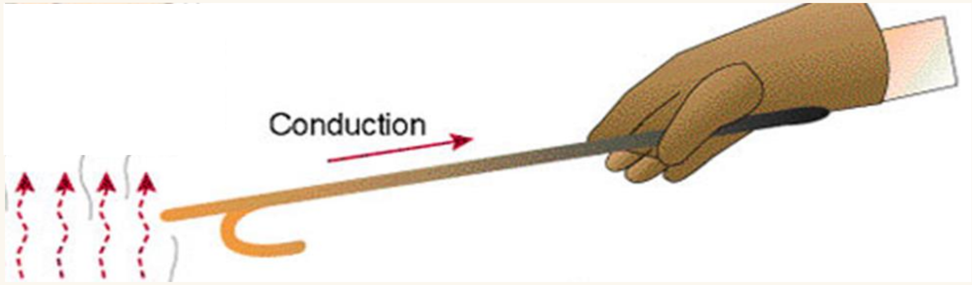
Loft insulation

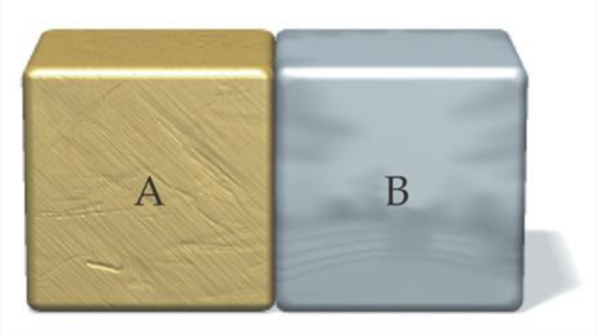
Uses of good conductors

Uses of poor conductors (insulators)

Conduction

Thermal conduction is the flow of thermal energy (heat) within one material or between materials in contact.





- The higher temperature region has molecules with more kinetic energy.
- Collisions between neighbouring molecules distribute this energy.
- If temperature difference between the ends is maintained, then heat continues to flow.
- But if objects allowed to reach thermal equilibrium, the temperature difference is reduced to zero.

Conduction

Why are solids better conductors than liquids or gases?

In solids atoms are close to each other, and can easily transmit the vibrations.

Liquids have weaker inter-molecular forces and more space between the particles, which makes the vibrations harder to transmit.

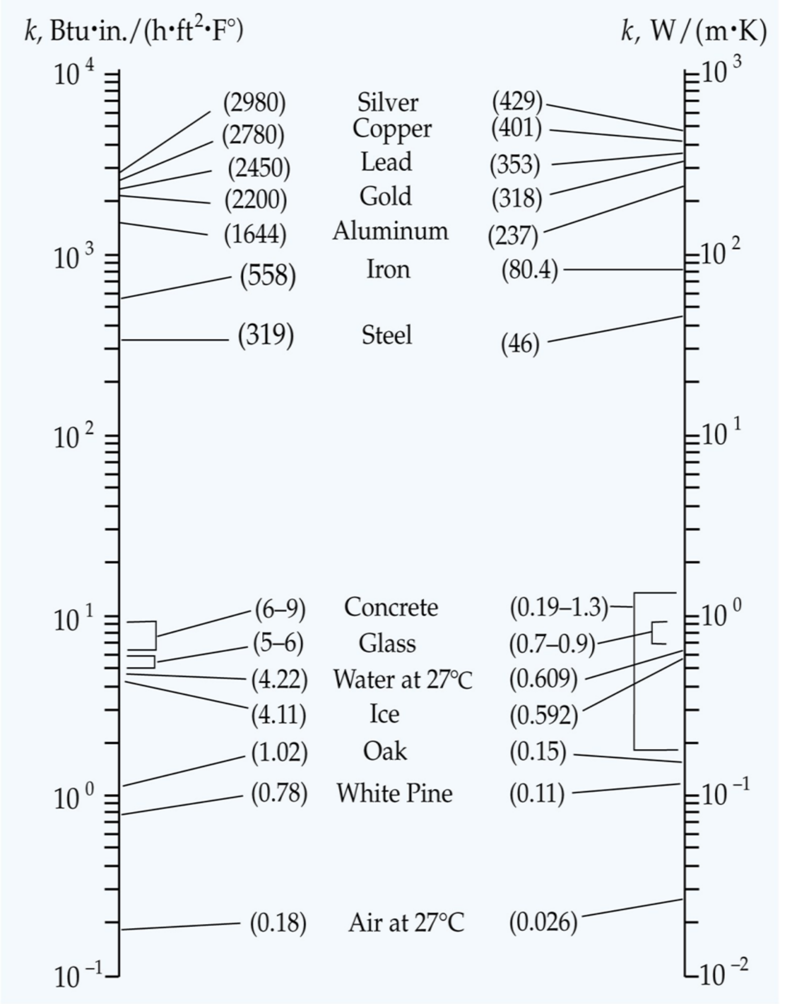
Gases have even more space, and therefore infrequent particle collisions.

Why are metals such good thermal conductors?

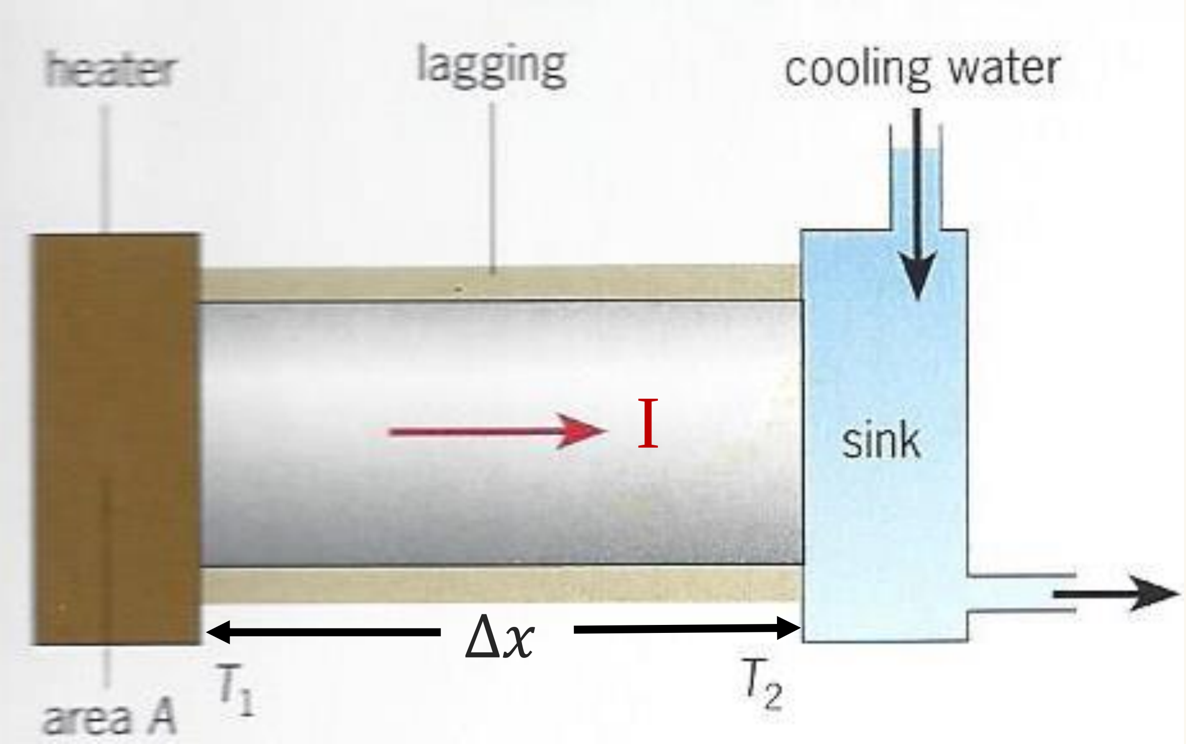
The free electrons which participate in electrical conduction also take part in the transfer of heat.

TABLE 20-3

Thermal Conductivities k for Various Materials



Conduction



$\Delta T = T_1 - T_2$ = temperature difference

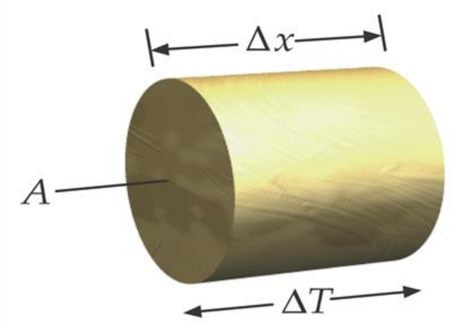
Temperatures maintained by heater and sink.

A = cross section area (m^2)

Δx = length of conductor

k = thermal conductivity ($Wm^{-1}K^{-1}$)

$I = \Delta Q/\Delta t$ = heat flow (J/s) or (W)

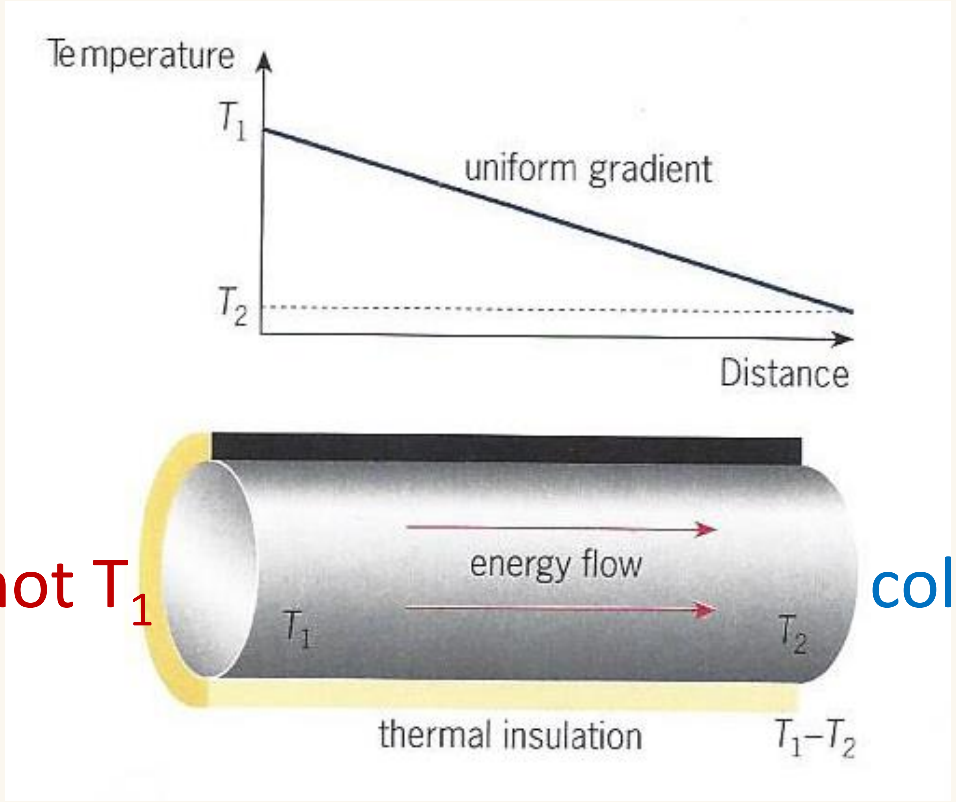


$$I = \frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

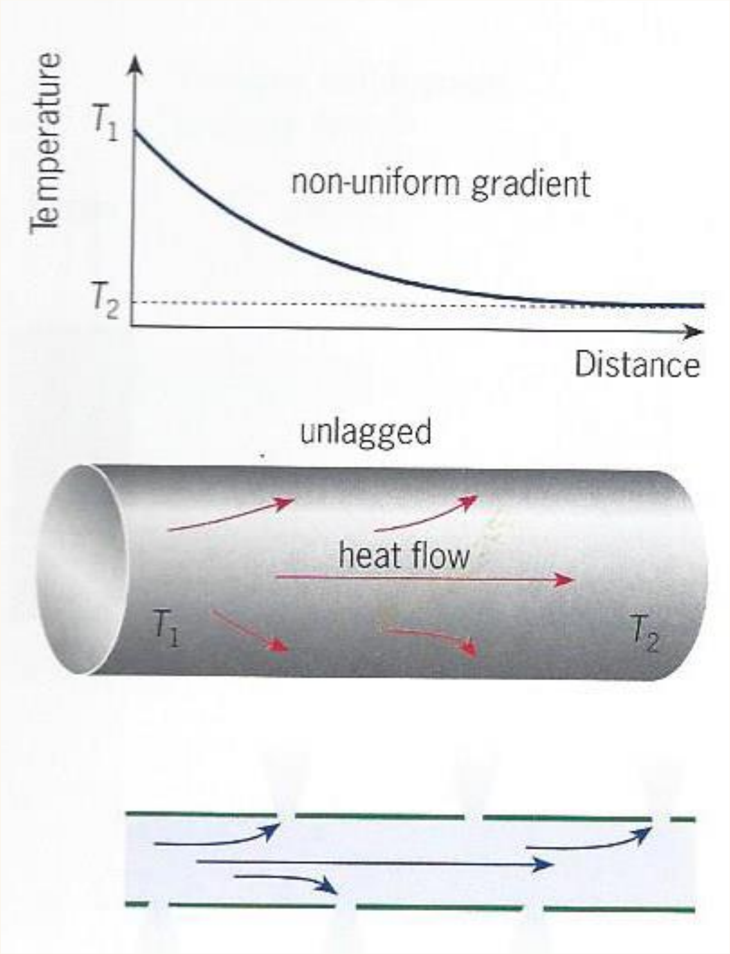
$$\frac{dQ}{dt} = -kA\frac{dT}{dx}$$

Conduction and Insulation (lagging)

hot T_1



cold T_2



Insulated (lagged) bar: Thermal current I (slope dQ/dt) is same at all points along the bar.

Unlagged: Like a hose pipe with holes

Theory – like electrical circuit

$$I = \frac{\Delta Q}{\Delta t} = kA\frac{\Delta T}{\Delta x}$$

Re-arranging:-

$$\Delta T = I\frac{\Delta x}{kA}$$

Temp difference drives a current through a thermal resistance

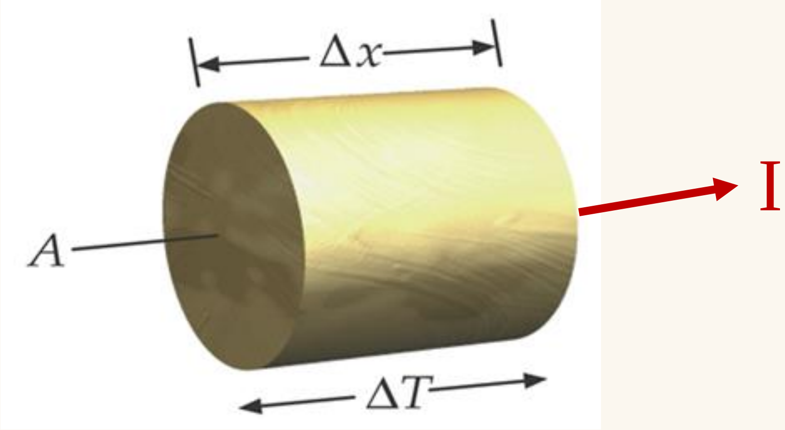
$$\Delta T = IR$$

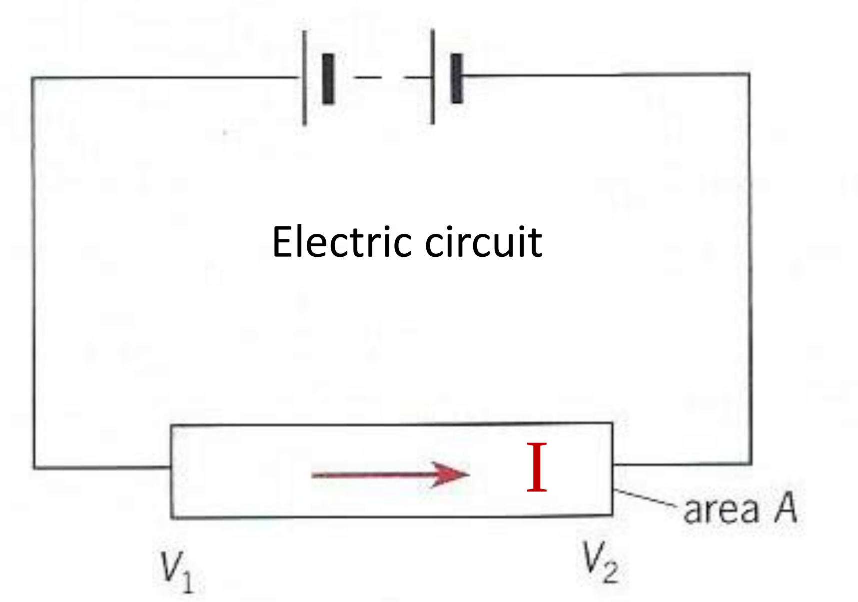
Like V=IR

$$R = \frac{\Delta x}{kA}$$

Thermal resistance

Units K/W

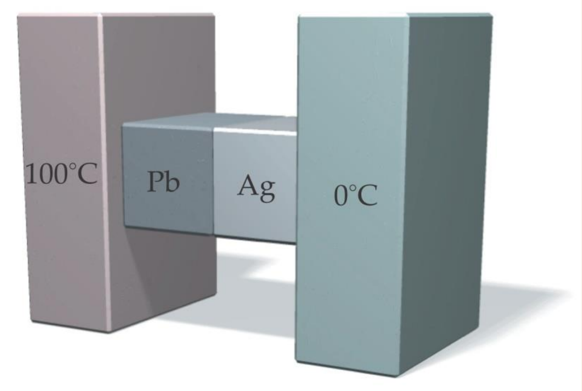




Series and Parallel Thermal Resistance

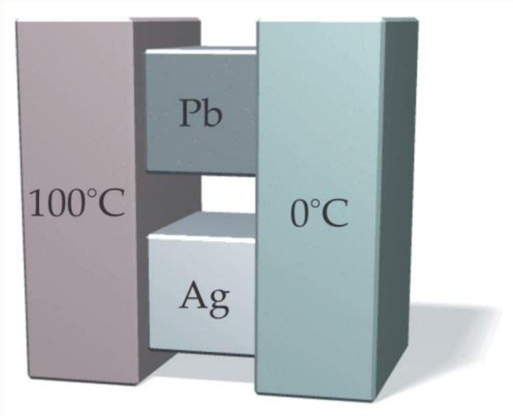
Series e.g.double glazing

$$R_{eq} = R_1 + R_2 + \cdots$$



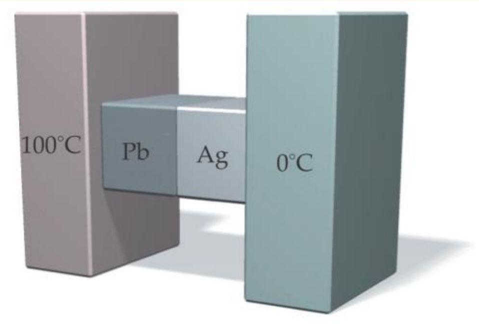
Parallel e.g. windows, doors, walls, roof, floor

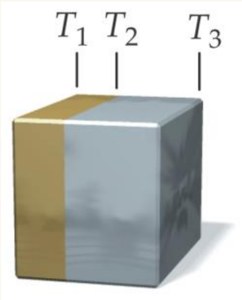
$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$



Question

Two insulated metal bars, each of length 5cm and rectangular cross section 2cm×3cm, are wedged between two walls held at 100°C and 0°C. The bars are lead and silver. Find (a) the thermal current through the bars (b) the temperature at the interface





(a) $R_L = \dfrac{\Delta x_L}{k_L A_L} = \dfrac{0.05}{353 \times 6\times10^{-4}} = 0.236\ \mathrm{K/W}$

$R_S = \dfrac{\Delta x_S}{k_S A_S} = \dfrac{0.05}{429 \times 6\times10^{-4}} = 0.194\ \mathrm{K/W}$

$I = \dfrac{\Delta T}{R_{eq}} = \dfrac{(100-0)}{0.236+0.194} = 232\ \mathrm{W}$

(b) $\Delta T_L = I R_L = 232 \times 0.236 = 54.8^\circ C$

$T_2 = 100 - 54.8 = 45.2^\circ C$

TABLE 20-3

Thermal Conductivities k for Various Materials

k, Btu·in./(h·ft²·F°)	Material	k, W/(m·K)
(2980)	Silver	(429)
(2780)	Copper	(401)
(2450)	Lead	(353)
(2200)	Gold	(318)
(1644)	Aluminum	(237)
(558)	Iron	(80.4)
(319)	Steel	(46)
(6–9)	Concrete	(0.19–1.3)
(5–6)	Glass	(0.7–0.9)
(4.22)	Water at 27°C	(0.609)
(4.11)	Ice	(0.592)
(1.02)	Oak	(0.15)
(0.78)	White Pine	(0.11)
(0.18)	Air at 27°C	(0.026)

Question

(a) A garage wall (5m x 3m x 10cm) is made of brick (thermal conductivity 1.31 W/m.K). On a day when the outside temperature is 5°C and the temperature inside the garage is 10°C, what is the rate of loss of heat through this wall?

(b) What difference would it make to the heat loss if a window (of area $1m^2$) was put in the wall? Assume the window is single glazed with glass of thickness 4mm. Thermal conductivity of glass = 0.8 W/m.K

Answer

(a) A garage wall (5m x 3m x 10cm) is made of brick (thermal conductivity 1.31 W/m.K). On a day when the outside temperature is 5°C and the temperature inside the garage is 10°C, what is the rate of loss of heat through this wall?

$$(a)\quad R_b = \frac{\Delta x_b}{k_b A_b} = \frac{0.1}{1.31 \times 5 \times 3} = 5.09 \times 10^{-3}\ \text{K/W}$$

$$I_b = \frac{\Delta T}{R_b} = \frac{(10-5)}{5.09 \times 10^{-3}} = 982\ \text{W}$$

Answer

(b) What difference would it make to the heat loss if a window (of area $1m^2$) was put in the wall? Assume the window is single glazed with glass of thickness 4mm. Thermal conductivity of glass = 0.8 W/m.K

(b)

$$R_w = \frac{\Delta x_w}{k_w A_w} = \frac{4\times10^{-3}}{0.8\times 1} = 5\times10^{-3}\ K/W$$

$$I_w = \frac{\Delta T}{R_w} = \frac{(10-5)}{5\times10^{-3}} = 1000\ W$$

total current (in parallel) $= I_b + I_w$

$= 982 + 1000$

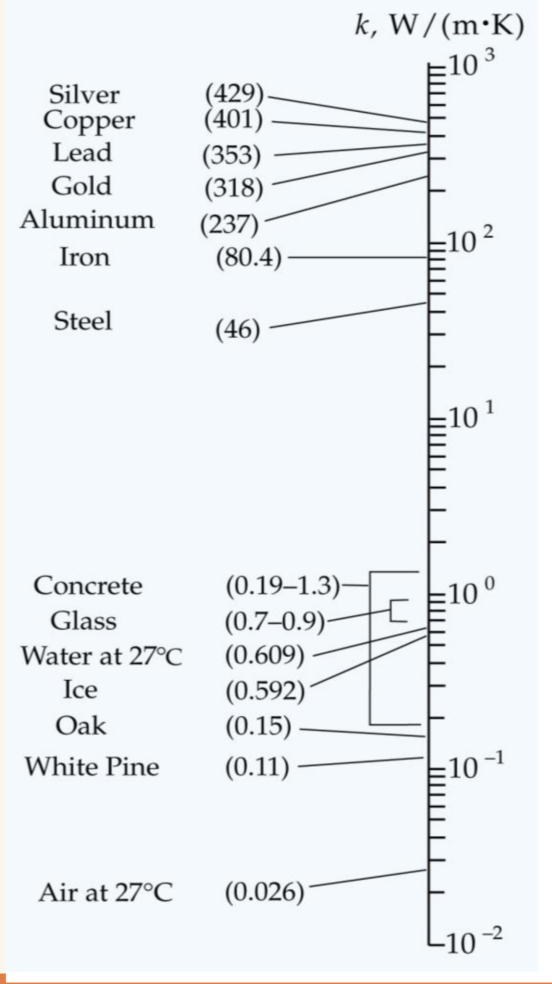
$= 1982\ W$

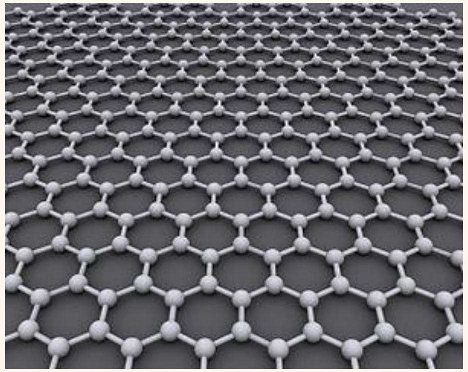
Strictly we should reduce the area of brick to $14m^2$ when adding the window. But effect is still similar, the window makes a massive increase to the rate of heat loss.

Thermal conductivities

TABLE 20-3

Thermal Conductivities *k* for Various Materials





Graphene

2-D structure $k \approx 5000 \mathrm{W/mK}$

has the highest thermal conductivity of known materials

Space Shuttle tile silica (SiO_2)

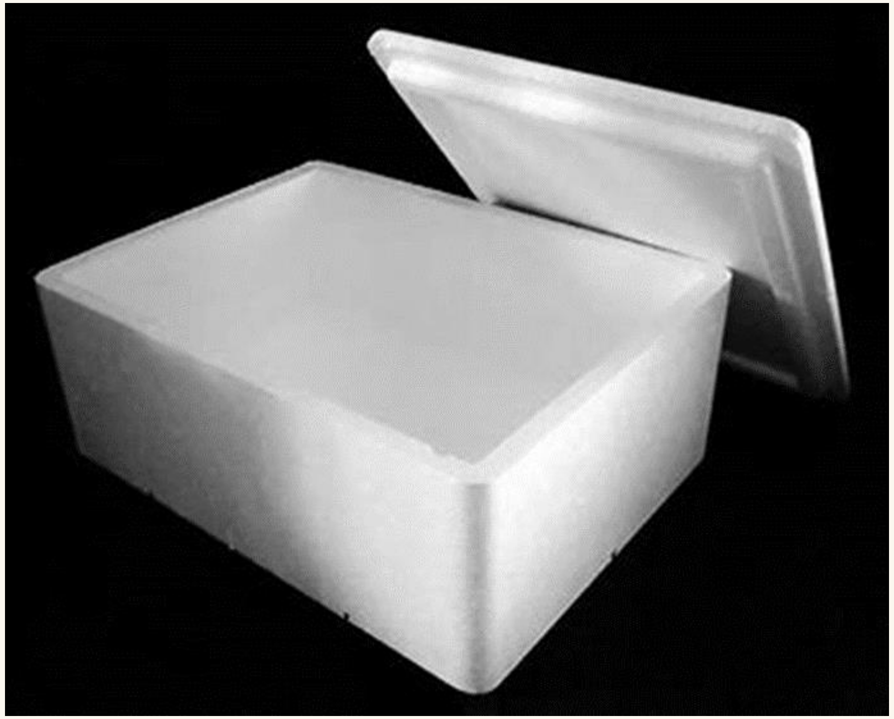
has one of the lowest thermal conductivities. To protect crew from heat on entry to earth's atmosphere

Click on the picture or the URL to see amazing demos with shuttle tiles.

https://www.youtube.com/watch?v=CchPemGaEmw

Question

A cooler box has a total surface area of 0.50 m^2 and an average thickness of 2.0 cm. How long will it take for 1.5 kg of ice (at 0°C) to melt in the cooler, if the outside temperature is 30°C? (Thermal conductivity of Styrofoam used to make the cooler is 0.030 W/m.K Latent heat of fusion of ice is 333 kJ/kg)



Answer

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conduction

$$\frac{dQ}{dt} = \frac{kA\,\Delta T}{\Delta x} = \frac{0.03 \times 0.5 \times (30-0)}{2\times10^{-2}} = 22.5\,\text{W}$$

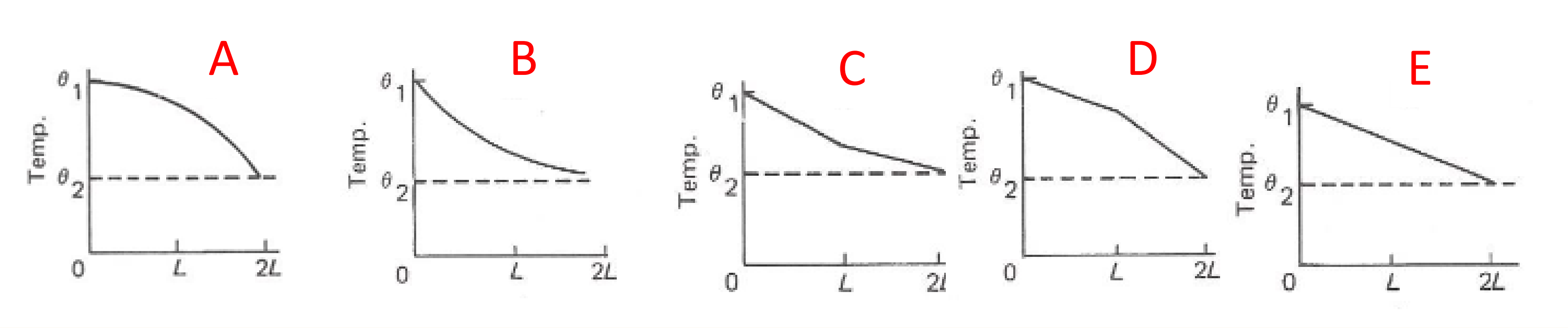
melting

$$Q = mL \qquad \frac{dQ}{dt} = L\frac{dm}{dt} = L\frac{\Delta m}{\Delta t}$$

$$\Delta t = \frac{L\,\Delta m}{dQ/dt} = \frac{333\times10^{3}\times 1.5}{22.5} = 2.22\times10^{4}\,\text{s}$$

$$= 6.2 \text{ hours}$$

Question



Which of these graphs……..

a. Shows a lagged bar

b. Shows an unlagged bar

c. Shows a lagged composite bar (with the highest thermal resistance on the left)

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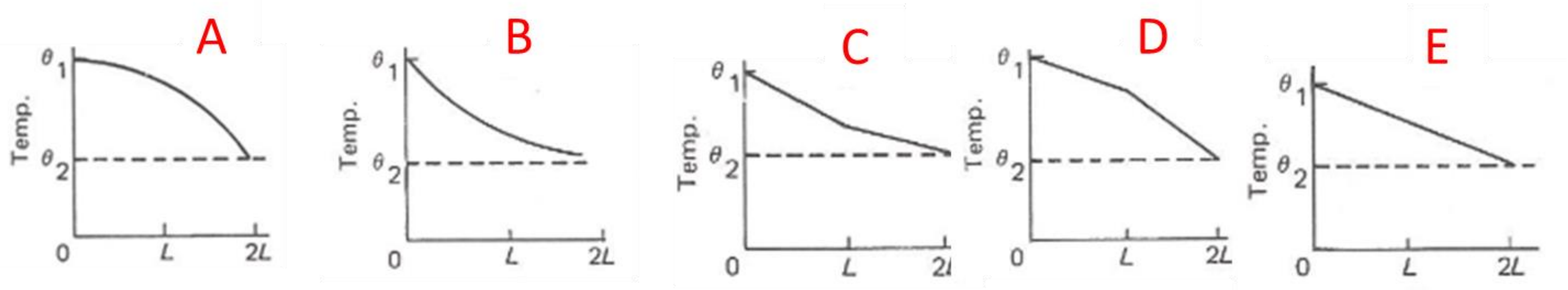
Which graph shows lagged bar?

A	0%
B	0%
C	0%
D	0%
E	0%



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Preparing Results

Which graph shows lagged bar?

A	0%
B	0%
C	0%
D	0%
E	0%

RESULTS SLIDE

0/0

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Question slide

Which graph shows unlagged bar?

A

0%

B

0%

C

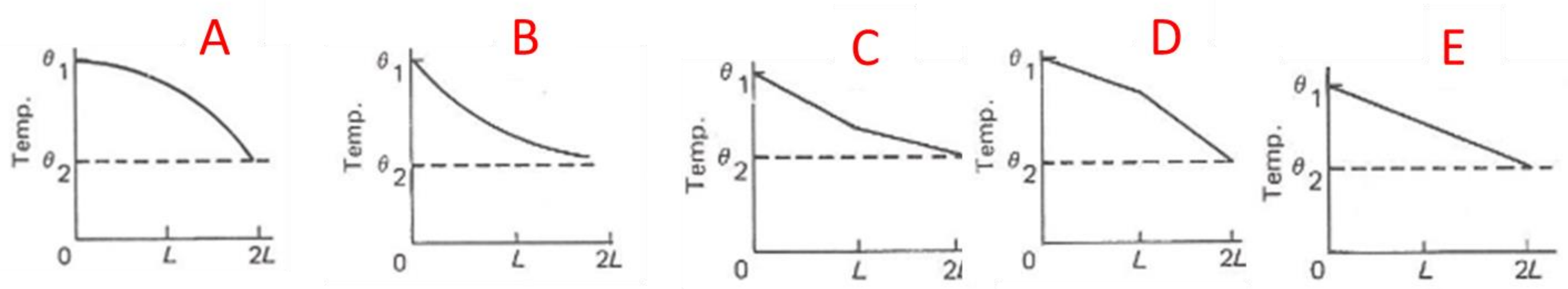
0%

D

0%

E

0%



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Preparing Results

Which graph shows unlagged bar?

A

0%

B

0%

C

0%

D

0%

E

0%

RESULTS SLIDE

Which graph shows lagged composite (higher thermal resistance on left)?

A

0%

B

0%

C

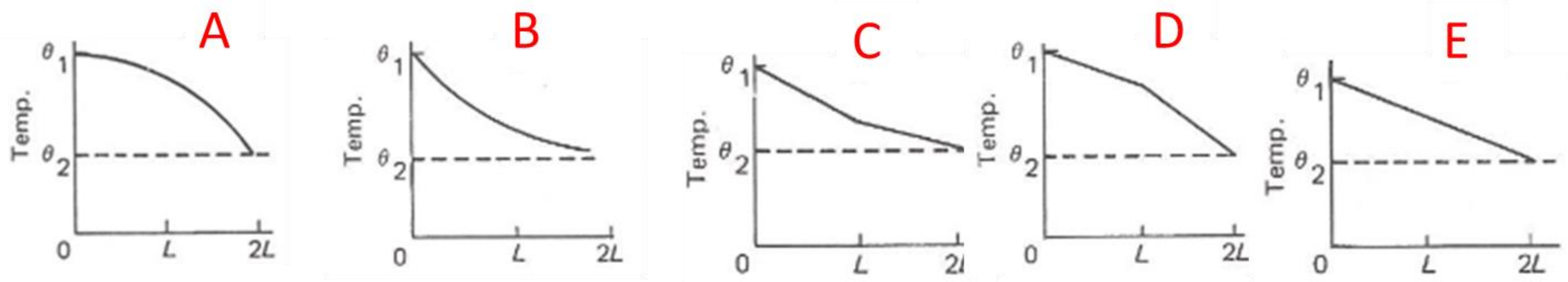
0%

D

0%

E

0%



Which graph shows lagged composite (higher thermal resistance on left)?

A 0%

B 0%

C 0%

D 0%

E 0%

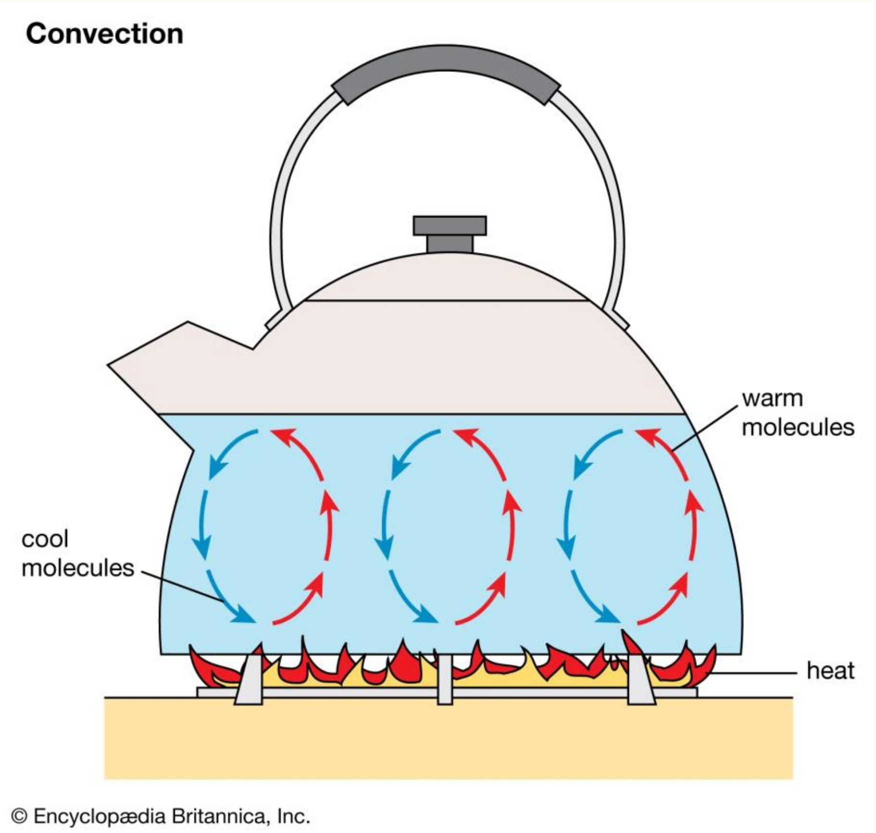
RESULTS SLIDE

Convection

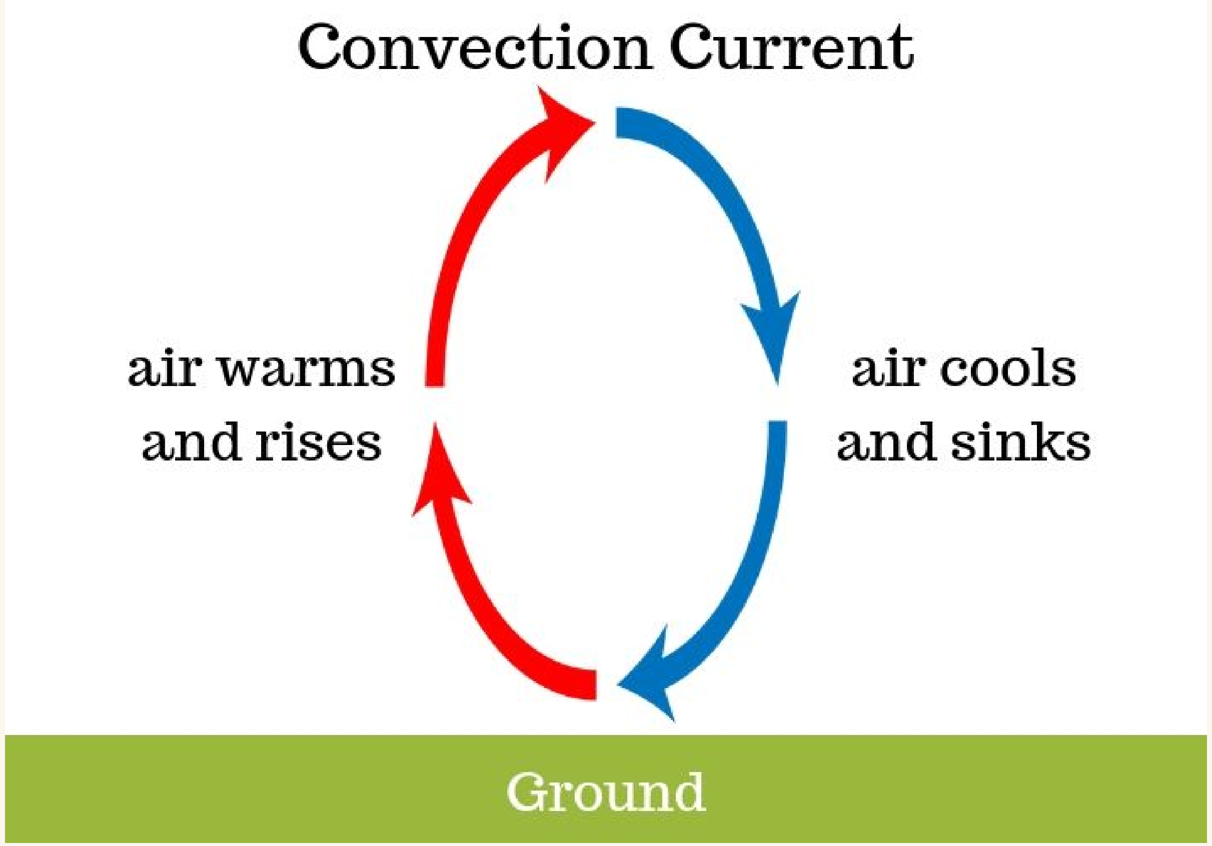
Convection

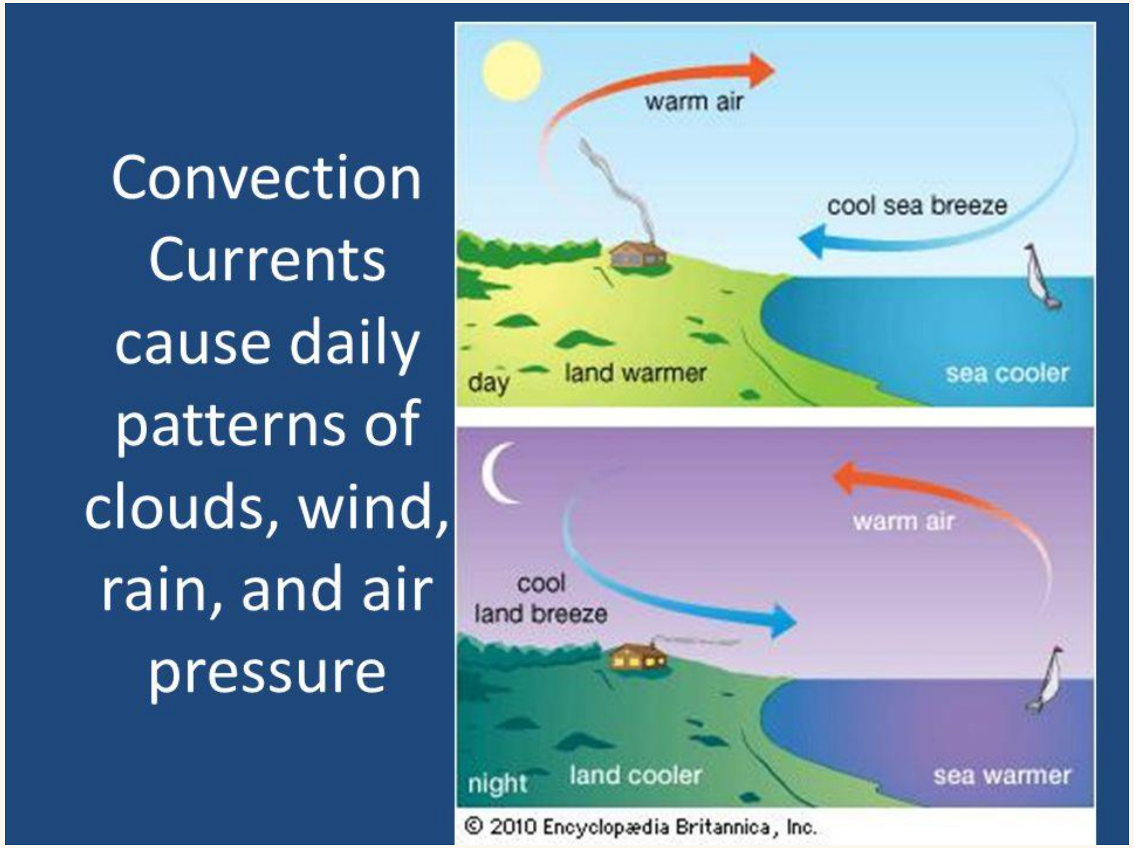
Convection is the transfer of thermal energy by direct mass transport in fluid

Fluid = liquid or gas



Why does the breeze blow in from the sea in day, and out to sea at night?

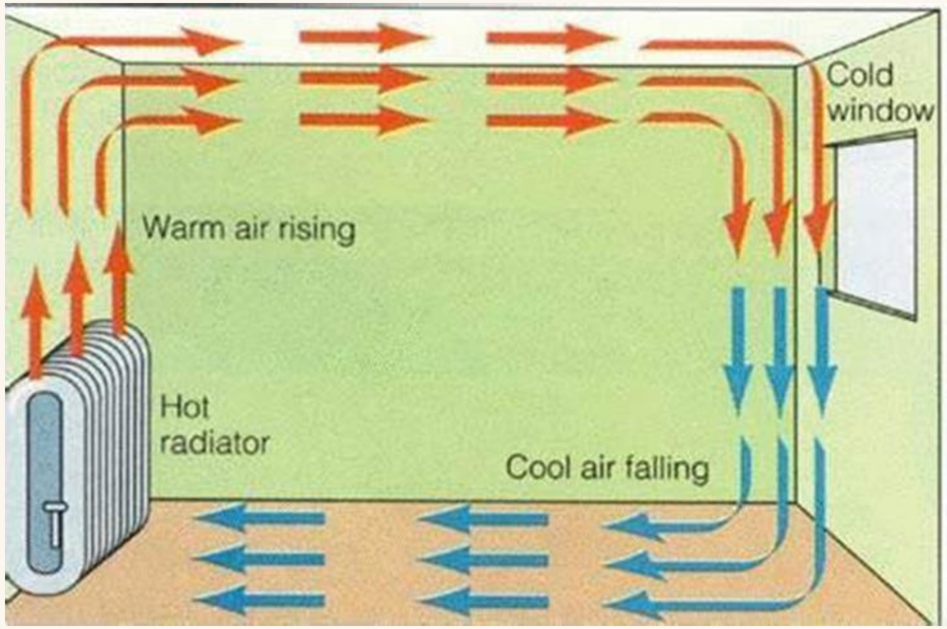


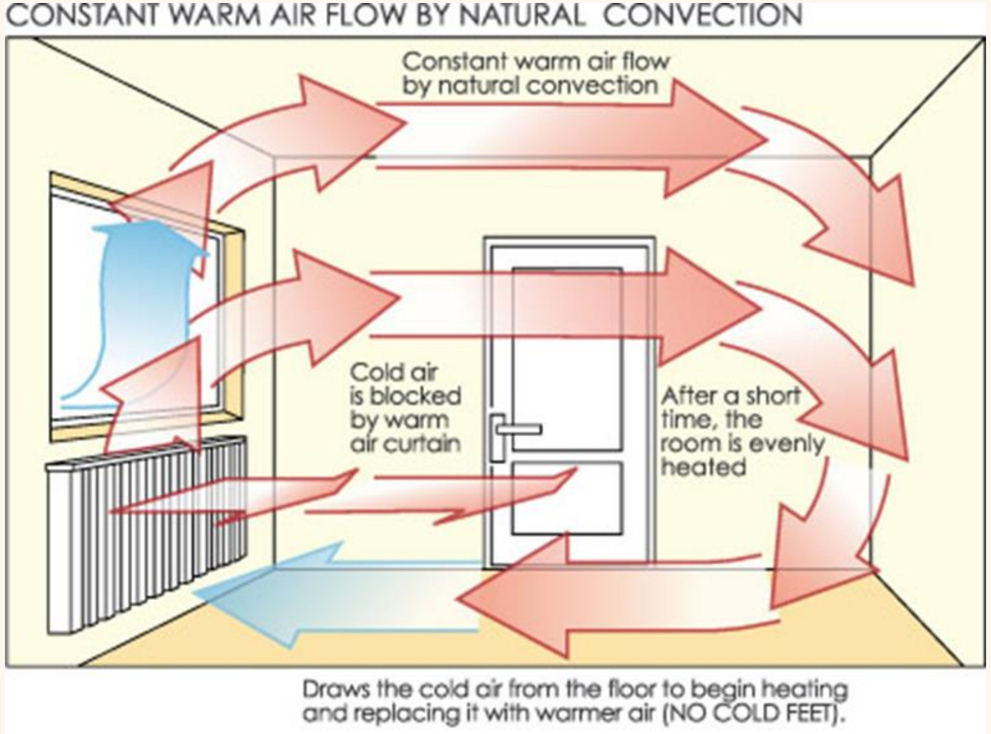


Specific heat capacity of water is high, so very little change in temp as heat gained or lost.
Land warms up in day to be hotter than sea. Land cools at night to be colder than sea.

Where is it best to position a radiator in a room?

- Under a window?
- On wall opposite a window?





Radiation

Thermal Radiation

All objects above absolute zero emit EM radiation from their surface

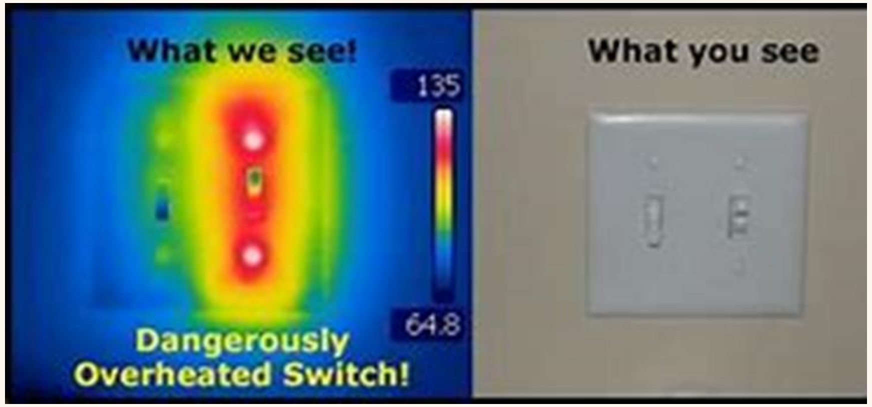
Thermal imaging camera

Electrical safety

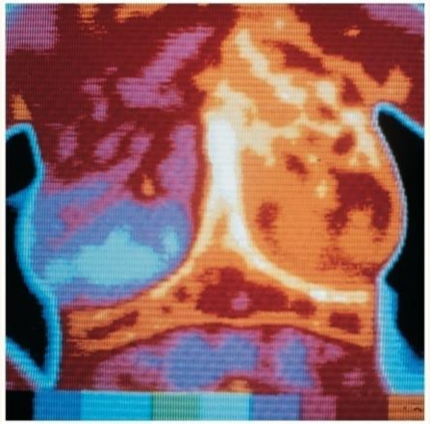
Investigate heat loss

Fire service find people in smoke

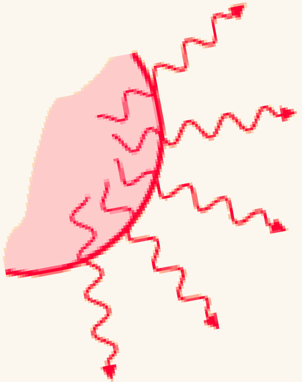
Police locate people in wood



Medical diagnosis



Stefan-Boltzmann Law



Fastest method of heat transfer. Requires neither contact or mass flow.

Power radiated depends on the surface: temp, area, nature

$$P_r = e\sigma A T^4$$

P_r = power radiated from surface
e = emissivity (= 1 for blackbody)
σ = Stefan Boltzmann constant $5.67 \times 10^{-8}\ \mathrm{W m^{-2} K^{-4}}$
A = surface area
T = temperature

Emissivity (between 0 and 1)

- e is lower for smooth shiny
- e is higher for dark rough

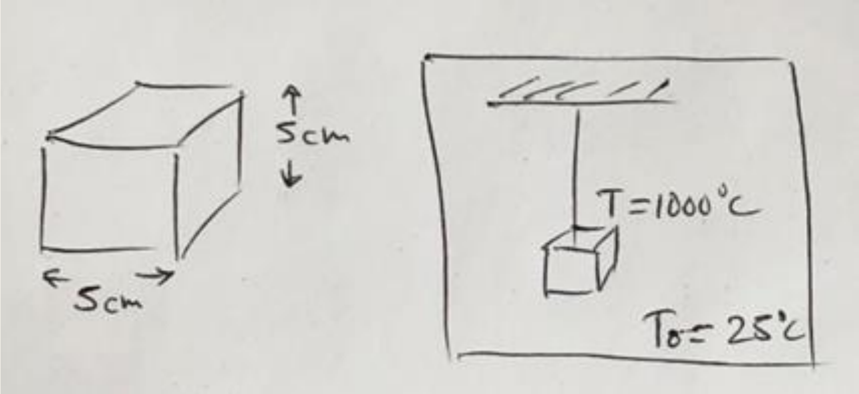
$$P_{net} = e\sigma A(T^4 - T_0^4)$$

Radiation also absorbed from surroundings at T_0

Images: Tipler

Question

A metal cube (of side length 5 cm) is heated to 1000°C. It is then suspended from the ceiling by an insulating string, in a large room at 25°C. Assuming the metal acts as a black body, and that convection and conduction are negligible, what is the initial net rate of heat loss from the cube.



Radiation

$$P_{net} = \frac{dQ}{dt} = eA\sigma\left(T^4 - T_0^4\right)$$

$T = 1000°C = 1273K$

$T_0 = 25°C = 298K$

A = surface area of cube

$= 6 \times$ face area

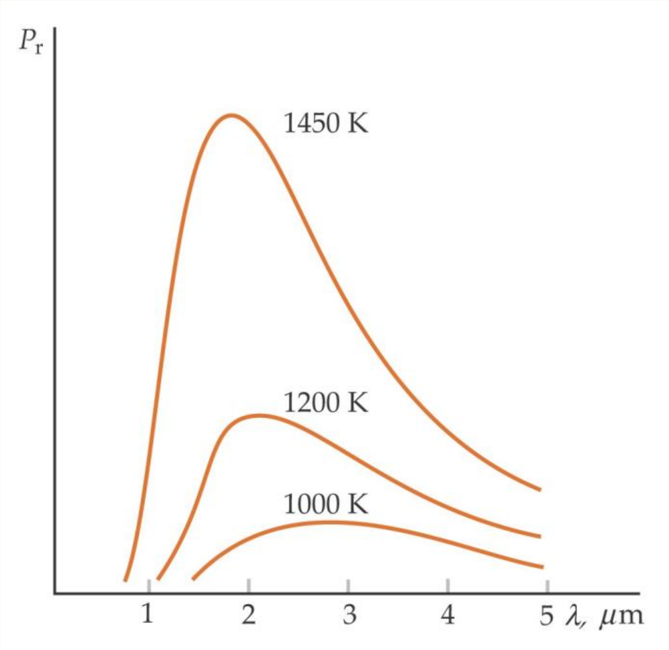
$= 6 \times 0.05^2$

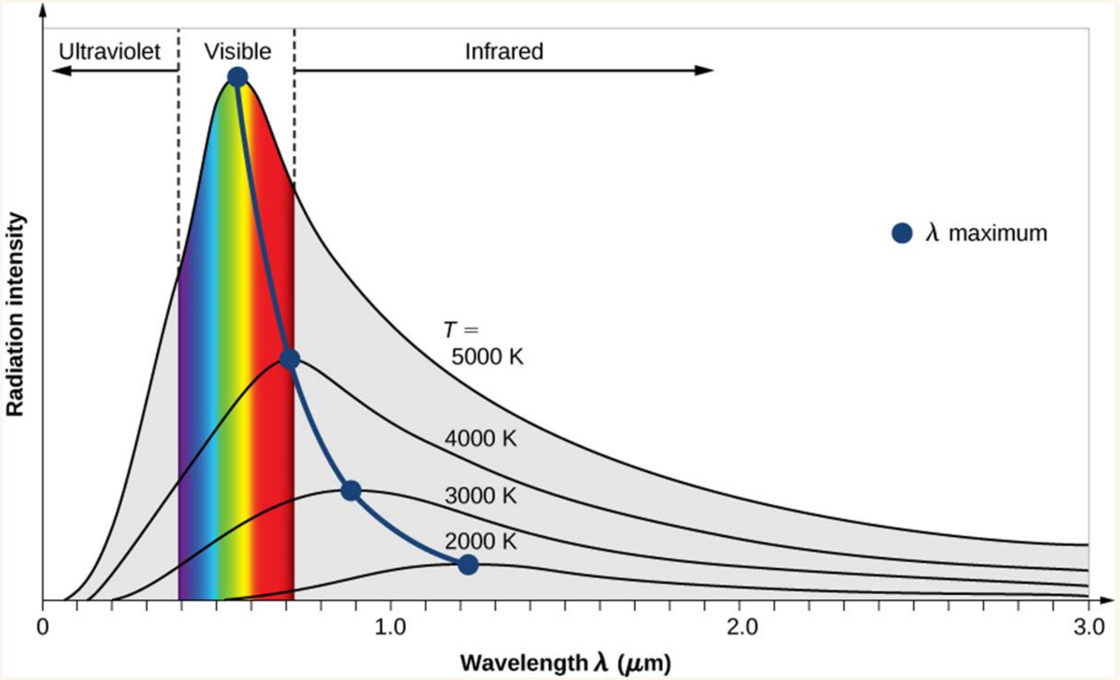
$= 0.015 m^3$

$$P_{net} = 1 \times 0.015 \times 5.67 \times 10^{-8} \left(1273^4 - 298^4\right)$$

$$\boxed{P_{net} = 2227 \text{ W}}$$

Wein’s Displacement Law





Total energy emitted is proportional to area under curve

λ_{max} = wavelength of maximum radiated power.

$$\lambda_{max} = \frac{2.898\ \mathrm{mm.K}}{T}$$

Question

Given that the sun has a radius of about 7.0 x 10^8 m and a surface temperature of 5800 K, calculate

(a) The wavelength at which the sun's radiation has peak emission

(b) the total energy emitted per second from the sun's surface

(a) Wien's law $\lambda_{MAX} = \frac{2.898}{T} = \frac{2.898}{5800}$ $= 4.996 \times 10^{-4}$ mm $\approx 5.0 \times 10^{-7}$ m

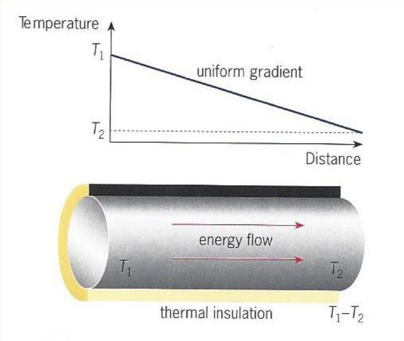
(b) $P = e\sigma A T^4$ surface area $= 4\pi r^2$

$= 1 \times 5.67 \times 10^{-8} \times 4\pi \times (7.0 \times 10^8)^2 \times 5800^4$

$= 3.95 \times 10^{26}$ W

Summary of conduction, convection and radiation

Conduction is the transfer of thermal energy by interaction between vibrating molecules



A lagged bar has a uniform temperature gradient (and constant

k = thermal conductivity (Wm^{-1}K^{-1})

$$\frac{dQ}{dt} = -kA\frac{dT}{dx}$$

$$\Delta T = I\frac{\Delta x}{kA} \qquad R = \frac{\Delta x}{kA}$$

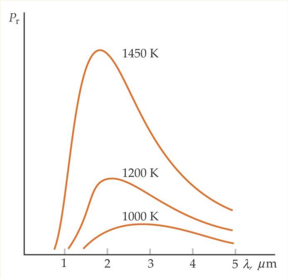
$$R_{eq} = R_1 + R_2 + \cdots$$ Series

$$\Delta T = IR$$

$$\frac{1}{R_{eq}} = \frac{1}{R_1} + \frac{1}{R_2} + \cdots$$ Parallel

Convection is the transfer of thermal energy by direct mass transport in fluid

Radiation is the transfer of thermal energy in the form of electromagnetic radiation. (No medium is necessary)



$$P_r = e\sigma AT^4 \qquad P_{net} = e\sigma A(T^4 - T_0^4) \qquad \lambda_{max} = \frac{2.898\ \text{mm.K}}{T}$$

Practice Questions

Practice Question

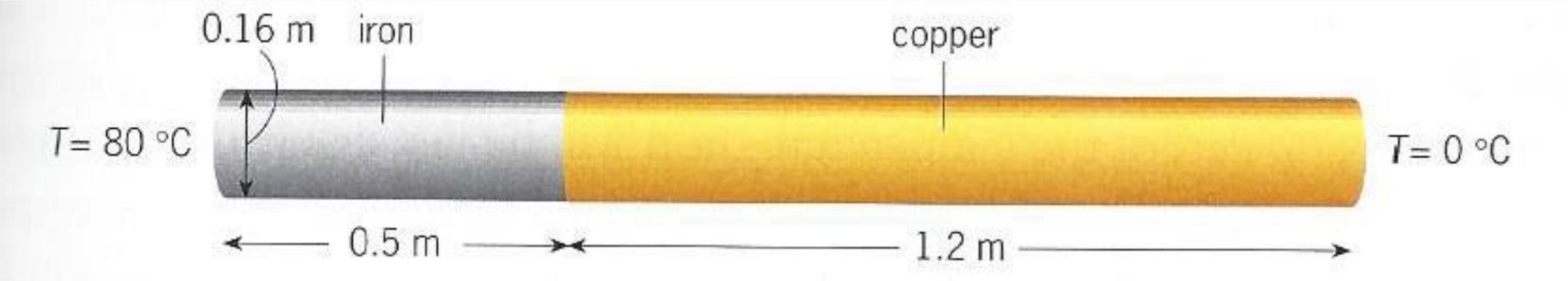
A iron bar 0.5m long and a copper bar 1.2 m long are joined end to end. The free end of the iron bar is kept at 80°C and the free end of the copper bar is kept at 0°C. Both bars have circular cross-section of diameter 0.16 m and both are lagged. In thermal equilibrium the junction is at temperature T_1.

Calculate

a) The rate of heat flow

b) The temperature T_1

Thermal conductivity of copper = 390 $Wm^{-1}K^{-1}$ and iron = 75 $Wm^{-1}K^{-1}$



Practice Question

A solid metal sphere is hung from a thin insulating thread, in a vacuum. When at 400 K the sphere radiates at a rate of 1W. What would be the rate of radiation of an identical sphere of half the radius at 800 K? (Ignore any heat absorbed from the surroundings).

A 2W **B** 4W **C** 8W **D** 16W **E** 64W

Practice Question

The element of an electric heater is a cylinder 25 cm long with diameter 1.5 cm. The heater behaves as a blackbody and radiates with power of 1.0 kW. Calculate it's temperature. Stefan's constant = 5.67×10^{-8} W m^{-2} K^{-4}.

Practice Question

On a sunny day, a swimming pool absorbs 2.0 x 109 J of heat. What is the change in volume of the water? Give your answer in cm3.

Data:

Coefficient of volume expansion of water = 207 x 10-6 K-1

Specific heat capacity of water = 4.2 kJ kg-1 K-1

Density of water (at temperature at start of day) = 1000 kg m-3

ANSWERS

Answer

A iron bar 0.5m long and a copper bar 1.2 m long are joined end to end. The free end of the iron bar is kept at 80°C and the free end of the copper bar is kept at 0°C. Both bars have circular cross-section of diameter 0.16 m and both are lagged. In thermal equilibrium the junction is at temperature T_1.

Calculate

a) The rate of heat flow
b) The temperature T_1

Thermal conductivity of copper = 390 $Wm^{-1}K^{-1}$ and iron = 75 $Wm^{-1}K^{-1}$

$$R = \frac{\Delta x}{kA}$$

cross-section area $= \pi r^2 = \pi \times \left(\frac{0.16}{2}\right)^2$

$= 0.020\ m^2$

$R_{iron} = \frac{0.5}{75 \times 0.02} = 0.33\ K/W$

$R_{copper} = \frac{1.2}{390 \times 0.02} = 0.15\ K/W$

the bars are in series

$R_{TOTAL} = R_{iron} + R_{copper}$
$= 0.33 + 0.15$
$= 0.48\ K/W$

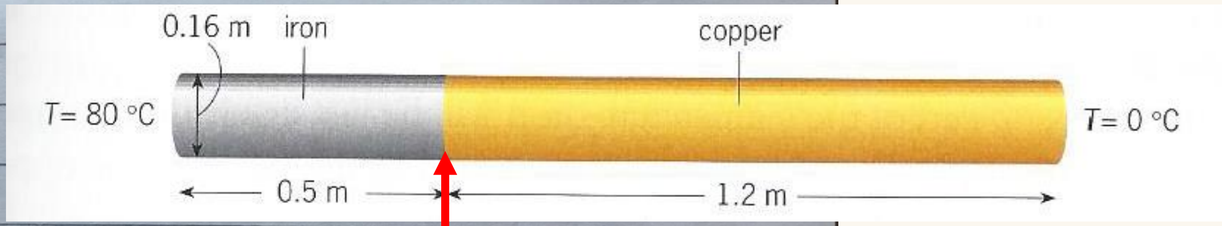
(a) $\Delta T = I R_{TOTAL}$

$I = \frac{\Delta T}{R_{TOTAL}} = \frac{(80-0)}{0.48} = \boxed{167\ W}$

(b) Find ΔT_{copper}

$\Delta T = I R_{copper}$
$= 167 \times 0.15$
$\Delta T = 25°C$

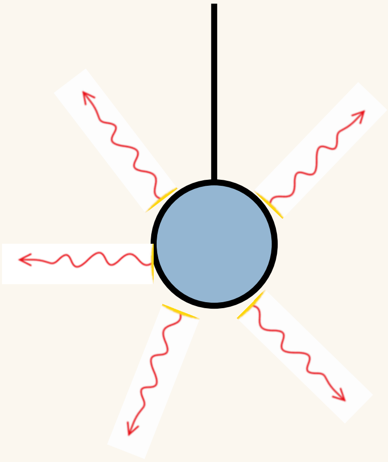
Since one end of copper is at 0°C, the junction is at $\boxed{25°C}$



Answer

A solid metal sphere is hung from a thin insulating thread, in a vacuum. When at 400 K the sphere radiates at a rate of 1W. What would be the rate of radiation of an identical sphere of half the radius at 800 K? (Ignore any heat absorbed from the surroundings).

A 2W **B** 4W **C** 8W **D** 16W **E** 64W

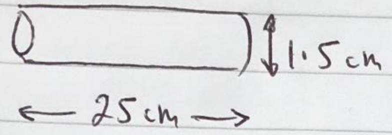


Stefan's eqn $P = e\sigma A T^4$ $A = 4\pi r^2$ surface area.

$$\frac{P_2}{P_1} = \left(\frac{r_2^2}{r_1^2}\right)\left(\frac{T_2^4}{T_1^4}\right) = \left(\frac{1}{2}\right)^2\left(\frac{2}{1}\right)^4 = 4$$

Answer

The element of an electric heater is a cylinder 25 cm long with diameter 1.5 cm. The heater behaves as a blackbody and radiates with power of 1.0 kW. Calculate it's temperature. Stefan's constant = 5.67 × 10^{-8} W m^{-2} K^{-4}.



$$\text{Surface area} = 2\pi r L + 2\times\pi r^2$$

$$= 2\pi \times \left(\frac{1.5\times10^{-2}}{2}\right)\times 0.25 + 2\times\pi\times\left(\frac{1.5\times10^{-2}}{2}\right)^2$$

$$= 0.01178 + 0.00035$$

$$= 0.0121\ m^2$$

$$P = e\sigma A T^4 \qquad T^4 = \frac{P}{e\sigma A}$$

$$T^4 = \frac{1000}{1\times 5.67\times10^{-8}\times 0.0121} = 1.4576\times10^{12}$$

$$T = \sqrt[4]{1.4576\times10^{12}} = 1098.7 \sim \boxed{1100\ K}$$

Answer

On a sunny day, a swimming pool absorbs 2.0×10^9 J of heat. What is the change in volume of the water? Give your answer in cm^3.

Data:
Coefficient of volume expansion of water = 207×10^{-6} K^{-1}
Specific heat capacity of water = 4.2 kJ kg^{-1} K^{-1}
Density of water (at temperature at start of day) = 1000 kg m^{-3}

$$\Delta V = \beta V_0 \Delta T$$

Rise in temperature is given by $Q = mc\Delta T$ so $\Delta T = \frac{Q}{mc}$

Mass given by density, so $m = \rho V$

Thus: $$\Delta V = \beta V_0 \frac{Q}{\rho_0 V_0 c} = \frac{\beta Q}{\rho_0 c} = \frac{207 \times 10^{-6} \times 2 \times 10^9}{1000 \times 4.2 \times 10^3}$$

$$= \boxed{0.09857 \text{ m}^3}$$