

2.3 Transfer of Thermal Energy

Demonstrating Conduction

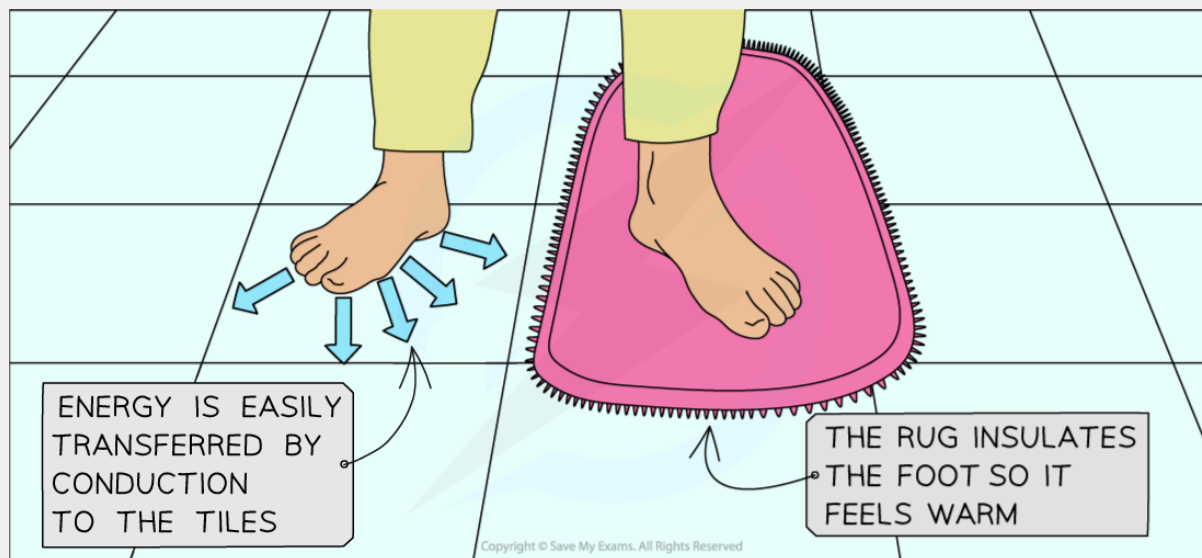
Experiments demonstrating thermal conductors

Good and bad thermal conductors

- Good thermal conductors are solids which easily transfer heat
 - For example, an aluminium pan or copper wire
- Bad thermal conductors (also called insulators) are solids which do not transfer heat well
 - For example, a wool blanket or layers of cardboard or paper

Comparing conduction in tiles and textiles

- This conduction experiment shows why homes use rugs and carpets
- Find a tiled or stone area of floor
 - In the same room leave a rug or bath towel (not a thin cloth, it must be thick)
 - The textile must stay in place on the floor for several hours to ensure they are at thermal equilibrium (the same temperature)
- Stand with bare feet (hands can be used)
 - Place one foot on the tiles or stone area, and the other on the textile (towel or rug)
 - Observe the apparent temperature of the two materials as felt through the feet
 - It will feel as though the tiles are cold while the rug is warm, however, they are at exactly the same temperature



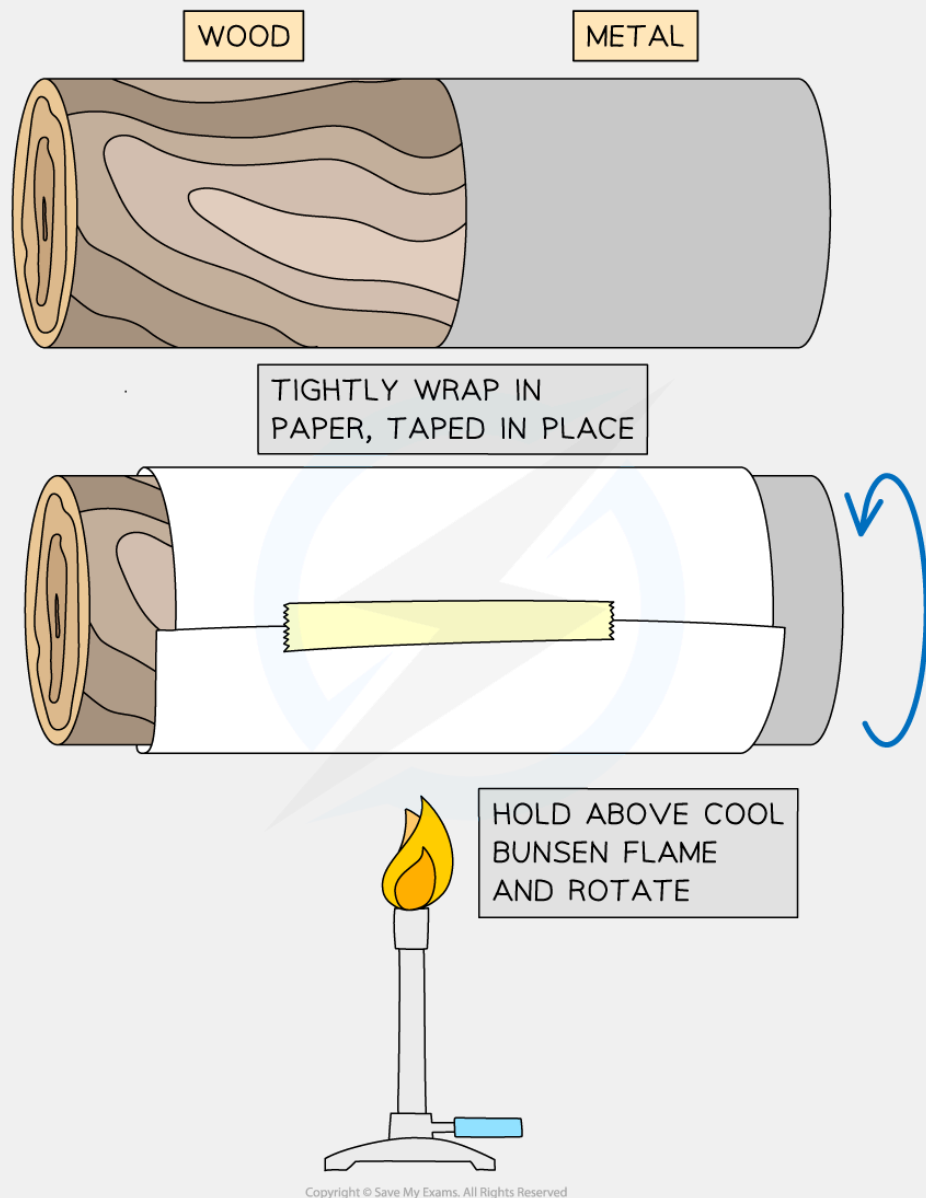
Energy is transferred by heating from the hotter foot to the cooler tiles by conduction

Explanation

- Tiles and stone are good conductors of heat
 - Where the foot touches the tiles, **heat is transferred away** from the foot, making it **feel** cold
 - The **foot** has become colder since it lost heat to the tiles
- Textiles such as rugs are good insulators, meaning they are poor conductors of heat
 - Where the foot touches the rug, heat is not transferred away from the foot
 - This foot feels relatively warmer than the one which has lost heat to the tiles
 - The foot has stayed at its starting temperature

Comparing conduction in wood and paper

- A cylindrical rod made of half wood and half metal is wrapped tightly in paper

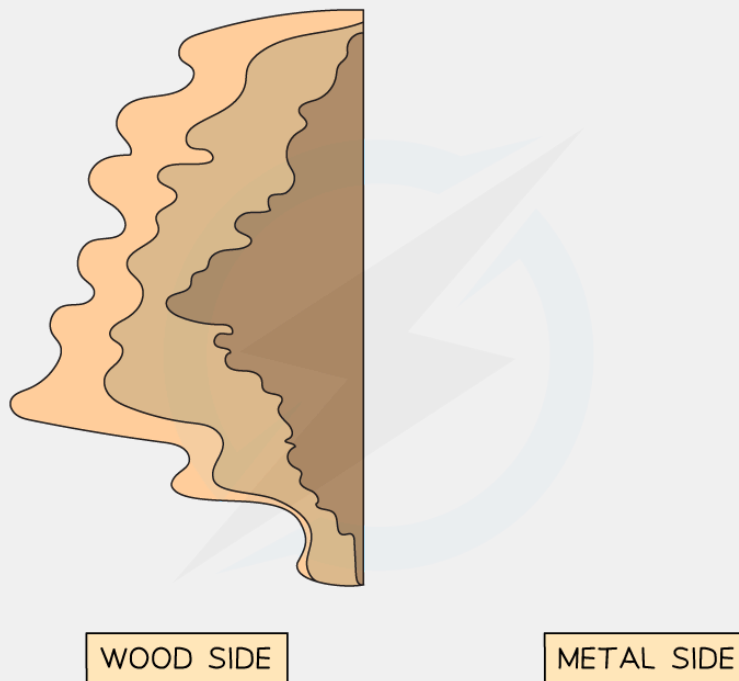


Method for showing different thermal conduction of wood and metal

- Using a gentle flame, and holding the rod clear of the top of the flame, gently heat the paper at the join of the wood and metal
 - Turn the rod so that the paper is well-heated all around the circumference of the rod
 - Stop when the paper is clearly discoloured

- Remove the rod from the flame, gently unwrap the paper and observe the burn pattern
 - A distinct pattern is seen;

- Where the paper touched the metal surface it is undamaged
- Where the paper touched the wood surface it is charred



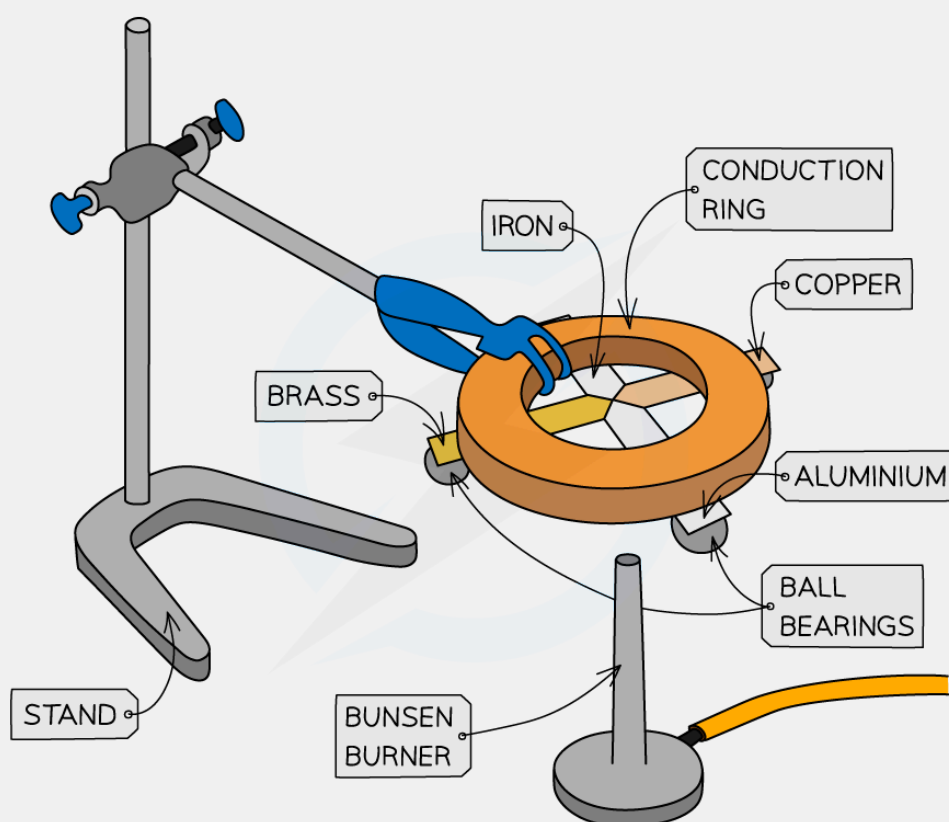
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Explanation

- Metal is a good conductor of heat
 - Where the paper touched the metal in this conduction experiment, heat was transferred from the paper into the metal and along the length of the metal
 - This prevented the paper getting hot
- Wood is a good insulator, meaning it is a poor conductor of heat
 - Where the paper touched the wood, heat was not transferred from the paper
 - This meant that the paper did get hot enough to start to burn

Demonstrating different rates of thermal conduction in metals

- A simple conduction experiment to demonstrate the relative conducting properties of different materials can be carried out using apparatus similar to that shown in the diagram below



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The above apparatus consists of 4 different metal strips of equal width and length arrange around an insulated circle, holding ball bearings with wax

- Ball bearings can be stuck to each of the strips and equal distance from the centre, using a small amount of wax
- The strips should then be turned upside down and the centre heated gently using a candle, so that each of the strips is heated at the point where they meet

- When the heat is conducted along to the ball bearing, the wax will melt and the ball bearing will drop
- By timing how long this takes for each of the strips, their relative thermal conductivities can be determined

Examiner Tips and Tricks

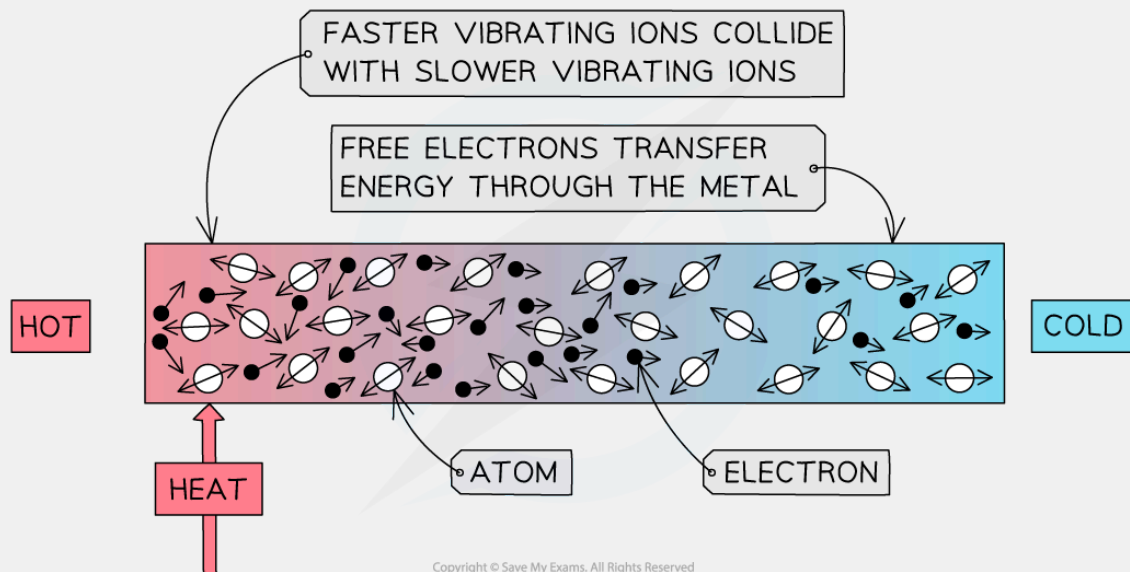
With two of the demonstrations above (the rug & tiles and the rod made of wood and metal) students often get confused, as the result may 'feel' as though it is the wrong way round. Think about the movement or transfer of the heat.

The more heat is taken away, the cooler something will be. That is why the paper doesn't burn when it is next to the metal (although usually everyone guesses that it will!)

The more heat is held in by a layer of insulation, the more heat remains, which is why rugs and carpets help your feet to feel warm.

Thermal Conduction

- Conduction is the transfer of heat from one region to another through particle vibrations and the movement of free electrons
- Conduction is the main method of thermal energy transfer in **solids**
- Metals are the best thermal **conductors**
 - This is because they have a high number of **free electrons**



Conduction: the atoms in a solid vibrate and collide, transferring energy

- Conduction can occur through two mechanisms:
 - Atomic vibrations
 - Free electron collisions
- When a substance is heated, the atoms, or ions, **start to move around (vibrate) more**
 - The atoms at the hotter end of the solid will vibrate more than the atoms at the cooler end
 - As they do so they **bump into each other**, transferring energy from atom to atom
 - These collisions transfer internal energy until **thermal equilibrium** is achieved throughout the substance
 - This occurs in **all solids**, metals and non-metals alike

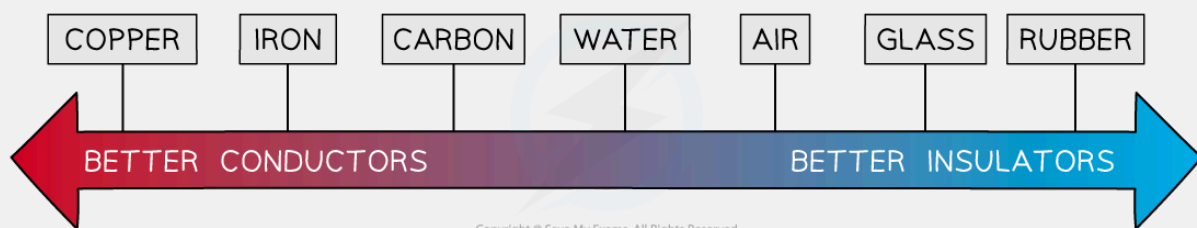
- Additionally, if a solid contains free electrons, these can travel through the material freely and transfer thermal energy through collisions

Thermal conduction in liquids & gases

- For thermal conduction to occur the particles need to be close together so that when they vibrate the vibrations are passed along
- This does not happen easily in fluids
 - In liquids particles are close, but slide past each other
 - In gases particles are widely spread apart and will not 'nudge' each other when they vibrate
- Both types of **fluid**, liquids and gases, are poor conductors of heat

Relative thermal conductivity

- Conductors tend to be **metals**
 - Better thermal conductors are those with delocalised electrons which can easily transfer energy
 - This means that there is a **wide range** of thermal conductivity



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Different materials have different levels of conductivity

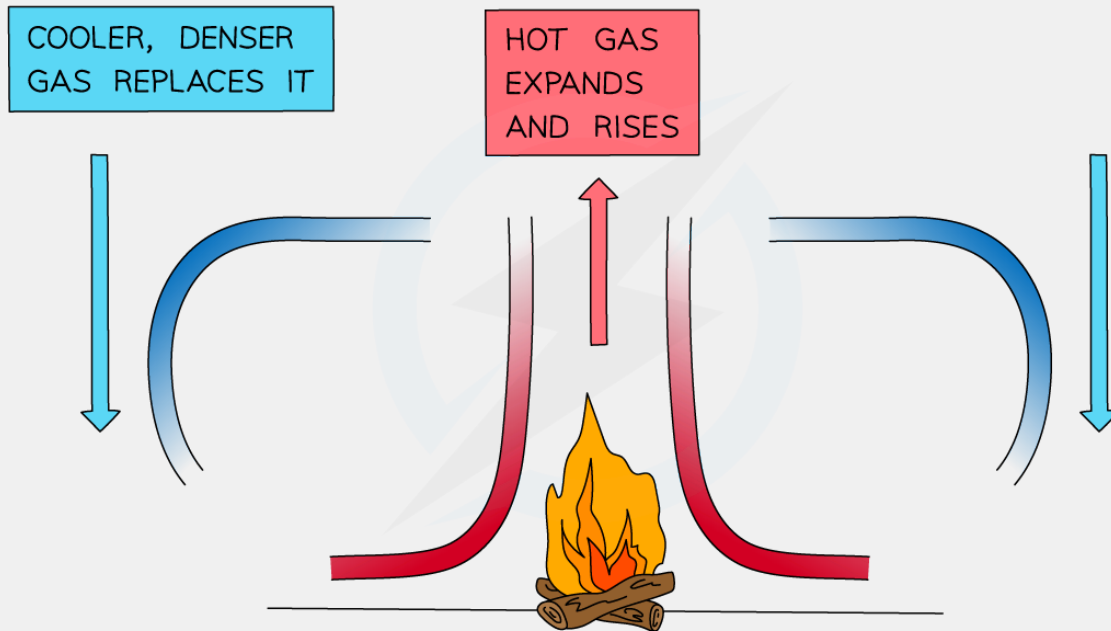
Convection

- Convection is the main way that heat travels through **liquids and gases**
 - Convection **only** occurs in fluids
 - Convection **cannot** happen in solids

Density & convection

- Descriptions of convection currents always need to refer to changes in temperature causing changes in **density**
- The temperature may fall or rise, both can create a convection current
- **When a liquid (or gas) is heated (for example by a radiator near the floor):**
- The heated molecules vibrate and push each other apart, **making the liquid/gas expand**
- This makes the hot liquid/gas **less dense** than the surroundings, causing them to **rise** (just like how objects float if it is less dense than the liquid it is in)
- As the **hot liquid/gas rises**, the cooler (surrounding) liquid/gas moves in to take its place
- Eventually the hot liquid/gas cools and contracts, increasing in density, and sinks back down again
- The resulting motion is called a **convection current**

Simple convection current diagram



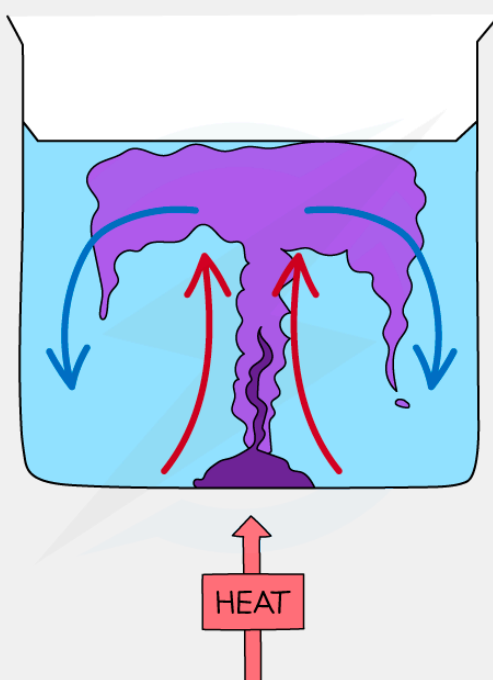
When a liquid or gas is heated, it becomes less dense and rises

- When a liquid (or gas) is cooled (for example by an A.C. unit high up on a wall):
 - The molecules lose energy and collide less, **making the liquid/gas contract**
 - This makes the cold liquid/gas **more dense** than the surroundings
 - The **cold liquid/gas falls**, so that warmer, less dense, liquid or gas can move into the space created
 - The warmer liquid/gas gets cooled and also contracts and falls down
 - The resulting motion is called a **convection current**

Demonstrating convection currents

- A simple demonstration of convection in liquids involves taking a beaker of water and placing a few crystals of potassium permanganate in it as shown in the simple convection current diagram below – this compound is purple in water

- When the water is heated around the crystals, the potassium permanganate will dissolve in the heated water and rise along with the warmed water, revealing the convection current
- As the warmed water cools and becomes more dense, it will fall and carry the potassium permanganate with it



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Diagram showing an experiment with potassium permanganate to demonstrate convection

Examiner Tips and Tricks

If a question on heat mentions **liquids or gases** the answer will probably be about **convection**.

Heat does not rise - it is the hot gases or liquids which rise due to the change in density when they were heated.

Radiation

What is thermal radiation?

- All objects give off thermal radiation
 - The hotter an object is, the more thermal radiation it emits
 - Thermal radiation is **infrared radiation** (part of the electromagnetic spectrum)
- Thermal radiation is **the only way in which heat can travel through a vacuum**
 - It is the way in which heat reaches us from the Sun through the vacuum of space
 - Thermal radiation does **not need a medium** to travel, unlike convection and conduction

Effects of different surfaces

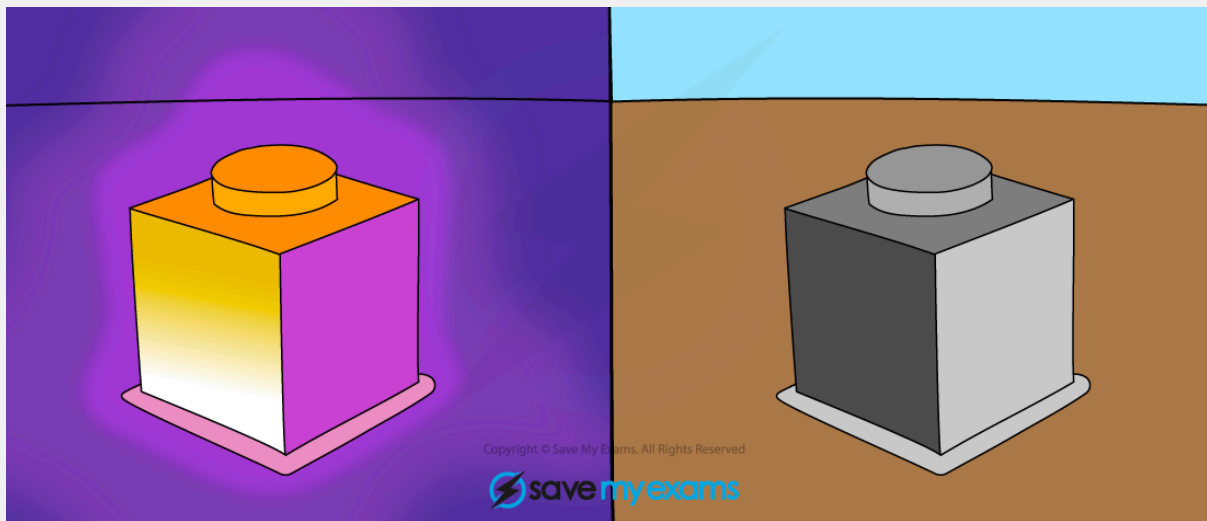
What two factors affect the rate of thermal energy transfer?

- The amount of thermal radiation emitted by an object depends on a number of factors:
 - The **surface colour** of the object (black = more radiation emitted and absorbed)
 - The **texture** of the surface (shiny surfaces = less radiation emitted and absorbed)

Table of the effect of coloured surfaces on absorbing and emitting ability

Colour/texture	Absorbing	Emitting
Black	Good absorber	Good emitter
Dull/dark	Reasonable absorber	Reasonable emitter
White	Poor absorber	Poor emitter
Shiny	Very poor absorber (it reflects)	Very poor emitter

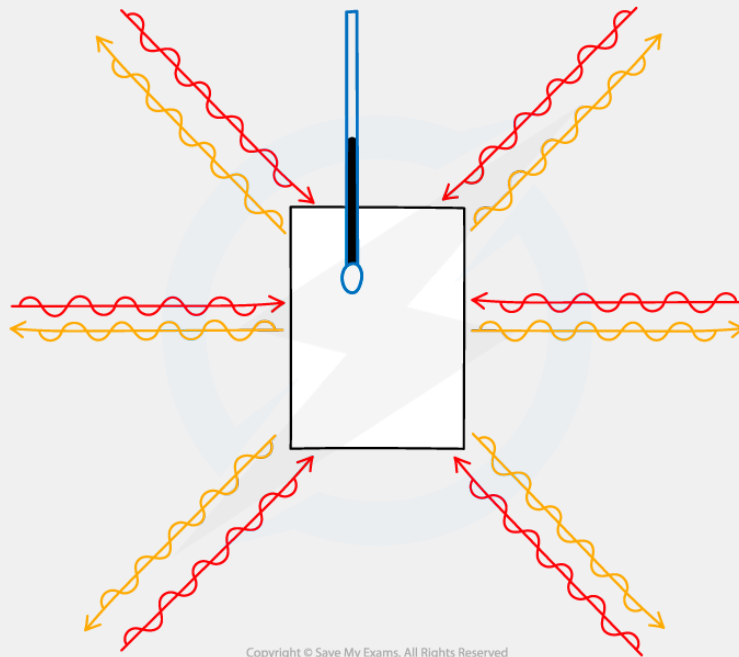
- Black objects are very good at absorbing thermal radiation, for example black clothes make you feel hotter in sunny weather
 - Black objects are also very good at emitting thermal radiation, which is the reason that some chargers for laptops, and radiators in cars are coloured black - it helps them to cool down
- Shiny objects reflect thermal radiation and so absorb very little
 - They also emit very little, though, and so take longer to cool down



The infrared radiation emitted from a hot object can be detected using a special camera. The dull black side of the cube (left) is seen to glow brighter with infrared radiation than the shiny light side of the cube (right)

Thermal equilibrium

- As an object **absorbs** thermal radiation it will become **hotter**
 - As it gets hotter it will also **emit** more thermal radiation
- Eventually, an object will reach a point where it is **absorbing** radiation at the **same rate** as it is **emitting** radiation
 - At this point, the object will be in **thermal equilibrium**
 - At thermal equilibrium, an object has **constant temperature**



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An object will remain at a constant temperature if it absorbs heat at the same rate as it loses heat

Heating & cooling by energy transfer

- If the rate at which an object **receives** energy is **greater** than the rate at which it **transfers** energy **away**:
 - then the object's temperature will **increase**
- If the rate at which an object **transfers** energy **away** is **greater** than the rate at which it **receives** energy:
 - then the object's temperature will **decrease**
- The process will **always** move towards thermal equilibrium
 - As temperature increases, the object emits more radiation until the rates are equal
 - As temperature decreases, the object transfers less energy until the rates are equal

Examiner Tips and Tricks

When a question on heat transfer mentions the surface properties of an object, such as describing it as shiny, black or white, then you are being clued-in to write about **thermal radiation**.

Shiny things are both poor emitters **and** poor absorbers of thermal radiation, while black surfaces are both good emitters **and** good absorbers.

The surface makes the object either good or bad at **both**, so you don't need to remember too many facts!

The Greenhouse Effect

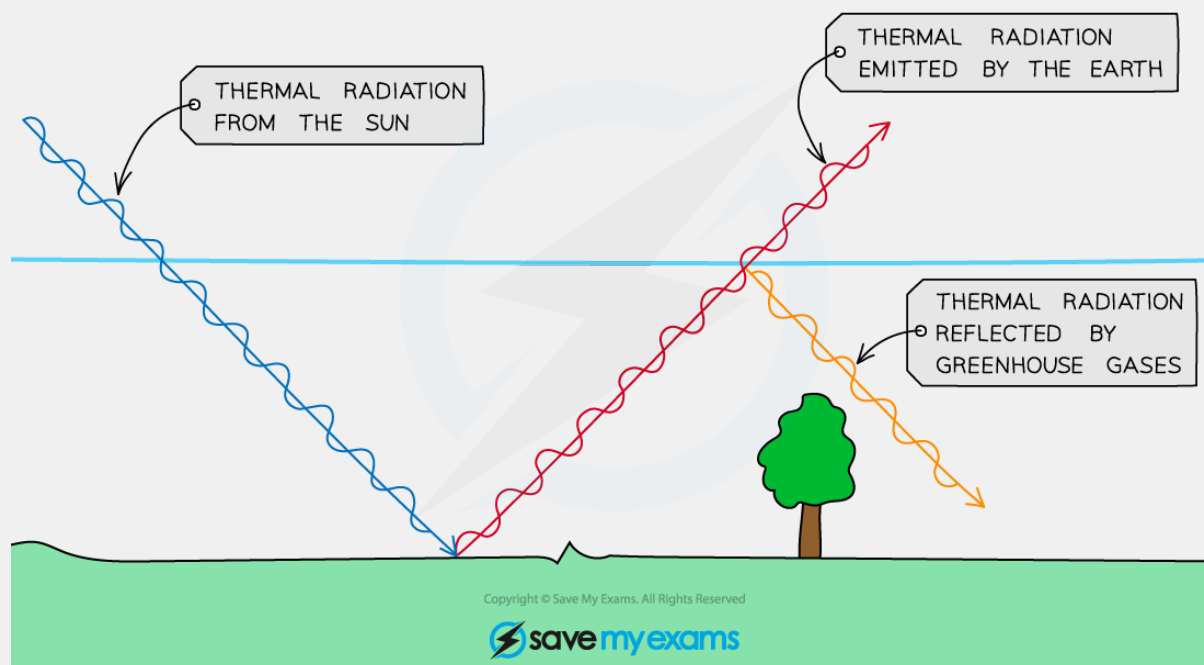
Temperature of Earth

- If the Earth had no atmosphere, the temperature on the surface would drop to about $-180\text{ }^{\circ}\text{C}$ at night, the same as the Moon's surface at night
 - This would happen because the surface would be emitting **all** the radiation from the Sun into space
- The temperature of the Earth is affected by factors controlling the balance between **incoming** radiation and radiation **emitted**
- The Earth receives the majority of its heat in the form of thermal radiation from the Sun
 - At the same time, the Earth **emits** its own thermal radiation, with a slightly longer wavelength than the thermal radiation it receives (this is caused by difference in surface temperature of the Earth and the Sun)

The greenhouse effect

- Some gases in the atmosphere, such as water vapour, methane, and carbon dioxide (greenhouse gases) absorb and reflect back longer-wavelength infrared radiation from the Earth and prevent it from escaping into space
 - These gases **absorb** the radiation and then **emit** it back to the **surface**
 - These gases keep the Earth's temperature at a reasonable level, and the process is called **the greenhouse effect**
- This process keeps the Earth warm

Radiation and the greenhouse effect



The Earth receives thermal radiation from the Sun but emits its own thermal radiation at the same time. The greenhouse effect is where this radiation is trapped by gases

- The temperature of the Earth, therefore, depends on several factors, such as the rate that infrared radiation is:
 - **Reflected** back into space
 - **Absorbed** by the Earth's atmosphere or by the Earth's surface
 - **Emitted** from the Earth's surface and from the Earth's atmosphere into space
- If there is an **excess of greenhouse gases** in the atmosphere, this causes more radiation to be **absorbed** by the Earth's atmosphere
- This increases the Earth's temperature above normal, causing **global warming**

Worked Example

Explain why adding an excess of carbon dioxide to the Earth's atmosphere would lead to an increase in the surface temperature of Earth.

Answer:

Step 1: Describe the greenhouse effect

- Radiation from the Sun is absorbed by the Earth
- Some is re-emitted by the Earth
- Greenhouse gases, such as carbon dioxide, reflect a fraction of this emitted radiation and heat the Earth's surface

Step 2: Describe the effect of increasing the amount of carbon dioxide

- If there is more carbon dioxide, more of the Earth's emitted radiation is reflected back to the Earth
- The rate of radiation absorbed by the Earth's surface increases, so its temperature increases

Examiner Tips and Tricks

Global warming is an important current topic in the world. Generally, it is important to understand how this process works, but this also means it appears in exams frequently. Learning more about this topic not only means that you are prepared for application questions on radiation, but it also means you are well-informed about the environmental issues we are facing as a society.

Investigating Thermal Radiation

Aims of the experiment

- The aim of the experiment is to investigate how the amount of infrared radiation absorbed or radiated by a surface depends on the nature of that surface

Variables

- **Independent variable** = Colour
- **Dependent variable** = Temperature
- Control variables:
 - Identical flasks (except for their colour)
 - Same amounts of hot water
 - Same starting temperature of the water
 - Same time interval

Equipment

Equipment List

Equipment	Purpose
Heatproof mat	To protect surfaces and reduce heat loss
Stop watch	To measure time taken for cooling
Kettle	To boil water
4 thermometers	To measure the water temperature in each flask
Flasks painted different colours (black, dull grey, white, silver)	To investigate the heat loss of different colours

- **Resolution** of measuring equipment:
 - Thermometer = 1°C
 - Stopwatch = 0.01 s

Method



Different coloured beakers for investigating infrared radiation apparatus

1. Set up the four identical flasks painted in different colours: black, grey, white and silver
2. Fill the flasks with hot water, ensuring the measurements start from the same initial temperature
3. Note the starting temperature, then measure the temperatures at regular intervals, e.g. every 30 seconds for 10 minutes

Results

Example results table

TIME / mins	BLACK / °C	WHITE / °C	DULL GREY / °C	SILVER / °C
0.5				
1.0				
1.5				
2.0				
2.5				
3.0				
3.5				
4.0				
4.5				
5.0				
5.5				
6.0				
6.5				
7.0				

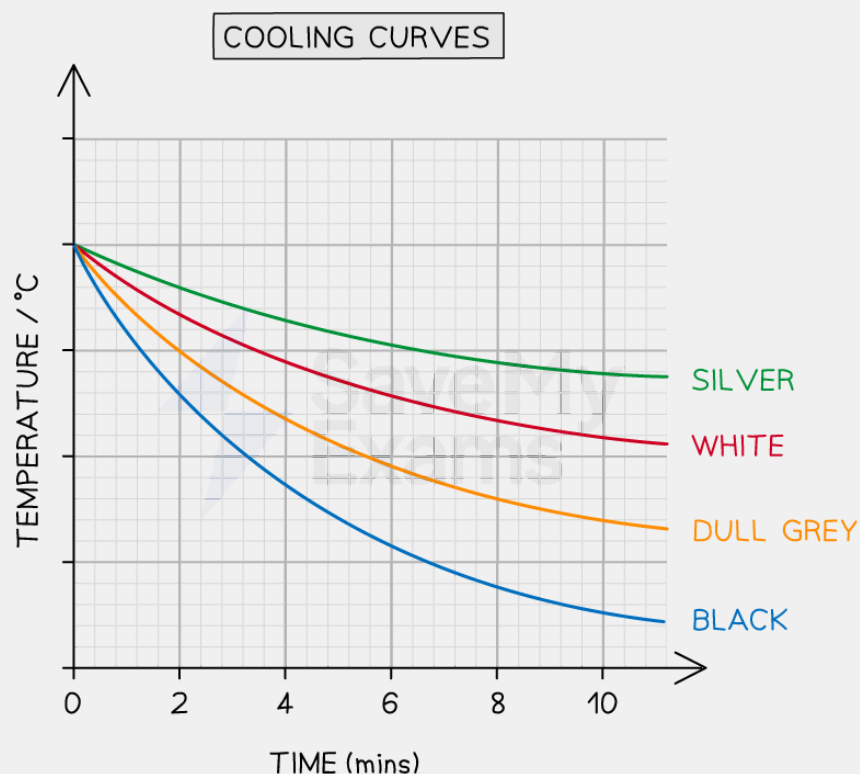
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Analysis of results

- All objects emit **infrared radiation**, but the hotter an object is, the more infrared waves are emitted
- The intensity (and wavelength) of the emitted radiation depends on:
 - The **temperature** of the body (hotter objects emit more thermal radiation)
 - The **surface area** of the body (a larger surface area allows more radiation to be emitted)
 - The **colour** of the surface
- Most of the energy lost from the beakers will be **by heating** due to **conduction** and **convection**
 - This will be **equal** for each beaker, as colour does not affect energy transferred by conduction and convection

- Any **difference** in energy transferred away from each beaker must, therefore, be due to infrared **radiation**

- To compare the rate of energy transfer away from each flask, plot a graph of **temperature** on the y-axis against **time** on the x-axis and draw curves of best fit
- The expected results are shown on the graph below:



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Example graph of the expected results for the different coloured beakers

Evaluating the experiments

Systematic errors

- Make sure the starting temperature of the water is the same for each material since this will cool very quickly
- It is best to do this experiment in pairs to coordinate starting the stopwatch and immersing the thermometer
- Use a data logger connected to a digital thermometer to get more accurate readings

Random errors

- Make sure the hole for the thermometer isn't too big, otherwise thermal energy will escape through the hole
- Take repeated readings for each coloured flask
- Read the values on the thermometer at eye level, to avoid parallax error

Safety considerations

- Safety goggles should be worn when filling the flasks with boiling water
- Keep water away from all electrical equipment
- Make sure not to touch the hot water directly
 - Run any burns immediately under cold running water for at least 5 minutes
- Do not overfill the kettle
- Make sure all the equipment is in the middle of the desk, and not at the end to avoid knocking over the beakers
- Carry out the experiments only whilst standing, in order to react quickly to any spills or burns

Consequences of Thermal Energy Transfer

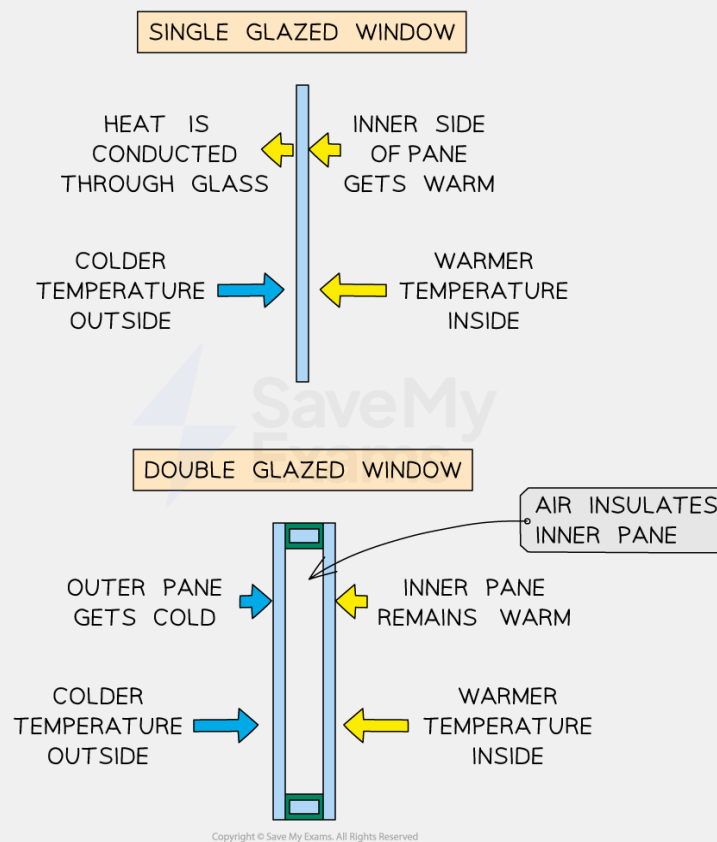
Simple consequences of energy transfer

- Conduction, convection and radiation have many everyday applications and consequences

Examples of conduction

- Good conductors help transfer thermal energy **quickly**
- Examples include:
 - Metal pans to heat food quickly
 - Metal radiators to transfer heat from water inside to the surrounding air quickly
- Bad conductors (insulators) help retain thermal energy as they transfer heat **slowly**
- Examples include:
 - Plastic handles of saucepans to slow thermal energy transferred to hands
 - Air spaces in the walls or windows of some houses help to retain heat, as air is a poor conductor

Double-glazed windows



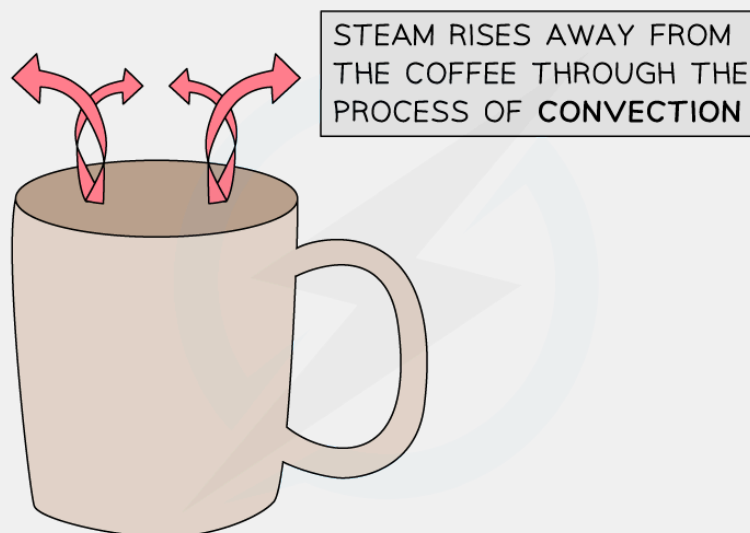
Double-glazed windows use a layer of air to act as an insulator and slow the transfer of thermal energy out of the house

Examples of convection

- Common applications of convection are:
 - heating a room with a radiator
 - steam rising which cools a hot liquid
- Radiators use convection to raise the temperature of a room in a building:
 1. The metal radiator is hot and transfers thermal energy to air nearby
 2. The particles of this hot air spread out, making it less dense
 3. The spread-out air is less dense than the air above it, so this hot air rises
 4. The radiator heats the cold air which replaces the hot air

5. The newly heated air also rises, cools and sinks (as it contracts and increases in density)

Convection in steam from coffee



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Thermal energy is transferred from the hot coffee to the air by convection currents rising from the surface

Examiner Tips and Tricks

Don't let the name 'radiator' confuse you, these should really be called 'convection heaters'. Their heating ability comes almost exclusively through convection, radiation plays a very small part.

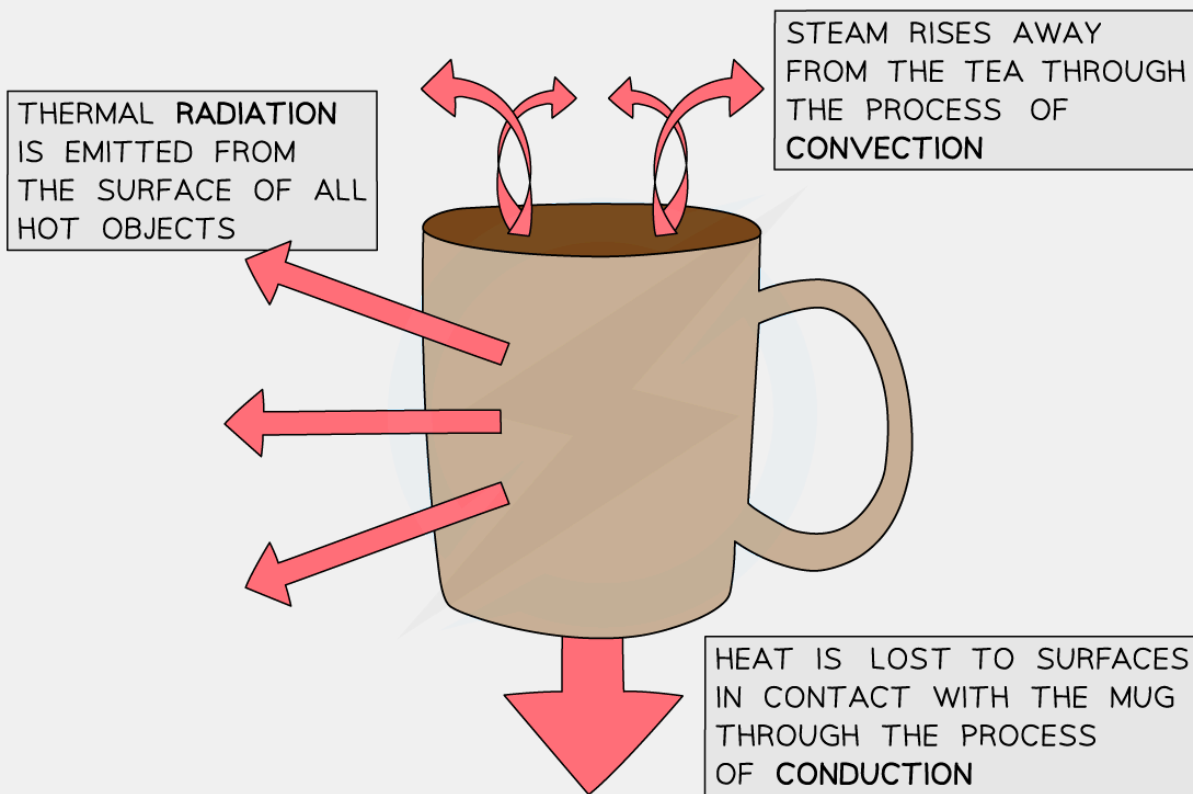
Complex consequences of energy transfer

Multiple paths of energy transfer

- In real situations there is very rarely only one form of energy transfer
 - Usually two or three happen at once
 - These are sometimes called 'complex' applications of energy transfer

Tea cup example

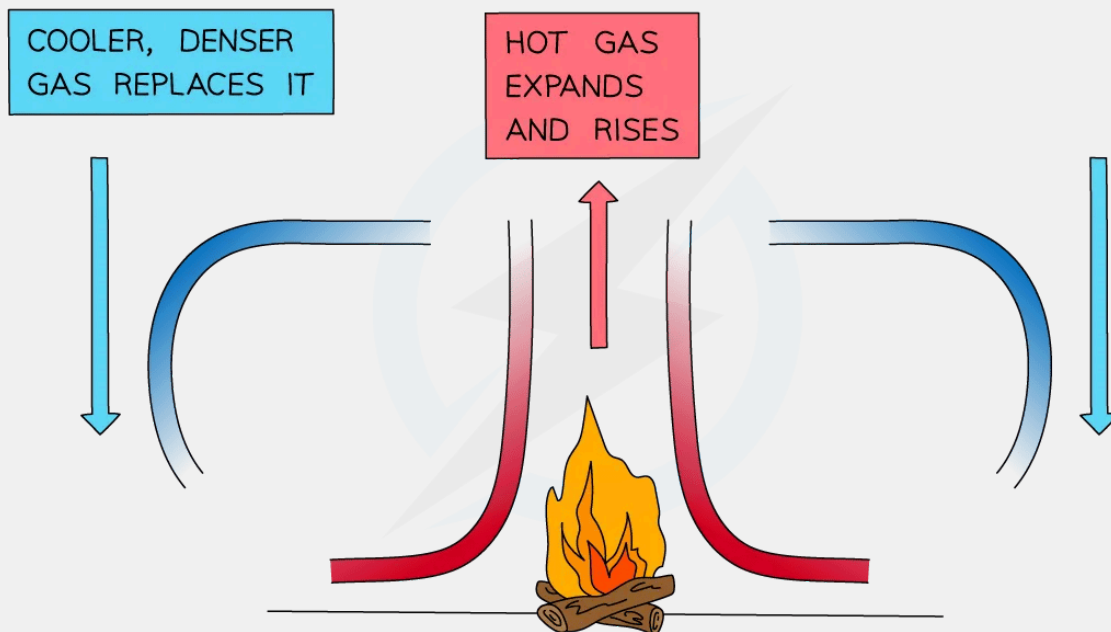
- In the diagram below a more complex - and more 'real' - version of the situation above is shown
- Thermal energy is transferred **from hotter areas (the tea) to cooler areas (the cup, hands and air)** by the processes of:
 - **Conduction**; by **direct contact** between the tea and the **solid** sides of the cup and also by direct contact from the cup to the surface it is sitting on
 - **Convection**; from the **surface** of the coffee to the air **directly above** it
 - **Radiation**; from the sides of the **hot cup** in **all directions** to the surrounding air



In this example, heat is lost via conduction, convection and radiation

Wood fire example

- A wood (or coal) fire in a room heats it through **radiation** and **convection**
- As the fuel is so hot in a wood fire, it transfers a lot of thermal energy to the room through radiation
 - The fire transfers a much greater amount of thermal energy to **nearby** objects via radiation
- Air surrounding the fire is heated and rises, forming a convection current
 - This transfers thermal energy throughout the whole room



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Convection currents are set up in a room with a wood or coal fire

Car radiator example

- A car radiator transfers heat away from the engine, which reaches high temperatures
- A liquid travels between the radiator and the engine
 - When the liquid passes over the engine, it absorbs energy from the engine through **conduction**
 - This liquid then travels back to the radiator and transfers heat to the radiator, again by **conduction**
 - The radiator then transfers thermal energy to the surrounding air through **radiation**
- A car radiator is a dark colour, which allows it to emit more radiation
 - A large surface area also helps

- Once the radiator has absorbed thermal energy from the liquid, the liquid is cooler and the cycle begins again

Examiner Tips and Tricks

The specification requires you to have knowledge of energy transfers in:

- A wood or coal fire
- A car radiator

Familiarise yourself with how these systems work and their main forms of energy transfer.