Revision Guide for Chapter 4

Contents

Student's Checklist

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I can show my understanding of effects, ideas and relationships by describing and explaining:

how the optical, electrical and mechanical properties of materials are linked to how they are used Revision Notes: Materials: properties and uses; Materials selection charts	
what refraction is Revision Notes: Refraction Summary Diagrams: Refraction: ray and wave points of view	
what total internal reflection is, and why it occurs Revision Notes: Total internal reflection	
the differences between metals, semiconductors and insulators Revision Notes: Conductors and insulators; Semiconductors	

I can use the following words and phrases accurately when describing the properties of materials:

Mechanical properties: stiff, elastic, plastic, ductile, hard, brittle, tough stress, strain, Young modulus, fracture stress, yield stress Revision Notes: Mechanical characteristics of materials; Stress and strain; Stretching and breaking Summary Diagrams: The Young modulus	
Optical properties: refraction, refractive index, total internal reflection, critical angle Revision Notes: Refraction; Total internal reflection Summary Diagrams: Refraction: ray and wave points of view	
Electrical properties: resistivity, conductivity Revision Notes: Electrical conductivity and resistivity Summary Diagrams: Conductivity and resistivity	

I can sketch and interpret:

stress–strain graphs to identify the quantities *yield stress, fracture stress, Young modulus*, and relate them to how materials are used Revision Notes: Stretching and breaking Summary Diagrams: Stress-strain graph	
tables and diagrams comparing materials by properties and relating them to how materials are used, e.g. *strength–density* and *stiffness–density* diagrams Revision Notes: Materials selection charts	
plots on a logarithmic scale of quantities such as resistivity and conductivity Summary Diagrams: Values of conductivity	

I can calculate:

the refractive index of a material using the equation $\frac{\sin i}{\sin r} = n$ and rearrange the equation to calculate the other quantities Revision Notes: Refraction	
the resistance of a conductor using the equation $R = \frac{\rho l}{A}$ and rearrange the equation to calculate the other quantities Revision Notes: Electrical conductivity and resistivity Summary Diagrams: Conductivity and resistivity	
the conductance of a conductor using the equations $G = \frac{1}{R}$ and $G = \frac{\sigma A}{l}$ and rearrange the equations to calculate the other quantities Revision Notes: Electrical conductivity and resistivity Summary Diagrams: Conductivity and resistivity	
tensile stress using the relationship *stress = force / area* tensile strain using the relationship strain = extension (or compression) / original length the Young modulus *E* using the relationship *E = stress / strain* Revision Notes: Stress and strain; Stretching and breaking Summary Diagrams: The Young modulus;	

I can show understanding of and their applications by giving and explaining my own examples of:

how the properties of a material determine how it is used Revision Notes: Mechanical characteristics of materials; Materials selection charts	

Revision Notes

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Materials: properties and uses

Here are some examples of how the properties of materials help to decide the choice of material for various uses.

An **aeroplane wing** must not bend much under load, so must be made of a **stiff** material. The wing must not break suddenly, so the material must be **tough**, not **brittle**. The wing must be light, so the material must not be **dense**. If the wing surface has to be pressed into shape the material must be **malleable**. The commonest choice of material for the wings of commercial aircraft is an aluminium alloy, though for certain parts (e.g. the rudder) carbon-fibre reinforced plastic has been used. **Cost**: civil aircraft normally use cheaper materials than do military aircraft.

The material for **spectacle lenses** must be **transparent**, and have a high **refractive index** so that the lenses need not be too thick and thus heavy. The surface should be **hard**, so as not to scratch easily. The material needs to be **stiff**, so that the lenses do not deform, and **strong** so that they do not break if dropped. The material chosen used to be glass, but increasingly transparent plastic materials are used. It is generally the case that the materials available are **brittle**, so that spectacle lenses do shatter if they break. The cost of shaping the lenses is much greater than the cost of the raw material.

Long distance **electricity cables** for the National Grid must be very **good conductors** of electricity. They must be **strong**, and not too **dense**, since the cables have to support their own weight in between pylons. The material must be **tough** so that the cables will not suddenly fracture. **Cost** is important because the cables use a lot of material. A common choice is an aluminium core, for lightness and high conductivity, with a steel wire sheath for strength, toughness and cheapness.

The outer sleeve of a **cartridge fuse** in a domestic electrical power plug must clearly be a very good **electrical insulator**. It must not melt or char when the fuse inside 'blows', so the material needs a high melting point and to be chemically stable. A **ceramic** material is often chosen. Millions are made and sold, so **cost** matters. Such ceramic materials are usually **stiff** and **strong**, making them equally suitable for the insulators of electricity cables, where they must support the weight of the cables.

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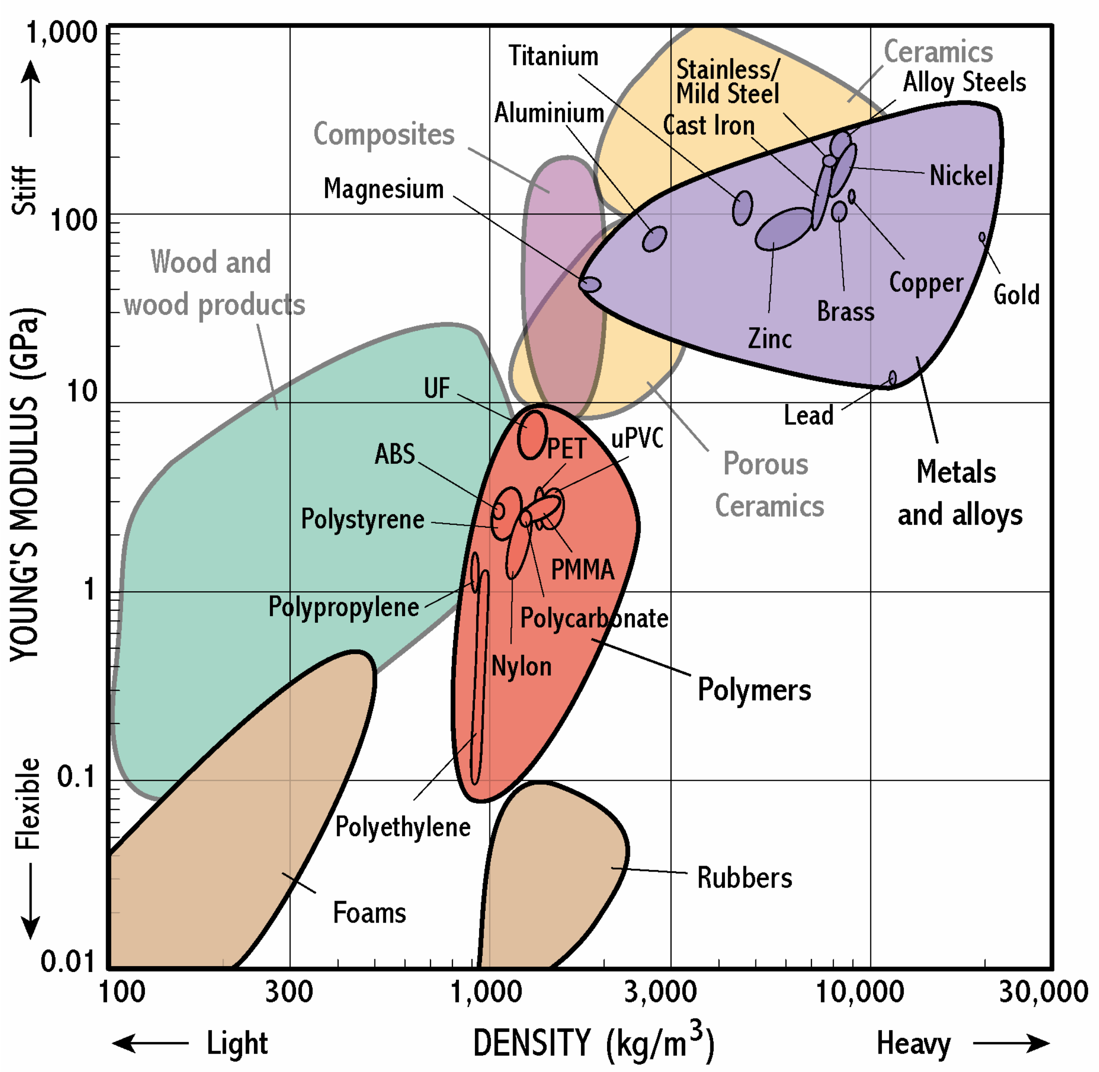
Materials selection charts

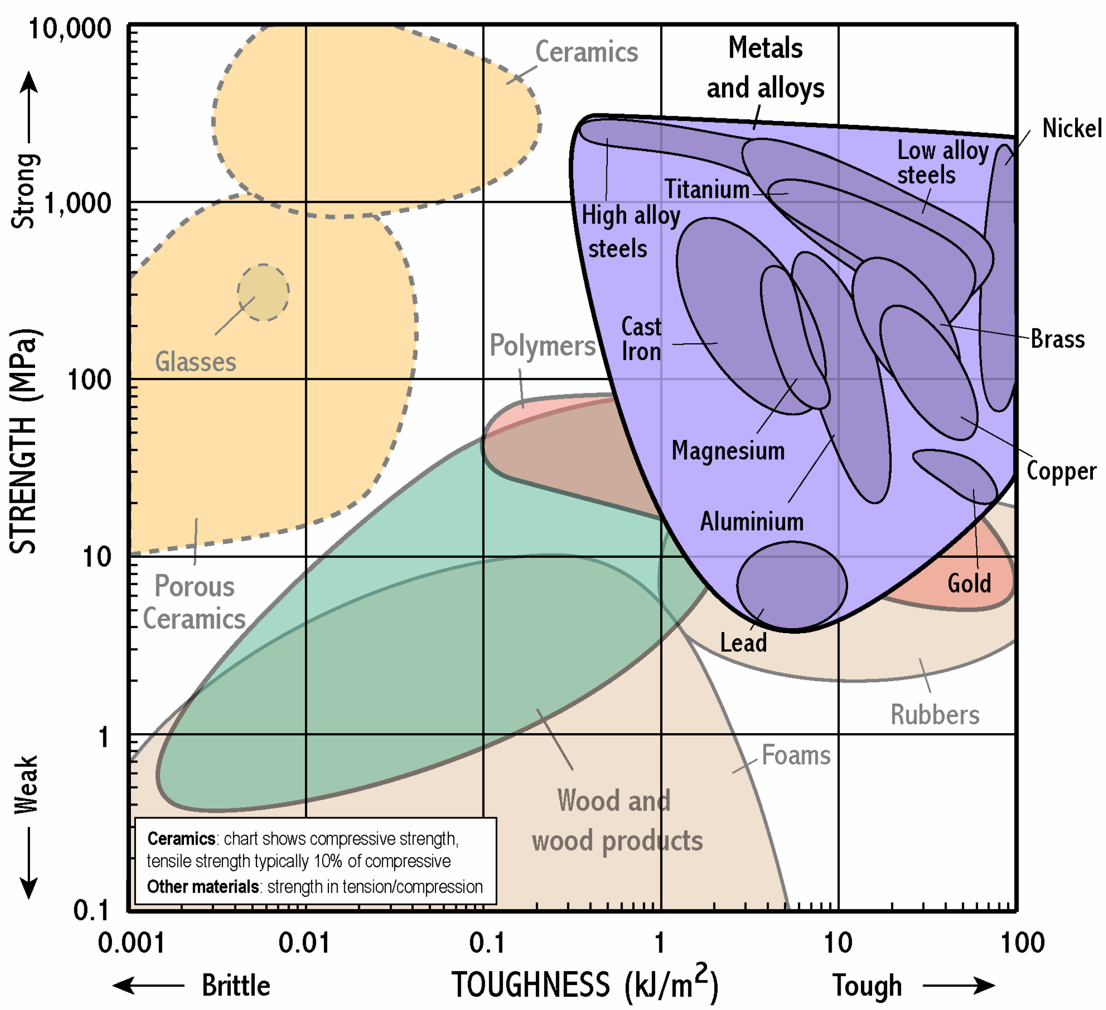
Materials selection charts are a graphical way of presenting data about properties of materials. Most mechanical properties extend over several orders of magnitude, so logarithmic scales are used. A 2D plot of a pair of properties is used. Below is Young modulus plotted against density. From this chart you can see:

- the range of values typical of materials in a given class (metals, ceramics, polymers etc)
- the values of Young modulus and density for different particular materials.

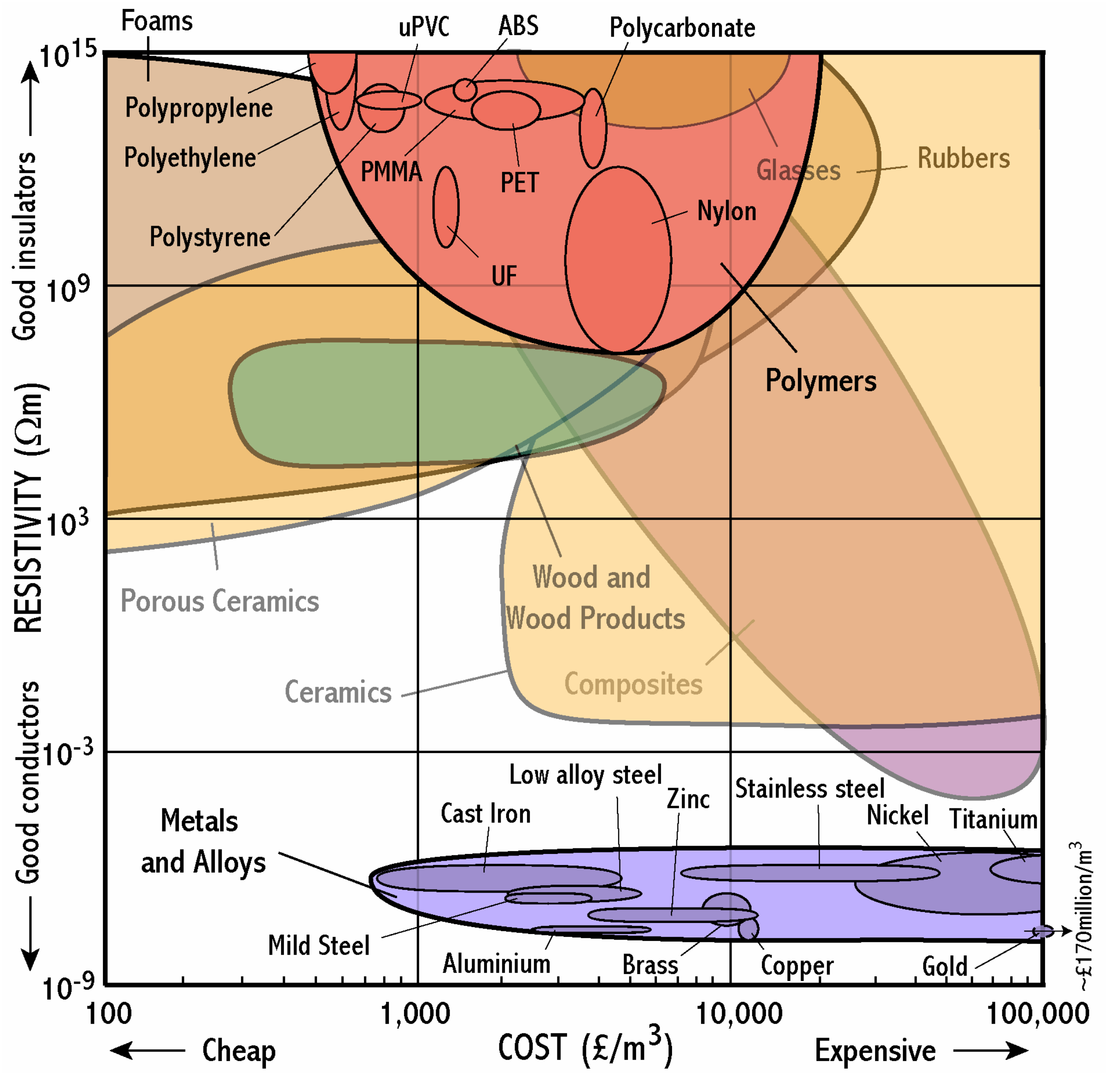


Designers have a challenging task in choosing materials for products, as they usually have to consider many competing objectives and constraints at once – light and stiff, strong and cheap, tough and recyclable (or maybe all of these at once!). Materials selection in design is therefore a matter of assessing trade-offs between several competing requirements.

For example – what materials might be used for a light, stiff bike frame? Notice that most of the metals are stiff, but rather heavy. Strength and toughness also matter. Look at the strength–toughness chart below, with a selection of metals illustrated. Note that in general the toughness of a type of alloy falls as its strength is increased.



Electrical Properties
The next chart shows electrical resistivity plotted against cost per cubic metre of material. In engineering design, cost is almost always important, so selection charts often show this on one axis.



This chart shows that metals have much lower resistivity than almost all other materials. Polymers and ceramics fall at the top of the chart, being insulators. The range of values of resistivity is huge – the diagram covers 24 orders of magnitude. Gold is an excellent conductor, but it is so expensive that it is even off the scale of the chart. Despite this, it is used for electrical contacts in microcircuits.

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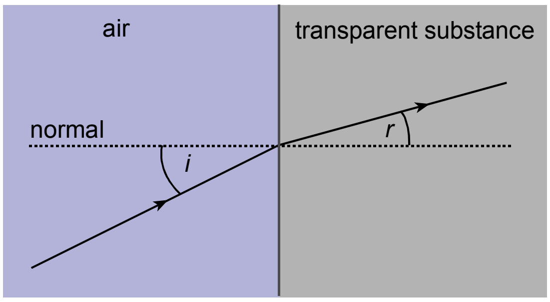
Refraction

Refraction is the bending of light caused by a change in its speed as light passes from one region to another. If the wave slows down on crossing the boundary, the direction of travel of the wavefront becomes nearer to the normal to the boundary (unless the wave is travelling along the normal). If the wave speeds up on crossing the boundary, either the direction of travel of the wavefront becomes further from the normal or total internal reflection occurs.

Refraction occurs with any kind of wave. For example, waves from the sea may travel more slowly as they enter shallow water near a beach.

For light, the **refractive index** $n = c_0 / c$, where c_0 is the wave speed in a vacuum and c is the wave speed in the substance. Refractive index is a pure ratio and has no units. The speed of light in a vacuum is greater than the speed of light in any transparent substance so the refractive index is greater than 1.

Refraction of light



$\frac{\sin i}{\sin r}$ = refractive index of substance

Snell's law of refraction states that sin i / sin r = constant, where i is the angle between the incident direction and the normal, and r is the angle between the refracted direction and the normal. The constant is equal to the ratio of the incident wave speed c_i to the wave speed c_r in the refracting medium. It is called the refractive index.

Relationships

$$n = \frac{\text{speed of light in air}}{\text{speed of light in the substance}}$$

$$n = \frac{\sin i}{\sin r}$$

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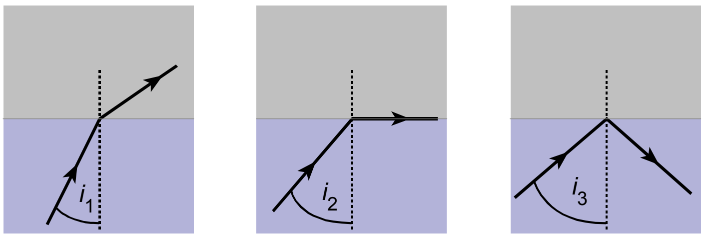
Total internal reflection

Total internal reflection is when a wave is reflected totally at a boundary between two substances.

Total internal reflection can occur if the speed of the incident wave in the first medium is less than the speed of the refracted wave in the second medium.

Total internal reflection



$i_1 < C$ $i_2 = C$ $i_3 > C$

where C = critical angle

If the angle of incidence is less than the **critical angle** C, the wave is refracted away from the normal. If the angle of incidence exceeds C, the wave is totally internally reflected. The critical angle is the angle of incidence for which the angle of refraction is 90º.

Applications of total internal reflection include thick optical fibres used in medicine. Total internal reflection of light occurs in the optical fibre every time a light ray inside the fibre reaches the boundary, provided the fibre is not bent too much.

Relationships
In general, Snell's law may be written:

$$n_i \sin i = n_r \sin r$$

Thus if $i = C$ and $r = 90°$ then since sin 90º = 1

$$\sin C = \frac{n_r}{n_i} \text{ or } \sin C = \frac{c_i}{c_r},$$

where c_i is the speed of the incident wave in the first medium and c_r is the speed of the refracted wave in the second medium.
For light passing into air from a refractive medium of refractive index n, the equation for the critical angle is simply:

$$\sin C = \frac{1}{n}$$

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Conductors and insulators

A **conductor** is any object that easily allows an electric current through it when it is in a circuit.

Materials can be grouped into conductors or insulators, or in-between as semiconductors, as indicated in the table below:

Classification	Conductivity / S m^{-1}	Resistivity / Ω m	Carrier density / m^3	Example
Conductor	About 10^6 or more	About 10^{-6} or less	About 10^{25} or more	Any metal, graphite
Insulator	About 10^{-6} or less	About 10^6 or more	Less than 10^{10}	Polythene
Semiconductor at room temperature	About 10^3	About 10^{-3}	About 10^{20}	Silicon, germanium

Metals are generally very good conductors.

An **electrical insulator** is a very poor conductor of electricity.

The resistivity of an insulator is of the order of a million million times greater than that of a metal. Insulators such as polythene and nylon are used to insulate wires and metal terminals in electrical fittings and appliances.

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Semiconductors

Semiconductors are used to make a wide range of electronic devices including electronic chips, light-emitting diodes and solid state lasers.

Semiconductors have conductivities in between the very high conductivity of metals and the very low conductivities of insulators. There are various types of semiconductor, including metal oxides as well as elements like silicon and germanium.

In insulators, essentially all the electrons are tightly bound to atoms or ions, and none are free to move under an external electric field. In effect, these materials do not conduct electricity at all. In metallic conductors, essentially all the atoms are ionised, providing free electrons which can move freely through the ions.

Semiconductors differ from both insulators and metallic conductors. Only a small proportion of atoms are ionised, so that conduction electrons are relatively few in number. Thus a semiconductor does conduct, but not well. The conductivity is increased and controlled by ‘doping’ with traces of other elements.

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Mechanical characteristics of materials

The mechanical characteristics of a material have to do with its behaviour when subjected to forces which try to stretch, compress, bend or twist it.

The mechanical characteristics of a material include its stiffness, its strength, its flexibility or brittleness and its toughness. Other characteristics include its density, whether or not it is elastic or plastic and whether or not it is ductile and malleable.

A material is:

dense if it has a large mass per unit volume. Solid materials vary in density mainly because elements have different atomic masses. Lead is much more dense than aluminium, mainly because lead atoms are much heavier than aluminium atoms.

stiff if it is difficult to stretch or bend the material (e.g. a metal sheet is stiffer than a polythene sheet of the same dimensions). The stiffness is indicated by the Young modulus.

hard if it is difficult to dent the surface of the material (e.g. a steel knife is much harder than a plastic knife). Hardness is tested by machines that indent the surface. Many ceramics are very hard.

brittle if it breaks by snapping cleanly. The brittleness of glass is a consequence of defects such as fine surface cracks, which propagate easily through the material.

tough if the material does not break by snapping cleanly. A tough material is resistant to the propagation of cracks. Toughness is the opposite of brittleness. Metals are tough, and break by plastic flow. There is no one simple measure of toughness, but a tough material will dissipate a large amount of energy per unit area of new fracture surface.

elastic if it regains its shape after stretching (e.g. a rubber band regains its original length when released). When a metal or ceramic stretches elastically, the bonds between neighbouring atoms extend very slightly. In a polymer the atoms rotate about their bonds.

plastic if it undergoes large permanent stretching or distortion before it breaks (e.g. a polythene strip stretches permanently if pulled).

ductile if it is easy to draw a material into a wire (e.g. copper is easier to draw into a wire than tungsten). Metals are ductile because the non-directional metallic bonds allow ions to slide past one another.

malleable if it is easy it is to hammer or press a sheet of material into a required shape (e.g. a lead sheet is easier to fit on a roof than a steel sheet).

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Stress and strain

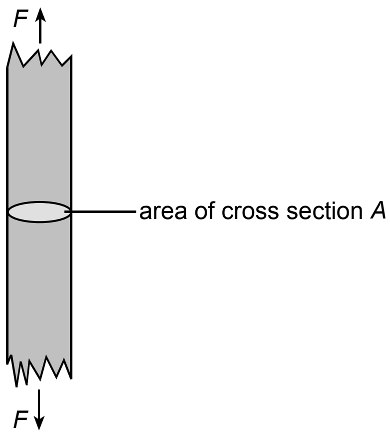
Tensile stress and compressive stress are the force per unit area acting at right angles to a surface.

Tensile strain is the change of length per unit length. Strain is a ratio of two lengths and therefore has no unit.

The SI unit of stress is the pascal (Pa), equal to 1 N m^{-2}.

If the solid is a bar of uniform cross-sectional area made from a single material, the stress at any point is the same, equal to the applied force divided by the area of cross section. If the cross section of the solid is non-uniform, the stress is greatest where the area of cross section is least.

Stress



tensile stress = $\frac{F}{A}$

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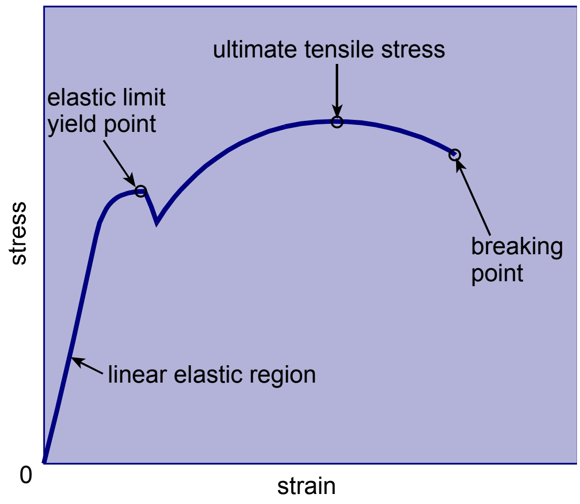
Stretching and breaking

The (engineering) **breaking stress** of a material = F / A where F is the force needed to break the material by stretching it and A is the initial area of cross section of the material. The actual stress in the material at this point will usually be rather larger, since the area of cross section will be somewhat reduced.

The Young modulus E of a material = tensile stress / tensile strain provided the limit of elasticity of the material is not exceeded.

Stress-Strain



A graph of stress against strain for a metal has these features:

1. Strain is proportional to stress, up to a limit. This is the initial straight section of the graph. In this part of the graph, the ratio stress / strain is constant and equal to the **Young modulus** of the material. Here the material behaves **elastically**.
2. The **elastic limit** is the point beyond which a material does not regain its initial shape when the tension is removed. It is also called the **yield point**.
3. When a material is stretched beyond its elastic limit, and is stretched beyond the yield point, it behaves plastically, suffering permanent deformation. The **yield stress** is the stress at the yield point.
4. As the tension is increased beyond the yield point, the strain increases and a neck forms. Further stretching causes the stress to concentrate at the neck until it breaks. The (engineering) **breaking stress** is equal to F / A where F is the force needed to break the material by stretching it and A is the initial area of cross section of the material. The breaking stress is also called the **tensile strength** of the material.

The **fracture energy** required to break a material can be defined in several ways. One is the energy needed to create the extra fractured surface area.

Relationships

Consider a length l of material of uniform cross-sectional area A. When under tension T, the material extends to a length $l + e$, where e is the extension of the material.

1. The tensile stress in the material = F / A where F is the tension and A the area of cross section.

The SI unit of tensile stress is the pascal (Pa) which is equal to 1 N m^{-2}.

2. The strain in the material = e / l, where e is the extension and l the initial length.
3. The Young modulus of elasticity E of a material is equal to tensile stress / tensile strain

$$E = \frac{F/A}{e/l}$$

The SI unit of E is the pascal (Pa) which is equal to 1 N m^{-2}.

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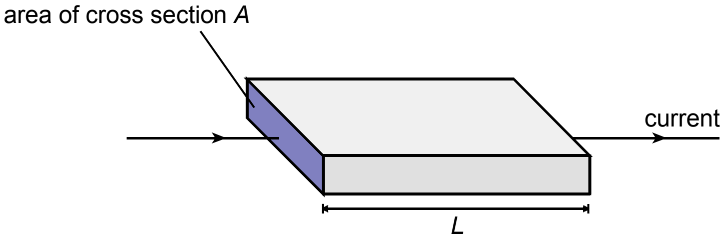
Electrical conductivity and resistivity

The conductivity measures how easily a material conducts electricity.

Conductivity



conductivity $\sigma = \frac{GL}{A}$

where G = conductance

For a conductor of uniform cross-sectional area A and length l, the conductance G is:

$$G = \frac{\sigma A}{l}$$

The **conductivity** σ of the material can be calculated from the measured conductance G using:

$$\sigma = \frac{Gl}{A}.$$

The SI unit of conductivity is the siemens per metre (S m^{-1}). The siemens is the same as the reciprocal of the ohm (i.e. Ω^{-1}).

The conductivity of a material depends on the number of charge carriers per unit volume in the material and also on how free those charge carriers are to move.

The **resistivity** ρ can be calculated from the resistance of a sample, and the length and cross-sectional area of the sample using:

$$\rho = \frac{RA}{l}.$$

The SI unit of resistivity is the ohm metre (Ω m). Conductivity and resistivity are each the reciprocal of the other:

Summary of relationships

$$\sigma = \frac{Gl}{A}. \qquad \rho = \frac{RA}{l}.$$

$$\sigma = \frac{1}{\rho} \qquad \rho = \frac{1}{\sigma}$$

$$G = \frac{\sigma A}{l} \qquad R = \frac{\rho l}{A}.$$

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Summary Diagrams (OHTs)

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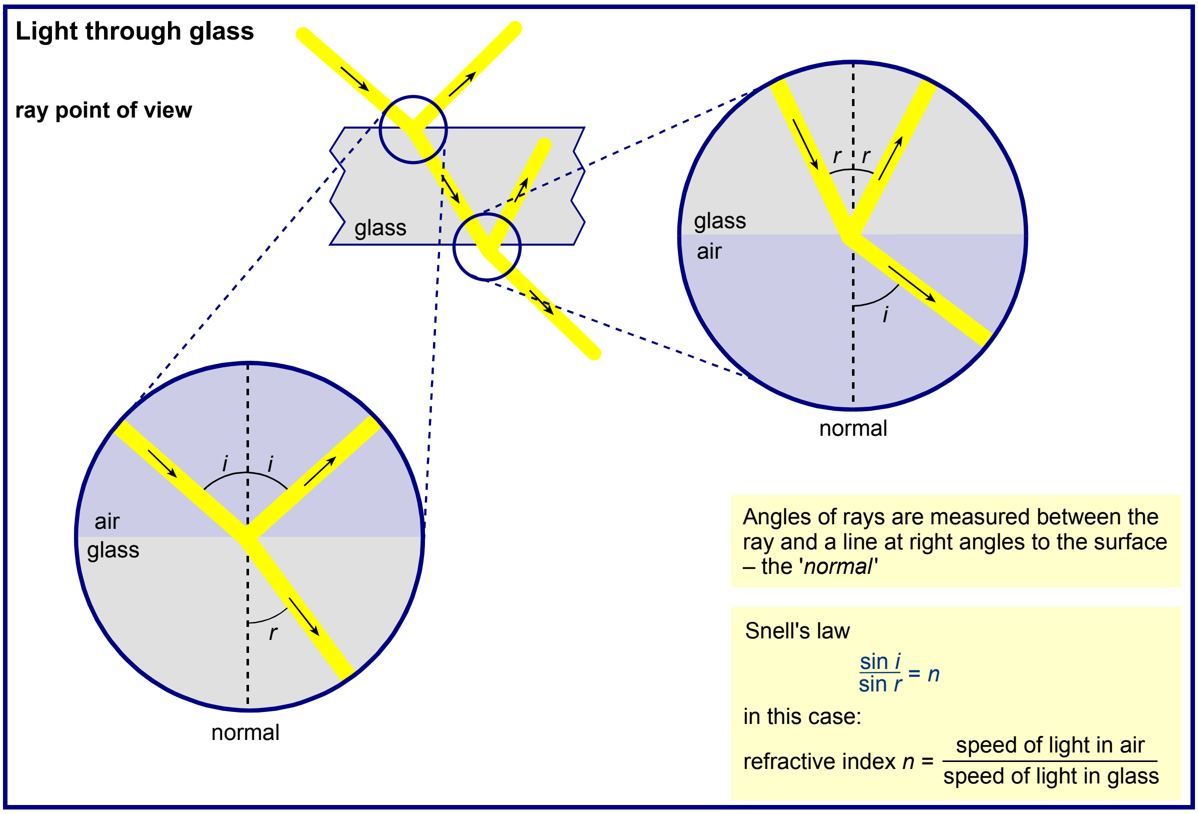
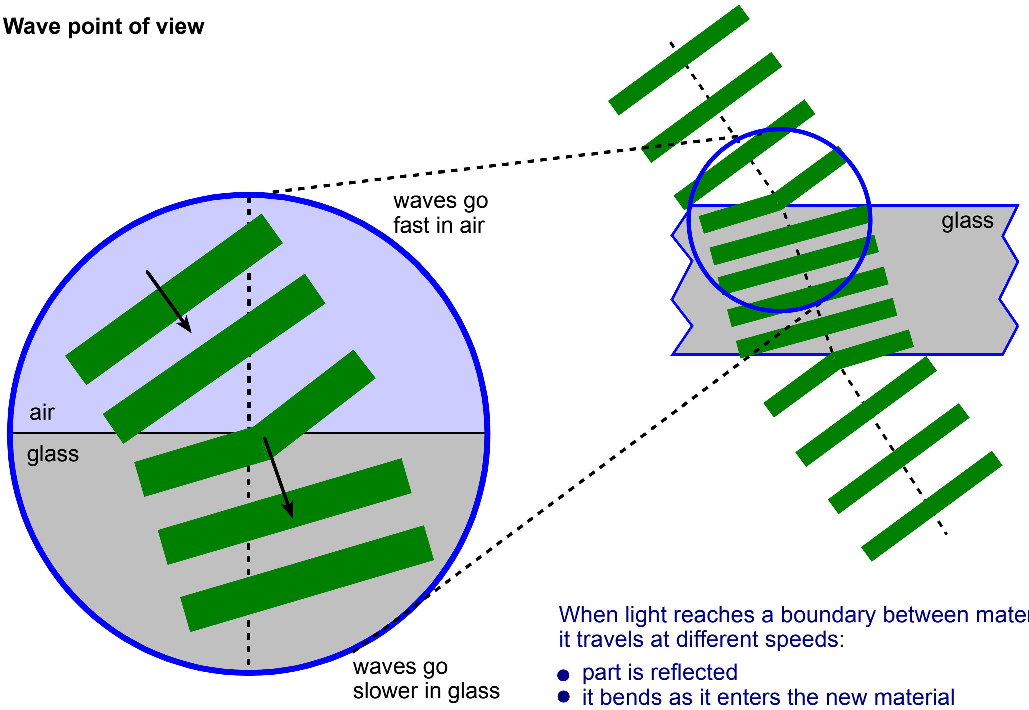
Refraction: ray and wave points of view

These diagrams show refraction from the ray point of view and from the wave point of view.



Light through glass

Wave point of view



When light reaches a boundary between materials in which it travels at different speeds:

- part is reflected
- it bends as it enters the new material

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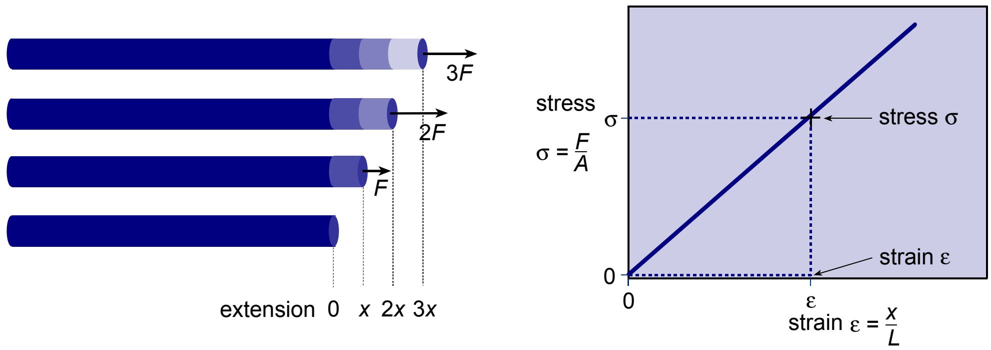
The Young modulus

The Young modulus tells you how a material behaves under stress.

The Young modulus 1

Many materials stretch in a uniform way. Increase the stretching force in equal steps, and the extension increases in equal steps too, in proportion. That is, the strain is proportional to the stress producing it. This is the same as Hooke's law – the stretching of a spring is proportional to the stretching force you apply.



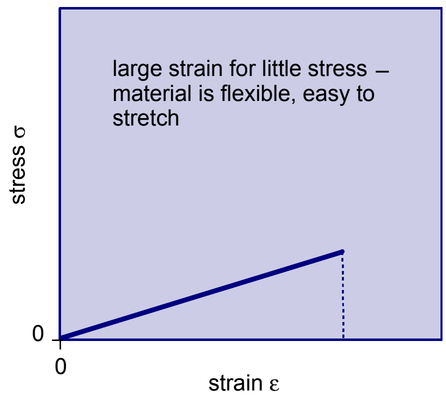
strain ∝ stress .... graph is straight line

ratio $\frac{\text{stress}}{\text{strain}}$ is constant

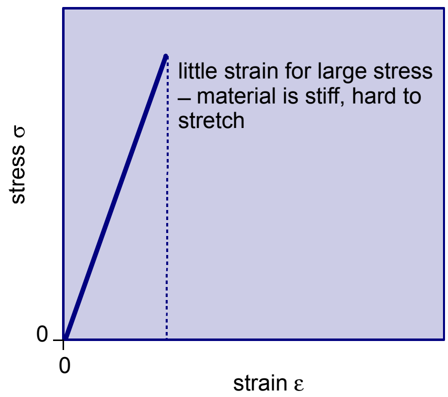
Young modulus = $\frac{\text{stress}}{\text{strain}}$

$E = \frac{\sigma}{\varepsilon}$

The Young modulus 2



e.g. polymer



e.g. diamond, steel

The Young modulus is *large* for a stiff material (large stress, small strain). Graph is steep.

The Young modulus is a property of the material not the specimen. Units of the Young modulus MN m^{-2} or MPa; for stiff materials GN m^{-2} or GPa. Same as units of stress, because strain is a ratio of two lengths, e.g. extension is 1% of length

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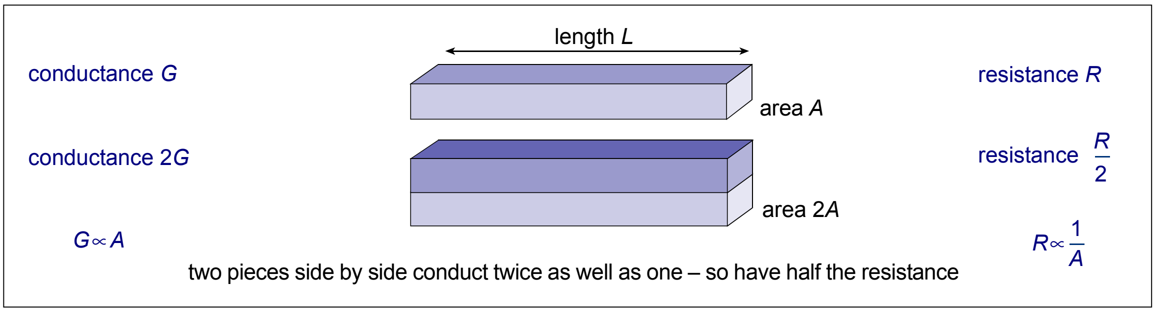
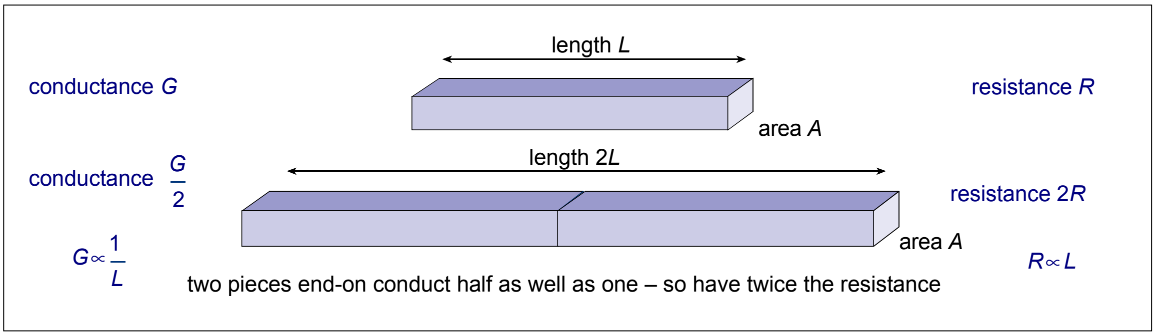
Conductivity and resistivity

These diagrams show the relationships between conductance and resistance for samples of different sizes, and how to calculate them from the conductivity or resistivity.

Conductivity and resistivity 1





Conductivity and resistivity 2

	Need to know	
to work out conductance G conductivity σ	length L cross sectional area A	to work out resistance R resistivity ρ
$G = \frac{\sigma A}{L}$ unit siemens S	$G = \frac{1}{R}$ $R = \frac{1}{G}$	$R = \frac{\rho L}{A}$ unit ohm Ω
$\sigma = \frac{GL}{A}$ unit S m^{-1}	$\sigma = \frac{1}{\rho}$ $\rho = \frac{1}{\sigma}$	$\rho = \frac{RA}{L}$ unit Ω m

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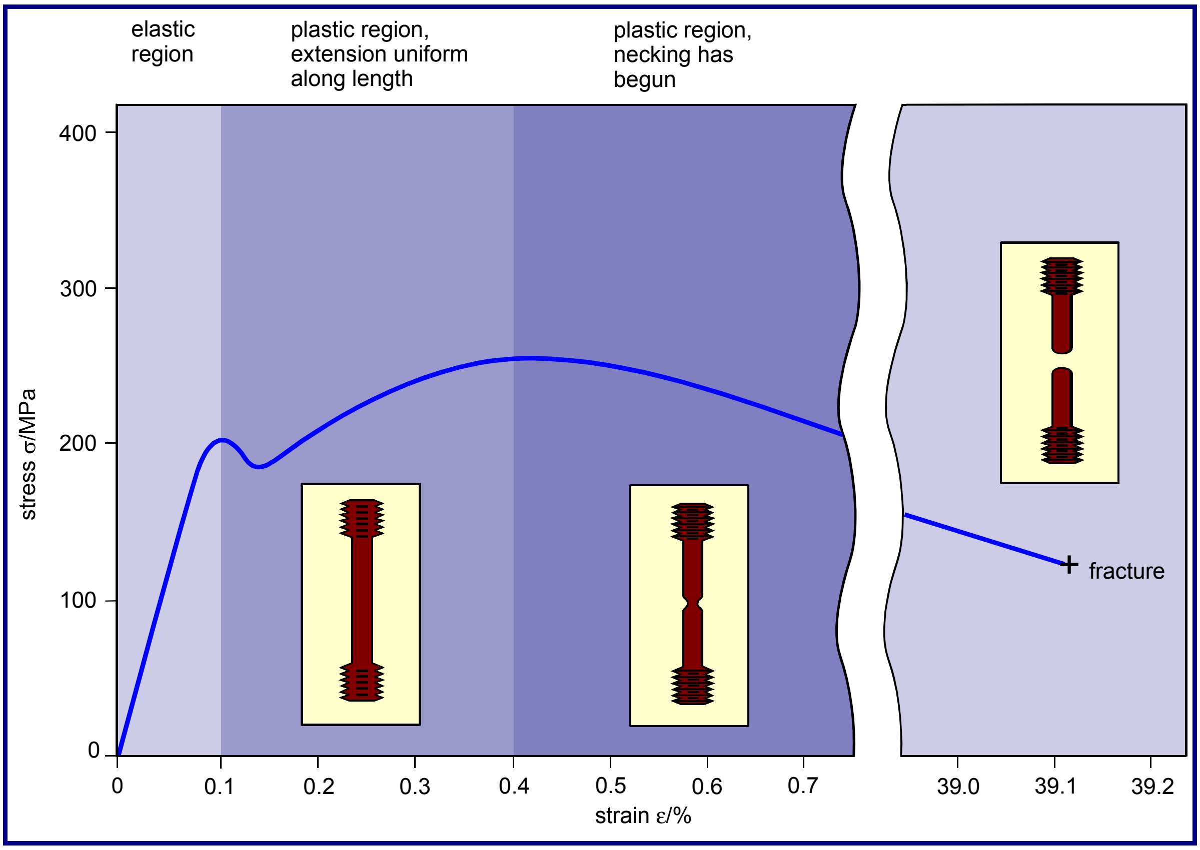
Stress–strain graph for mild steel

The graph shows how the behaviour of mild steel changes as the stress increases.



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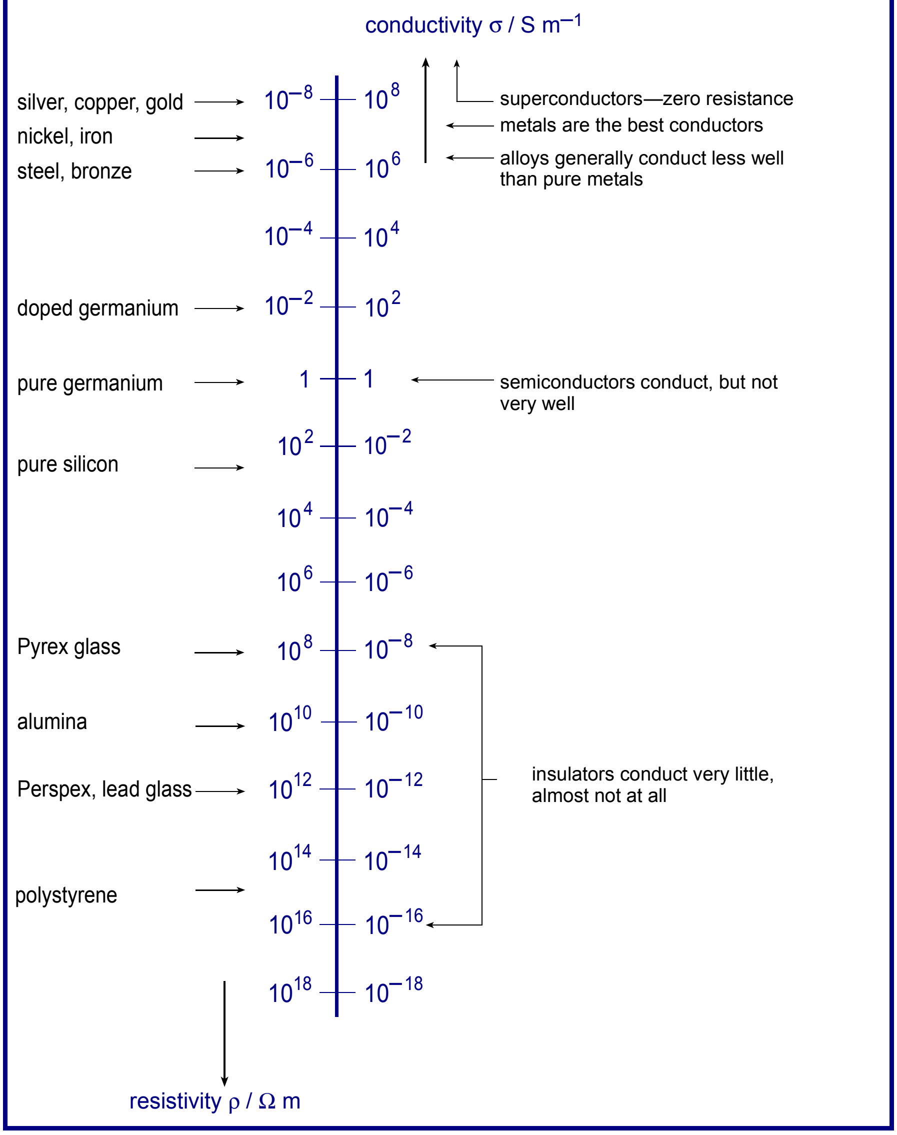
Range of values of conductivity

The conductivity of the best conductor shown below (silver) is 10^{24} times greater than the conductivity of the best insulator (polystyrene).

Logarithmic scale of resistivity and conductivity



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