Interfacial thermal resistance

**Interfacial thermal resistance**, also known as **thermal boundary resistance**, or **Kapitza resistance**, is a measure of an interface's resistance to thermal flow. This thermal resistance differs from [contact resistance](https://wikivisually.com/wiki/Thermal_contact_conductance) (not to be confused with [electrical contact resistance](https://wikivisually.com/wiki/Contact_resistance)), as it exists even at atomically perfect interfaces. Due to the differences in electronic and vibrational properties in different materials, when an energy carrier (phonon or electron, depending on the material) attempts to traverse the interface, it will scatter at the interface. The probability of transmission after scattering will depend on the available energy states on side 1 and side 2 of the interface.

Assuming a constant thermal flux is applied across an interface, this interfacial thermal resistance will lead to a finite temperature discontinuity at the interface. From an extension of Fourier's law, we can write

where  is the applied flux,  is the observed temperature drop,  is the thermal boundary resistance, and  is its inverse, or thermal boundary conductance.

Understanding the thermal resistance at the interface between two materials is of primary significance in the study of its thermal properties. Interfaces often contribute significantly to the observed properties of the materials. This is even more critical for [nanoscale](https://wikivisually.com/wiki/Nanoscopic_scale) systems where interfaces could significantly affect the properties relative to bulk materials.

Low thermal resistance at interfaces is technologically important for applications where very high heat dissipation is necessary. This is of particular concern to the development of microelectronic semiconductor devices as defined by the International Technology Roadmap for Semiconductors in 2004 where an 8 nm feature size device is projected to generate up to 100000 W/cm2 and would need efficient heat dissipation of an anticipated die level heat flux of 1000 W/cm2 which is an order of magnitude higher than current devices.[[1]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-1) On the other hand, applications requiring good thermal isolation such as jet engine turbines would benefit from interfaces with high thermal resistance. This would also require material interfaces which are stable at very high temperature. Examples are metal-ceramic composites which are currently used for these applications. High thermal resistance can also be achieved with multilayer systems.

As stated above, thermal boundary resistance is due to carrier scattering at an interface. The type of carrier scattered will depend on the materials governing the interfaces. For example, at a metal-metal interface, electron scattering effects will dominate thermal boundary resistance, as electrons are the primary thermal energy carriers in metals.

Two widely used predictive models are the acoustic mismatch model (AMM) and the diffuse mismatch model (DMM). The AMM assumes a geometrically perfect interface and phonon transport across it is entirely elastic, treating phonons as waves in a continuum. On the other hand, the DMM assumes scattering at the interface is diffusive, which is accurate for interfaces with characteristic roughness at elevated temperatures.

[Molecular dynamics](https://wikivisually.com/wiki/Molecular_dynamics) (MD) simulations are a powerful tool to investigate interfacial thermal resistance. Recent MD studies have demonstrated that the solid-liquid interfacial thermal resistance is reduced on nanostructured solid surfaces by enhancing the solid-liquid interaction energy per unit area, and reducing the difference in vibrational [density of states](https://wikivisually.com/wiki/Density_of_states) between solid and liquid.[[2]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-2)

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## Theoretical models

There are two primary models that are used to understand the thermal resistance of interfaces, the acoustic mismatch and diffuse mismatch models (AMM and DMM respectively). Both models are based only on phonon transport, ignoring electrical contributions. Thus it should apply for interfaces where at least one of the materials is electrically insulating. For both models the interface is assumed to behave exactly as the bulk on either side of the interface (e.g. bulk phonon dispersions, velocities, etc.). The thermal resistance then results from the transfer of phonons across the interface. Energy is transferred when higher energy phonons which exist in higher density in the hotter material propagate to the cooler materials, which in turn transmits lower energy phonons, creating a net [energy flux](https://wikivisually.com/wiki/Energy_flux).[[3]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-3)

A crucial factor in determining the thermal resistance at an interface is the overlap of phonon states. Given two materials, A and B, if material A has a low population (or no population) of phonons with certain k value, there will be very few phonons of that [wavevector](https://wikivisually.com/wiki/Wavevector) to propagate from A to B. Further, due to the [detailed balance](https://wikivisually.com/wiki/Detailed_balance), very few phonons of that wavevector will propagate the opposite direction, from B to A, even if material B has a large population of phonons with that wavevector. Thus as the overlap between phonon dispersions is small, there are less modes to allow for heat transfer in the material, giving at a high thermal interfacial resistance relative to materials with a high degree of overlap.[[4]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-Swartz.2C_E.T._1989-4) Both AMM and DMM reflect this principle, but differ in the conditions they require for propagation across the interface. Neither model is universally effective for predicting the thermal interface resistance (with the exception of very low temperature), but rather for most materials they act as upper and lower limits for real behavior.

Both models differ greatly in their treatment of scattering at the interface. In AMM the interface is assumed to be perfect, resulting in no scattering, thus phonons propagate elastically across the interface. The wavevectors that propagate across the interface are determined by conservation of momentum. In DMM, the opposite extreme is assumed, a perfectly scattering interface. In this case the wavevectors that propagate across the interface are random and independent of incident phonons on the interface. For both models the detailed balance must still be obeyed.

For both models some basic equations apply. The flux of energy from one material to the other is just:

where n is the number of phonons at a given wavevector and [momentum](https://wikivisually.com/wiki/Momentum), E is the energy, and α is the probability of transmission across the interface. The net flux is thus the difference of the energy fluxes:

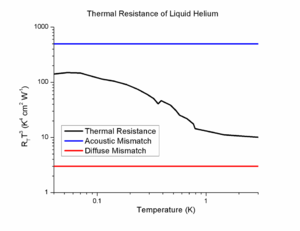
Since both fluxes are dependent on T1 and T2, the relationship between the flux and the temperature difference can be used to determine the thermal interface resistance based on:

where A is the area of the interface. These basic equations form the basis for both models. n is determined based on the [Debye model](https://wikivisually.com/wiki/Debye_model) and [Bose–Einstein statistics](https://wikivisually.com/wiki/Bose%E2%80%93Einstein_statistics). Energy is given simply by:

where ν is the [speed of sound](https://wikivisually.com/wiki/Speed_of_sound) in the material. The main difference between the two models is the [transmission probability](https://wikivisually.com/wiki/Transmission_coefficient), whose determination is more complicated. In each case it is determined by the basic assumptions that form the respective models. The assumption of elastic scattering makes it more difficult for phonons to transmit across the interface, resulting in lower probabilities. As a result, the acoustic mismatch model typically represents an upper limit for thermal interface resistance, while the diffuse mismatch model represents the lower limit.[[5]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-5)

## Examples

### Liquid helium interfaces

[](https://wikivisually.com/wiki/File:InterfacialHeliumResistance.png)

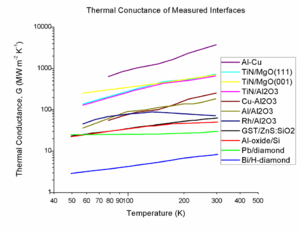
Typical Interfacial Resistance of Liquid Helium with metals. Resistance has been multiplied by T3 to remove the expected T−3 dependence. Adapted from [[6]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-6)

The presence of thermal interface resistance, corresponding to a discontinuous temperature across an interface was first proposed from studies of [liquid helium](https://wikivisually.com/wiki/Liquid_helium) in 1936. While this idea was first proposed in 1936,[[4]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-Swartz.2C_E.T._1989-4) it wasn’t until 1941 when [Pyotr Kapitsa](https://wikivisually.com/wiki/Pyotr_Kapitsa) (Peter Kapitza) carried out the first systematic study of thermal interface behavior in liquid helium.[[7]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-Kapitza.2C_P.L._1941-7) The first major model for [heat transfer](https://wikivisually.com/wiki/Heat_transfer) at interfaces was the acoustic mismatch model which predicted a T−3temperature dependence on the interfacial resistance, but this failed to properly model the thermal conductance of helium interfaces by as much as two orders of magnitude. Another surprising behavior of the thermal resistance was observed in the [pressure](https://wikivisually.com/wiki/Pressure) dependence. Since the speed of sound is a strong function of temperature in liquid helium, the acoustic mismatch model predicts a strong pressure dependence of the interfacial resistance. Studies around 1960 surprisingly showed that the interfacial resistance was nearly independent of pressure, suggesting that other mechanisms were dominant.

The acoustic mismatch theory predicted a very high thermal resistance (low thermal conductance) at solid-helium interfaces. This was potentially disastrous to researchers working at ultra-cold temperatures because it greatly impedes cooling rates at low temperatures. Fortunately such a large thermal resistance was not observed due to many mechanisms which promoted phonon transport. In liquid helium, [Van der Waals forces](https://wikivisually.com/wiki/Van_der_Waals_forces) actually work to solidify the first few monolayers against a solid. This boundary layer functions much like an [anti-reflection coating](https://wikivisually.com/wiki/Anti-reflection_coating) in optics, so that phonons which would typically be reflected from the interface actually would transmit across the interface. This also helps to understand the pressure independence of the thermal conductance. The final dominant mechanism to anomalously low thermal resistance of liquid helium interfaces is the effect of [surface roughness](https://wikivisually.com/wiki/Surface_roughness), which is not accounted for in the acoustic mismatch model. For a more detailed theoretical model of this aspect see the paper by A. Khater and J. Szeftel.[[8]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-A._Khater_2011-8) Like [electromagnetic waves](https://wikivisually.com/wiki/Electromagnetic_radiation) which produce [surface plasmons](https://wikivisually.com/wiki/Surface_plasmons) on rough surfaces, phonons can also induce surface waves. When these waves eventually scatter, they provide another mechanism for heat to transfer across the interface. Similarly, phonons are also capable of producing [evanescent waves](https://wikivisually.com/wiki/Evanescent_waves) in a [total internal reflection](https://wikivisually.com/wiki/Total_internal_reflection) geometry. As a result, when these waves are scattered in the solid, additional heat is transferred from the helium beyond the prediction of the acoustic mismatch theory. For a more complete review on this topic see the review by Swartz.[[9]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-H._Lyeo.2C_D._G_2006-9)

### Notable room temperature thermal conductance

In general there are two types of heat carriers in materials: phonons and electrons. The free electron gas found in metals is a very good conductor of heat and dominates thermal conductivity. All materials though exhibit heat transfer by phonon transport so heat flows even in dielectric materials such as silica. Interfacial thermal conductance is a measure of how efficiently heat carriers flow from one material to another. The lowest room temperature thermal conductance measurement to date is the Bi/Hydrogen-terminated [diamond](https://wikivisually.com/wiki/Diamond) with a thermal conductance of 8.5 MW m−2 K−1. As a metal, [bismuth](https://wikivisually.com/wiki/Bismuth) contains many electrons which serve as the primary heat carriers. Diamond on the other hand is a very good electrical insulator (although it has a very high thermal conductivity) and so electron transport between the materials is nil. Further, these materials have very different lattice parameters so phonons do not efficiently couple across the interface. Finally, the [Debye temperature](https://wikivisually.com/wiki/Debye_model)between the materials is significantly different. As a result, bismuth, which has a low Debye temperature, has many phonons at low frequencies. Diamond on the other hand has a very high Debye temperature and most of its heat-carrying phonons are at frequencies much higher than are present in bismuth.[[10]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-M._Costescu.2C_M._A_2003-10)

[](https://wikivisually.com/wiki/File:InterfacialThermalConductance.png)

Thermal Conductance Data adapted from,[[9]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-H._Lyeo.2C_D._G_2006-9)[[10]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-M._Costescu.2C_M._A_2003-10)[[11]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-11)

Increasing in thermal conductance, most phonon mediated interfaces (dielectric-dielectric and metal-dielectric) have thermal conductances between 80 and 300 MW m−2 K−1. The largest phonon mediated thermal conductance measured to date is between [TiN (Titanium Nitride)](https://wikivisually.com/wiki/Titanium_nitride) and [MgO](https://wikivisually.com/wiki/Magnesium_oxide). These systems have very similar [lattice structures](https://wikivisually.com/wiki/Crystal_lattice) and Debye temperatures. While there are no free electrons to enhance the thermal conductance of the interface, the similar physical properties of the two crystals facilitate a very efficient phonon transmission between the two materials.[[7]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-Kapitza.2C_P.L._1941-7)

At the highest end of the spectrum, one of the highest thermal conductances *measured* is between [aluminum](https://wikivisually.com/wiki/Aluminum) and [copper](https://wikivisually.com/wiki/Copper). At room temperature, the Al-Cu interface has a conductance of 4 GW m−2 K−1. The high thermal conductance of the interface should not be unexpected given the high electrical conductivity of both materials.[[12]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-12)

### Interfacial resistance in carbon nanotubes

The superior thermal conductivity of Carbon nanotubes makes it an excellent candidate for making composite materials. But interfacial resistance impacts the effective thermal conductivity. This area is not well studied and only a few studies have been done to understand the basic mechanism of this resistance.[[13]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-13)[[14]](https://wikivisually.com/wiki/Kapitza_resistance#cite_note-14)

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9. ^ [***a***](https://wikivisually.com/wiki/Kapitza_resistance#cite_ref-H._Lyeo.2C_D._G_2006_9-0) [***b***](https://wikivisually.com/wiki/Kapitza_resistance#cite_ref-H._Lyeo.2C_D._G_2006_9-1) H. Lyeo, D. G. Cahill, Phys. Rev. B. 73 144301 (2006)
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1. [Contact resistance](https://wikivisually.com/wiki/Contact_resistance) – The term contact resistance refers to the contribution to the total resistance of a system which can be attributed to the contacting interfaces of electrical leads and connections as opposed to the intrinsic resistance, which is an inherent property, independent of the measurement method. This effect is often described by the term Electrical Contact Resistance or ECR and may vary with time, most often decreasing, in a process known as resistance creep. The idea of potential drop on the injection electrode was introduced by William Shockley to explain the difference between the experimental results and the model of gradual channel approximation. In addition to the term ECR, "Interface resistance", "transitional resistance", or just simply "correction term" are also used. The term "parasitic resistance" has been used as a more general term, where it is usually still assumed that the contact resistance has a major contribution. Experimental characterization Here we need to distinguish the contact resistance evaluation in two-electrode systems (e.g. diodes) and three-electrode systems (e.g. transistors). For two electrode systems the specific contact resistivity is experimentally defined as the slope of the I-V curve at V=0: r c = { ∂ V ∂ J } V = 0 {\displaystyle r\_{c}=\left\{{\frac {\partial V}{\partial J}}\right\}\_{V=0}} where J is the current density = current/area. The units of specific contact resistivity are typically therefore in Ω ⋅ cm 2 {\displaystyle \Omega \cdot {\text{cm}}^{2}} where Ω {\displaystyle \Omega } stands for ohms. When the current is a linear function of the voltage, the device is said to have ohmic contacts. The resistance of contacts can be crudely estimated by comparing the results of a four terminal measurement to a simple two-lead measurement made with an ohmmeter. In a two-lead experiment, the measurement current causes a potential drop across both the test leads and the contacts so that the resistance of these elements is inseparable from the resistance of the actual device, with which they are in series. In a four-point probe measurement, one pair of leads is used to inject the measurement current while a second pair of leads, in parallel with the first, is used to measure the potential drop across the device. In the four-probe case, there is no potential drop across the voltage measurement leads so the contact resistance dr

  Contact resistance – Sketch of the contact resistance estimation by the transmission line method.

2. [Density of states](https://wikivisually.com/wiki/Density_of_states) – In solid-state and condensed matter physics, the density of states (DOS) of a system describes the number of states per interval of energy at each energy level available to be occupied. It is mathematically represented by a density distribution and it is generally an average over the space and time domains of the various states occupied by the system. A high DOS at a specific energy level means that there are many states available for occupation. A DOS of zero means that no states can be occupied at that energy level. The DOS is usually represented by one of the symbols g, ρ, D, n, or N. Generally, the density of states of matter is continuous. In isolated systems however, like atoms or molecules in the gas phase, the density distribution is discrete like a spectral density. Local variations, most often due to distortions of the original system, are often called local density of states (LDOS). If the DOS of an undisturbed system is zero, the LDOS can locally be non-zero due to the presence of a local potential. Introduction In quantum mechanical (QM) systems, waves, or wave-like particles, can occupy modes or states with wavelengths and propagation directions dictated by the system. For example, in some systems, the interatomic spacing and the atomic charge of a material could allow only electrons of certain wavelengths to exist. In other systems, the crystalline structure of a material could allow waves to propagate in one direction, while suppressing wave propagation in another direction. Often, only specific states are permitted. Thus, it can happen that many states are available for occupation at a specific energy level, while no states are available at other energy levels . For example, the density of states of electrons at the bandedge between the conduction band and the valence band in a semiconductor is shown in orange in Fig. 4 (in the subsequent section " Density of states and distribution functions"). For an electron in the conduction band, an increase of the electron energy causes more states to become available for occupation. Alternatively, the density of state is discontinuous for an interval of energy, which means that there are no states available for electrons to occupy within the bandgap of the material. This also means that an electron at the conduction band edge must lose at least the bandgap energy of the material in order to transition to another state in the valence band. Depending on the QM system, the density of states can be calculated for electrons, photons, or phonons, and can be given as a function of either energy or the wave vector k. To convert between the DOS as a function of the energy and the DOS as a function of the wave vector, the system-specific energy dispersion relation between E and k must be known. In general, the topological properties of the system have a major impact on the properties of the density of states. The most well-known systems, like neutronium in neutron stars and free electron gases in

  Density of states – Figure 1: Spherical surface in k-space for electrons in three dimensions.  
  Density of states – Figure 3: Density of states for electrons in bulk semiconductors (3D; in blue), quantum wells (2D; red), quantum wires (1D; green) and quantum dots (0D; black).

3. [Momentum](https://wikivisually.com/wiki/Momentum) – In Newtonian mechanics, linear momentum, translational momentum, or simply momentum (pl. momenta) is the product of the mass and velocity of an object. It is a three-dimensional vector quantity, possessing a direction and a magnitude. If m is an object's mass and v is the velocity (also a vector), then the momentum is p = m v , {\displaystyle \mathbf {p} =m\mathbf {v} ,} In SI units, it is measured in kilogram meters per second (kg · m/s). Newton's second law of motion states that a body's rate of change in momentum is equal to the net force acting on it. Momentum depends on the frame of reference, but in all frames, it is a conserved quantity, meaning that if a closed system is not affected by external forces, its total linear momentum cannot change. Momentum is also conserved in special relativity (with a modified formula) and, in a modified form, in electrodynamics, quantum mechanics, quantum field theory, and general relativity. It is an expression of one of the fundamental symmetries of space and time, that of translational symmetry. Advanced formulations of classical mechanics, Lagrangian and Hamiltonian mechanics, allow one to choose coordinate systems that incorporate symmetries and constraints. In these systems the conserved quantity is generalized momentum, and in general this is different from the kinetic momentum defined above. The concept of generalized momentum is carried over into quantum mechanics, where it becomes an operator on a wave function. The momentum and position operators are related by the Heisenberg uncertainty principle. In continuous systems such as electromagnetic fields, fluids and deformable bodies, a momentum density can be defined, and a continuum version of the conservation of momentum leads to equations such as the Navier–Stokes equations for fluids or the Cauchy momentum equation for deformable solids or fluids. Newtonian Momentum has both magnitude and direction. Since momentum has a direction, it can be used to predict the resulting direction of objects after they collide, and their speeds. Below, the basic properties of momentum are described in one dimension. The vector equations are almost identical to the scalar equations (see multiple dimensions). Single particle The momentum of a particle is traditionally represented by the letter p. It is the product of two quantities, the mass (represented by the letter m) and velocity (v): p = m v . {\displaystyle p=mv.} The units of momentum are the product of the units of mass and velocity. In SI units, if the mass is in kilograms and the velocity in meters per second then the momentum is in kilogram meters/second (kg m/s). In cgs units, if the mass is in grams and the velocity in centimeters per second, then the momentum is in gram centimeters/second (g cm/s). Being a vec

  Momentum – A pool break-off shot

4. [Debye model](https://wikivisually.com/wiki/Debye_model) – In thermodynamics and solid state physics, the Debye model is a method developed by Peter Debye in 1912 for estimating the phonon contribution to the specific heat (heat capacity) in a solid. It treats the vibrations of the atomic lattice (heat) as phonons in a box, in contrast to the Einstein model, which treats the solid as many individual, non-interacting quantum harmonic oscillators. The Debye model correctly predicts the low temperature dependence of the heat capacity, which is proportional to T 3 {\displaystyle T^{3}} – the Debye T3 law. Just like the Einstein model, it also recovers the Dulong–Petit law at high temperatures. But due to simplifying assumptions, its accuracy suffers at intermediate temperatures. See M. Shubin and T. Sunada for a rigorous treatment of the Debye model. Derivation The Debye model is a solid-state equivalent of Planck's law of black body radiation, where one treats electromagnetic radiation as a gas of photons in a box. The Debye model treats atomic vibrations as phonons in a box (the box being the solid). Most of the calculation steps are identical. Consider a cube of side L {\displaystyle L} . From the particle in a box article, the resonating modes of the sonic disturbances inside the box (considering for now only those aligned with one axis) have wavelengths given by λ n = 2 L n , {\displaystyle \lambda \_{n}={2L \over n}\,,} where n {\displaystyle n} is an integer. The energy of a phonon is E n = h ν n , {\displaystyle E\_{n}\ =h\nu \_{n}\,,} where h {\displaystyle h} is Planck's constant and ν n {\displaystyle \nu \_{n}} is the frequency of the phonon. Making the approximation that the frequency is inversely proportional to the wavelength, we have: E n = h ν n = h c s λ n = h

  Debye model – [Peter Debye](https://wikivisually.com/wiki/Peter_Debye)  
  Debye model

5. [Liquid helium](https://wikivisually.com/wiki/Liquid_helium) – At standard pressure, the chemical element helium exists in a liquid form only at the extremely low temperature of −269 °C (about 4 K or −452.2 °F). Its boiling point and critical point depend on which isotope of helium is present: the common isotope helium-4 or the rare isotope helium-3. These are the only two stable isotopes of helium. See the table below for the values of these physical quantities. The density of liquid helium-4 at its boiling point and a pressure of one atmosphere (101.3 kilopascals) is about 0.125 grams per cm3, or about 1/8th the density of liquid water. Liquefaction Helium was first liquefied on July 10, 1908, by the Dutch physicist Heike Kamerlingh Onnes at the University of Leiden in the Netherlands. At that time, helium-3 was unknown because the mass spectrometer had not yet been invented. In more recent decades, liquid helium has been used as a cryogenic refrigerant, and liquid helium is produced commercially for use in superconducting magnets such as those used in magnetic resonance imaging (MRI), nuclear magnetic resonance (NMR), Magnetoencephalography (MEG), and experiments in physics, such as low temperature Mössbauer spectroscopy. Characteristics The temperature required to produce liquid helium is low because of the weakness of the attractions between the helium atoms. These interatomic forces in helium are weak to begin with because helium is a noble gas, but the interatomic attractions are reduced even more by the effects of quantum mechanics. These are significant in helium because of its low atomic mass of about four atomic mass units. The zero point energy of liquid helium is less if its atoms are less confined by their neighbors. Hence in liquid helium, its ground state energy can decrease by a naturally occurring increase in its average interatomic distance. However at greater distances, the effects of the interatomic forces in helium are even weaker. Because of the very weak interatomic forces in helium, this element would remain a liquid at atmospheric pressure all the way from its liquefaction point down to absolute zero. Liquid helium solidifies only under very low temperatures and great pressures. At temperatures below their liquefaction points, both helium-4 and helium-3 undergo transitions to superfluids. (See the table below.) Liquid helium-4 and the rare helium-3 are not completely miscible. Below 0.9 kelvin at their saturated vapor pressure, a mixture of the two isotopes undergoes a phase separation into a normal fluid (mostly helium-3) that floats on a denser superfluid consisting mostly of helium-4. This phase separation happens because the overall mass of liquid helium can reduce its thermodynamic enthalpy by separating. At extremely low temperatures, the superfluid phase, rich in helium-4, can contain up to 6% of helium-3 in solution. This makes possible the small-scale use of the dilution refrigerator, which is capable of reaching temperatures of a few millikelvins. Superfluid helium-4 h

  Liquid helium – Liquid helium cooled below the [Lambda point](https://wikivisually.com/wiki/Lambda_point), where it exhibits properties of [superfluidity](https://wikivisually.com/wiki/Superfluidity)

6. [Heat transfer](https://wikivisually.com/wiki/Heat_transfer) – Heat transfer is a discipline of thermal engineering that concerns the generation, use, conversion, and exchange of thermal energy (heat) between physical systems. Heat transfer is classified into various mechanisms, such as thermal conduction, thermal convection, thermal radiation, and transfer of energy by phase changes. Engineers also consider the transfer of mass of differing chemical species, either cold or hot, to achieve heat transfer. While these mechanisms have distinct characteristics, they often occur simultaneously in the same system. Heat conduction, also called diffusion, is the direct microscopic exchange of kinetic energy of particles through the boundary between two systems. When an object is at a different temperature from another body or its surroundings, heat flows so that the body and the surroundings reach the same temperature, at which point they are in thermal equilibrium. Such spontaneous heat transfer always occurs from a region of high temperature to another region of lower temperature, as described by the second law of thermodynamics. Heat convection occurs when bulk flow of a fluid (gas or liquid) carries heat along with the flow of matter in the fluid. The flow of fluid may be forced by external processes, or sometimes (in gravitational fields) by buoyancy forces caused when thermal energy expands the fluid (for example in a fire plume), thus influencing its own transfer. The latter process is often called "natural convection". All convective processes also move heat partly by diffusion, as well. Another form of convection is forced convection. In this case the fluid is forced to flow by use of a pump, fan or other mechanical means. Thermal radiation occurs through a vacuum or any transparent medium (solid or fluid). It is the transfer of energy by means of photons in electromagnetic waves governed by the same laws. Overview Heat is defined in physics as the transfer of thermal energy across a well-defined boundary around a thermodynamic system. The thermodynamic free energy is the amount of work that a thermodynamic system can perform. Enthalpy is a thermodynamic potential, designated by the letter "H", that is the sum of the internal energy of the system (U) plus the product of pressure (P) and volume (V). Joule is a unit to quantify energy, work, or the amount of heat. Heat transfer is a process function (or path function), as opposed to functions of state; therefore, the amount of heat transferred in a thermodynamic process that changes the state of a system depends on how that process occurs, not only the net difference between the initial and final states of the process. Thermodynamic and mechanical heat transfer is calculated with the heat transfer coefficient, the proportionality between the heat flux and the thermodynamic driving force for the flow of heat. Heat flux is a quantitative, vectorial representation of heat-flow through a surface. In engineering contexts, the term heat is taken as synonymous to

  Heat transfer – Simulation of thermal convection in the [Earth's mantle](https://wikivisually.com/wiki/Mantle_(geology)). Colors span from red and green to blue with decreasing temperatures. A hot, less-dense lower boundary layer sends plumes of hot material upwards, and cold material from the top moves downwards.  
  Heat transfer – Red-hot iron object, transferring heat to the surrounding environment through thermal radiation  
  Heat transfer – Nucleate boiling of water.  
  Heat transfer – Heat exposure as part of a fire test for firestop products

7. [Pyotr Kapitsa](https://wikivisually.com/wiki/Pyotr_Kapitsa) – Pyotr Leonidovich Kapitsa or Peter Kapitza (Russian: Пётр Леони́дович Капи́ца, Romanian: Petre Capiţa (8 July [O.S. 26 June] 1894 – 8 April 1984) was a leading Soviet physicist and Nobel laureate, best known for his work in low-temperature physics. Biography Kapitsa was born in Kronstadt, Russian Empire to Bessarabian-Volhynian-born parents Leonid Petrovich Kapitsa (Moldovan Leonid Petrovici Capiţa), a military engineer who constructed fortifications, and Olga Ieronimovna Kapitsa from a noble Polish Stebnicki family. Besides Russian, the Kapitsa family also spoke Romanian. Kapitsa's studies were interrupted by the First World War, in which he served as an ambulance driver for two years on the Polish front. He graduated from the Petrograd Polytechnical Institute in 1918. He subsequently studied in Britain, working for over ten years with Ernest Rutherford in the Cavendish Laboratory at the University of Cambridge, and founding the influential Kapitza club. He was the first director (1930–34) of the Mond Laboratory in Cambridge. In the 1920s he originated techniques for creating ultrastrong magnetic fields by injecting high current for brief periods into specially constructed air-core electromagnets. In 1928 he discovered the linear dependence of resistivity on magnetic field for various metals in very strong magnetic fields. In 1934 Kapitsa returned to Russia to visit parents but was not allowed by Stalin's government to travel back to Great Britain. As his equipment for high magnetic field research remained in Cambridge (although later Ernest Rutherford negotiated with British government the possibility of shipping it to the USSR), he changed the direction of his research to low temperature research, beginning with a critical analysis of the existing methods for obtaining low temperatures. In 1934 he developed new and original apparatus (based on the adiabatic principle) for making significant quantities of liquid helium. Kapitsa formed the Institute for Physical Problems, in part using equipment which the Soviet government bought from the Mond Laboratory in Cambridge (with the assistance of Rutherford, once it was clear that Kapitsa would not be permitted to return). In Russia, Kapitsa began a series of experiments to study liquid helium, leading to the discovery in 1937 of its superfluidity (not to be confused with superconductivity). He reported the properties of this new state of matter in a series of papers, for which he was later awarded the Nobel Prize in Physics "for basic inventions and discoveries in the area of low-temperature physics". In 1939 he developed a new method for liquefaction of air with a low-pressure cycle using a special high-efficiency expansion turbine. Consequently, during World War II he was assigned to head the Department of Oxygen Industry attached to the USSR Council of Ministers, where he developed his low-pressure expansion techniques for industrial purposes. He invented high power microwave generators (1950–19

  Pyotr Kapitsa – Pyotr Kapitsa in the 1930s  
  Pyotr Kapitsa – Kapitsa (left) and [Nikolay Semyonov](https://wikivisually.com/wiki/Nikolay_Semyonov), the physics and chemistry [Nobel laureate](https://wikivisually.com/wiki/Nobel_laureate)s (portrait by [Boris Kustodiev](https://wikivisually.com/wiki/Boris_Kustodiev), 1921).

8. [Pressure](https://wikivisually.com/wiki/Pressure) – Pressure (symbol: p or P) is the force applied perpendicular to the surface of an object per unit area over which that force is distributed. Gauge pressure (also spelled gage pressure) is the pressure relative to the ambient pressure. Various units are used to express pressure. Some of these derive from a unit of force divided by a unit of area; the SI unit of pressure, the pascal (Pa), for example, is one newton per square metre; similarly, the pound-force per square inch (psi) is the traditional unit of pressure in the imperial and US customary systems. Pressure may also be expressed in terms of standard atmospheric pressure; the atmosphere (atm) is equal to this pressure, and the torr is defined as  1⁄760 of this. Manometric units such as the centimetre of water, millimetre of mercury, and inch of mercury are used to express pressures in terms of the height of column of a particular fluid in a manometer. Definition Pressure is the amount of force applied perpendicular to the surface of an object per unit area. The symbol for it is p or P. The IUPAC recommendation for pressure is a lower-case p. However, upper-case P is widely used. The usage of P vs p depends upon the field in which one is working, on the nearby presence of other symbols for quantities such as power and momentum, and on writing style. Formula Mathematically: p = F A , {\displaystyle p={\frac {F}{A}},} where: p {\displaystyle p} is the pressure, F {\displaystyle F} is the normal force, A {\displaystyle A} is the area of the surface on contact. Pressure is a scalar quantity. It relates the vector surface element (a vector normal to the surface) with the normal force acting on it. The pressure is the scalar proportionality constant that relates the two normal vectors: d F n = − p d A = − p n d A . {\displaystyle d\mathbf {F} \_{n}=-p\,d\mathbf {A} =-p\,\mathbf {n} \,dA.} The minus sign comes from the fact that the force is considered towards the surface element, while the normal vector points outward. The equation has meaning in that, for any surface S in contact with the fluid, the total force exerted by the fluid on that surface is the surface integral over S of the right-hand side of the above equation. It is incorrect (although rather usual) to say "the pressure is directed in such or such direction". The pressure, as a scalar, has no direction. The force given by the previous relationship to the quantity has a direction, but the pressure

  Pressure – Mercury column  
  Pressure – The effects of an external pressure of 700 bar on an aluminum cylinder with 5 mm wall thickness  
  Pressure – Low-pressure chamber in [Bundesleistungszentrum Kienbaum](https://wikivisually.com/wiki/Bundesleistungszentrum_Kienbaum), Germany

9. [Van der Waals forces](https://wikivisually.com/wiki/Van_der_Waals_forces) – In physical chemistry, the van der Waals forces, named after Dutch scientist Johannes Diderik van der Waals, are distance-dependent interactions between atoms or molecules. Unlike ionic or covalent bonds, these attractions are not a result of any chemical electronic bond, and they are comparatively weak and more susceptible to being perturbed. van der Waals forces quickly vanish at longer distances between interacting molecules. van der Waals forces play a fundamental role in fields as diverse as supramolecular chemistry, structural biology, polymer science, nanotechnology, surface science, and condensed matter physics. van der Waals forces also define many properties of organic compounds and molecular solids, including their solubility in polar and non-polar media. If no other forces are present, the point at which the force becomes repulsive rather than attractive as two atoms near one another is called the van der Waals contact distance. This results from the electron clouds of two atoms unfavorably coming into contact. It can be shown that van der Waals forces are of the same origin as the Casimir effect, arising from quantum interactions with the zero-point field. The resulting van der Waals forces can be attractive or repulsive. It is also sometimes used loosely as a synonym for the totality of intermolecular forces. The term includes the force between permanent dipoles (Keesom force), the force between a permanent dipole and a corresponding induced dipole (Debye force), and the force between instantaneously induced dipoles (London dispersion force). Definition van der Waals forces include attraction and repulsions between atoms, molecules, and surfaces, as well as other intermolecular forces. They differ from covalent and ionic bonding in that they are caused by correlations in the fluctuating polarizations of nearby particles (a consequence of quantum dynamics). Being the weakest of the weak chemical forces, with a strength between 0.4 and 4kJ/mol they may still support an integral structural load when multitudes of such interactions are present. Such a force results from a transient shift in electron density. Specifically, as the electrons are in orbit of the protons and neutrons within an atom the electron density may tend to shift more greatly on a side. Thus, this generates a transient charge to which a nearby atom can be either attracted or repelled. When the interatomic distance of two atoms is greater than 0.6 nm the force is not strong enough to be observed. In the same vein, when the interatomic distance is below 0.4 nm the force becomes repulsive. Intermolecular forces have four major contributions: A repulsive component resulting from the Pauli exclusion principle that prevents the collapse of molecules. Attractive or repulsive electrostatic interactions between permanent charges (in the case of molecular ions), dipoles (in the case of molecules without inversion center), quadrupoles (all molecules with symmetry lower than cu

  Van der Waals forces – [Gecko](https://wikivisually.com/wiki/Gecko)s can stick to walls and ceilings because of van der Waals forces.  
  Van der Waals forces – [Gecko](https://wikivisually.com/wiki/Gecko) climbing a glass surface

10. [Anti-reflection coating](https://wikivisually.com/wiki/Anti-reflection_coating) – An antireflective or anti-reflection (AR) coating is a type of optical coating applied to the surface of lenses and other optical elements to reduce reflection. In typical imaging systems, this improves the efficiency since less light is lost. In complex systems such as a telescope, the reduction in reflections also improves the contrast of the image by elimination of stray light. This is especially important in planetary astronomy. In other applications, the primary benefit is the elimination of the reflection itself, such as a coating on eyeglass lenses that makes the eyes of the wearer more visible to others, or a coating to reduce the glint from a covert viewer's binoculars or telescopic sight. Many coatings consist of transparent thin film structures with alternating layers of contrasting refractive index. Layer thicknesses are chosen to produce destructive interference in the beams reflected from the interfaces, and constructive interference in the corresponding transmitted beams. This makes the structure's performance change with wavelength and incident angle, so that color effects often appear at oblique angles. A wavelength range must be specified when designing or ordering such coatings, but good performance can often be achieved for a relatively wide range of frequencies: usually a choice of IR, visible, or UV is offered. Applications Anti-reflective coatings are used in a wide variety of applications where light passes through an optical surface, and low loss or low reflection is desired. Examples include anti-glare coatings on corrective lenses and camera lens elements, and antireflective coatings on solar cells. Corrective lenses Opticians may recommend "anti-reflection lenses" because the decreased reflection enhances the cosmetic appearance of the lenses. Such lenses are often said to reduce glare, but the reduction is very slight. Eliminating reflections allows slightly more light to pass through, producing a slight increase in contrast and visual acuity. Antireflective ophthalmic lenses should not be confused with polarized lenses, which decrease (by absorption) the visible glare of sun reflected off surfaces such as sand, water, and roads. The term "antireflective" relates to the reflection from the surface of the lens itself, not the origin of the light that reaches the lens. Many anti-reflection lenses include an additional coating that repels water and grease, making them easier to keep clean. Anti-reflection coatings are particularly suited to high-index lenses, as these reflect more light without the coating than a lower-index lens (a consequence of the Fresnel equations). It is also generally easier and cheaper to coat high index lenses. Photolithography Antireflective coatings are often used in microelectronic photolithography to help reduce image distortions associated with reflections off the surface of the substrate. Different types of antireflective coatings are applied either before or after the photoresist,

  Anti-reflection coating – Uncoated glasses lens (top) versus lens with antireflective coating. Note the tinted reflection from the coated lens.  
  Anti-reflection coating – Anti-reflective coatings are often used in camera lenses, giving lens elements distinctive colours.  
  Anti-reflection coating – An anti-reflection coated window, shown at a 45° and a 0° angle of incidence  
  Anti-reflection coating – Reflections are blocked by a circular polarizer

11. [Surface roughness](https://wikivisually.com/wiki/Surface_roughness) – Surface roughness often shortened to roughness, is a component of surface texture. It is quantified by the deviations in the direction of the normal vector of a real surface from its ideal form. If these deviations are large, the surface is rough; if they are small, the surface is smooth. In surface metrology, roughness is typically considered to be the high-frequency, short-wavelength component of a measured surface. However, in practice it is often necessary to know both the amplitude and frequency to ensure that a surface is fit for a purpose. Roughness plays an important role in determining how a real object will interact with its environment. In tribology, rough surfaces usually wear more quickly and have higher friction coefficients than smooth surfaces. Roughness is often a good predictor of the performance of a mechanical component, since irregularities on the surface may form nucleation sites for cracks or corrosion. On the other hand, roughness may promote adhesion. Generally speaking, rather than scale specific descriptors, cross-scale descriptors such as surface fractality provide more meaningful predictions of mechanical interactions at surfaces including contact stiffness and static friction. Although a high roughness value is often undesirable, it can be difficult and expensive to control in manufacturing. For example, it is difficult and expensive to control surface roughness of fused deposition modelling (FDM) manufactured parts. Decreasing the roughness of a surface usually increases its manufacturing cost. This often results in a trade-off between the manufacturing cost of a component and its performance in application. Roughness can be measured by manual comparison against a "surface roughness comparator" (a sample of known surface roughness), but more generally a surface profile measurement is made with a profilometer. These can be of the contact variety (typically a diamond stylus) or optical (e.g.: a white light interferometer or laser scanning confocal microscope). However, controlled roughness can often be desirable. For example, a gloss surface can be too shiny to the eye and too slippery to the finger (a touchpad is a good example) so a controlled roughness is required. This is a case where both amplitude and frequency are very important. Parameters A roughness value can either be calculated on a profile (line) or on a surface (area). The profile roughness parameter (Ra, Rq,...) are more common. The area roughness parameters (Sa, Sq,...) give more significant values. Profile roughness parameters Each of the roughness parameters are calculated using a formula for describing the surface. Standard references that describe each in detail are Surfaces and their Measurement. The profile roughness parameters are included in BS EN ISO 4287:2000 British standard, identical with the ISO 4287:1997 standard. The standard is based on the ″M″ (mean line) system. There are many different roughness parameters in use, but

  Surface roughness – The basic symbol of surface roughness  
  Surface roughness – Digital Holographic Microscope measuring hip prosthesis roughness

12. [Electromagnetic radiation](https://wikivisually.com/wiki/Electromagnetic_radiation) – In physics, electromagnetic radiation (EM radiation or EMR) refers to the waves (or their quanta, photons) of the electromagnetic field, propagating (radiating) through space carrying electromagnetic radiant energy. It includes radio waves, microwaves, infrared, (visible) light, ultraviolet, X-, and gamma rays. Classically, electromagnetic radiation consists of electromagnetic waves, which are synchronized oscillations of electric and magnetic fields that propagate at the speed of light through a vacuum. The oscillations of the two fields are perpendicular to each other and perpendicular to the direction of energy and wave propagation, forming a transverse wave. The wavefront of electromagnetic waves emitted from a point source (such as a lightbulb) is a sphere. The position of an electromagnetic wave within the electromagnetic spectrum could be characterized by either its frequency of oscillation or its wavelength. The electromagnetic spectrum includes, in order of increasing frequency and decreasing wavelength: radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X-rays and gamma rays. Electromagnetic waves are produced whenever charged particles are accelerated, and these waves can subsequently interact with other charged particles. EM waves carry energy, momentum and angular momentum away from their source particle and can impart those quantities to matter with which they interact. Quanta of EM waves are called photons, whose mass is zero. Electromagnetic radiation is associated with those EM waves that are free to propagate themselves ("radiate") without the continuing influence of the moving charges that produced them, because they have achieved sufficient distance from those charges. Thus, EMR is sometimes referred to as the far field. In this language, the near field refers to EM fields near the charges and current that directly produced them, specifically, electromagnetic induction and electrostatic induction phenomena. In the quantum theory of electromagnetism, EMR consists of photons, the elementary particles responsible for all electromagnetic interactions. Quantum effects provide additional sources of EMR, such as the transition of electrons to lower energy levels in an atom and black-body radiation. The energy of an individual photon is quantized and is greater for photons of higher frequency. This relationship is given by Planck's equation E = hν, where E is the energy per photon, ν is the frequency of the photon, and h is Planck's constant. A single gamma ray photon, for example, might carry ~100,000 times the energy of a single photon of visible light. The effects of EMR upon chemical compounds and biological organisms depend both upon the radiation's power and its frequency. EMR of visible or lower frequencies (i.e., visible light, infrared, microwaves, and radio waves) is called non-ionizing radiation, because its photons do not individually have enough energy to ionize atoms or molecules. The effe

  Electromagnetic radiation – [Electromagnetic spectrum](https://wikivisually.com/wiki/Electromagnetic_spectrum) with visible light highlighted

13. [Total internal reflection](https://wikivisually.com/wiki/Total_internal_reflection) – Total internal reflection is the phenomenon which occurs when a propagated wave strikes a medium boundary at an angle larger than a particular critical angle with respect to the normal to the surface. If the refractive index is lower on the other side of the boundary and the incident angle is greater than the critical angle, the wave cannot pass through and is entirely reflected. The critical angle is the angle of incidence above which the total internal reflection occurs. This is particularly common as an optical phenomenon, where light waves are involved, but it occurs with many types of waves, such as electromagnetic waves in general or sound waves. When a wave reaches a boundary between different materials with different refractive indices, the wave will in general be partially refracted at the boundary surface, and partially reflected. However, if the angle of incidence is greater (i.e. the direction of propagation is closer to being parallel to the boundary) than the critical angle – the angle of incidence at which light is refracted such that it travels along the boundary – then the wave will not cross the boundary, but will instead be totally reflected back internally. This can only occur when the wave in a medium with a higher refractive index (n1) reaches a boundary with a medium of lower refractive index (n2). For example, it will occur with light reaching air from glass, but not when reaching glass from air. Optical description Total internal reflection of light can be demonstrated using a semi-circular block of glass or plastic. A "ray box" shines a narrow beam of light (a "ray") onto the glass medium. The semi-circular shape ensures that a ray pointing towards the centre of the flat face will hit the curved surface at a right angle; this will prevent refraction at the air/glass boundary of the curved surface. At the glass/air boundary of the flat surface, what happens will depend on the angle. If θc is the critical angle, then the following scenarios depict what will happen according to the size of the incident angle. If θ ≤ θc, the ray will split; some of the ray will reflect off the boundary, and some will refract as it passes through. This is not total internal reflection. If θ > θc, the entire ray reflects from the boundary. None passes through. This is called total internal reflection. TIR is the abbreviation. This physical property makes optical fibers useful and prismatic binoculars possible. It is also what gives diamonds their distinctive sparkle, as diamond has an unusually high refractive index. Critical angle The critical angle is the angle of incidence for which the angle of refraction is 90°. The angle of incidence is measured with respect to the normal at the refractive boundary (see diagram illustrating Snell's law). Consider a light ray passing from glass into air. The light emanating from the interface is bent towards the glass. When the incident angle is increased sufficiently, the transmitted angle (in air)

  Total internal reflection – Total internal reflection of a [laser](https://wikivisually.com/wiki/Laser) beam in a block of [acrylic](https://wikivisually.com/wiki/Poly(methyl_methacrylate))  
  Total internal reflection – Total internal reflection in a semi-circular acrylic block  
  Total internal reflection – Mirror like effect  
  Total internal reflection

14. [Diamond](https://wikivisually.com/wiki/Diamond) – Diamond ( or ) is a metastable allotrope of carbon, where the carbon atoms are arranged in a variation of the face-centered cubic crystal structure called a diamond lattice. Diamond is less stable than graphite, but the conversion rate from diamond to graphite is negligible at standard conditions. Diamond is renowned as a material with superlative physical qualities, most of which originate from the strong covalent bonding between its atoms. In particular, diamond has the highest hardness and thermal conductivity of any bulk material. Those properties determine the major industrial application of diamond in cutting and polishing tools and the scientific applications in diamond knives and diamond anvil cells. Because of its extremely rigid lattice, it can be contaminated by very few types of impurities, such as boron and nitrogen. Small amounts of defects or impurities (about one per million of lattice atoms) color diamond blue (boron), yellow (nitrogen), brown (lattice defects), green (radiation exposure), purple, pink, orange or red. Diamond also has relatively high optical dispersion (ability to disperse light of different colors). Most natural diamonds are formed at high temperature and pressure at depths of 140 to 190 kilometers (87 to 118 mi) in the Earth's mantle. Carbon-containing minerals provide the carbon source, and the growth occurs over periods from 1 billion to 3.3 billion years (25% to 75% of the age of the Earth). Diamonds are brought close to the Earth's surface through deep volcanic eruptions by magma, which cools into igneous rocks known as kimberlites and lamproites. Diamonds can also be produced synthetically in a HPHT method which approximately simulates the conditions in the Earth's mantle. An alternative, and completely different growth technique is chemical vapor deposition (CVD). Several non-diamond materials, which include cubic zirconia and silicon carbide and are often called diamond simulants, resemble diamond in appearance and many properties. Special gemological techniques have been developed to distinguish natural diamonds, synthetic diamonds, and diamond simulants. The word is from the ancient Greek ἀδάμας – adámas "unbreakable". History The name diamond is derived from the ancient Greek αδάμας (adámas), "proper", "unalterable", "unbreakable", "untamed", from ἀ- (a-), "un-" + δαμάω (damáō), "I overpower", "I tame". Diamonds are thought to have been first recognized and mined in India, where significant alluvial deposits of the stone could be found many centuries ago along the rivers Penner, Krishna and Godavari. Diamonds have been known in India for at least 3,000 years but most likely 6,000 years. Diamonds have been treasured as gemstones since their use as religious icons in ancient India. Their usage in engraving tools also dates to early human history. The popularity of diamonds has risen since the 19th century because of increased supply, improved cutting and polishing techniques, growth in the world eco

  Diamond – The slightly misshapen octahedral shape of this rough diamond crystal in matrix is typical of the mineral. Its lustrous faces also indicate that this crystal is from a primary deposit.  
  Diamond – [Geologic province](https://wikivisually.com/wiki/Geologic_province)s of the world. The pink and orange areas are [shields](https://wikivisually.com/wiki/Shield_(geology)) and [platforms](https://wikivisually.com/wiki/Platform_(geology)), which together constitute cratons.  
  Diamond – Schematic diagram of a volcanic pipe  
  Diamond – Diamond and graphite are two [allotrope](https://wikivisually.com/wiki/Allotrope)s of carbon: pure forms of the same element that differ in structure.

15. [Bismuth](https://wikivisually.com/wiki/Bismuth) – Bismuth is a chemical element with symbol Bi and atomic number 83. Bismuth, a pentavalent post-transition metal and one of the pnictogens, chemically resembles its lighter homologs arsenic and antimony. Elemental bismuth may occur naturally, although its sulfide and oxide form important commercial ores. The free element is 86% as dense as lead. It is a brittle metal with a silvery white color when freshly produced, but surface oxidation can give it a pink tinge. Bismuth is the most naturally diamagnetic element, and has one of the lowest values of thermal conductivity among metals. Bismuth metal has been known since ancient times, although it was often confused with lead and tin, which share some physical properties. The etymology is uncertain, but possibly comes from Arabic bi ismid, meaning having the properties of antimony or the German words weiße Masse or Wismuth ("white mass"), translated in the mid-sixteenth century to New Latin bisemutum. Bismuth was long considered the element with the highest atomic mass that is stable. However, in 2003 it was discovered to be extremely weakly radioactive: its only primordial isotope, bismuth-209, decays via alpha decay with a half-life more than a billion times the estimated age of the universe. Because of its tremendously long half-life, bismuth may still be considered stable for almost all purposes. Bismuth compounds account for about half the production of bismuth. They are used in cosmetics, pigments, and a few pharmaceuticals, notably bismuth subsalicylate, used to treat diarrhea. Bismuth's unusual propensity to expand upon freezing is responsible for some of its uses, such as in casting of printing type. Bismuth has unusually low toxicity for a heavy metal. As the toxicity of lead has become more apparent in recent years, there is an increasing use of bismuth alloys (presently about a third of bismuth production) as a replacement for lead. History The name bismuth dates from around the 1660s, and is of uncertain etymology. It is one of the first 10 metals to have been discovered. Bismuth appears in the 1660s, from obsolete German Bismuth, Wismut, Wissmuth (early 16th century); perhaps related to Old High German hwiz ("white"). The New Latin bisemutum (due to Georgius Agricola, who Latinized many German mining and technical words) is from the German Wismuth, perhaps from weiße Masse, "white mass". The element was confused in early times with tin and lead because of its resemblance to those elements. Bismuth has been known since ancient times, so no one person is credited with its discovery. Agricola, in De Natura Fossilium (c. 1546) states that bismuth is a distinct metal in a family of metals including tin and lead. This was based on observation of the metals and their physical properties. Miners in the age of alchemy also gave bismuth the name tectum argenti, or "silver being made," in the sense of silver still in the process of being formed within the Earth. Beginning with Johann Heinrich Po

  Bismuth – [Alchemical symbol](https://wikivisually.com/wiki/Alchemical_symbol) used by [Torbern Bergman](https://wikivisually.com/wiki/Torbern_Bergman), 1775  
  Bismuth – Bismuth crystal illustrating the many iridescent refraction hues of its oxide surface  
  Bismuth – Artificially grown bismuth crystal illustrating the stairstep crystal structure, with a 1 cm3 cube of bismuth metal  
  Bismuth – [Bismite](https://wikivisually.com/wiki/Bismite) mineral

16. [Titanium nitride](https://wikivisually.com/wiki/Titanium_nitride) – Titanium nitride (TiN) (sometimes known as tinite) is an extremely hard ceramic material, often used as a coating on titanium alloys, steel, carbide, and aluminium components to improve the substrate's surface properties. Applied as a thin coating, TiN is used to harden and protect cutting and sliding surfaces, for decorative purposes (due to its gold appearance), and as a non-toxic exterior for medical implants. In most applications a coating of less than 5 micrometres (0.00020 in) is applied. Characteristics TiN has a Vickers hardness of 1800–2100, a modulus of elasticity of 251 GPa, a thermal expansion coefficient of 9.35×10−6 K−1, and a superconducting transition temperature of 5.6 K. TiN will oxidize at 800 °C in a normal atmosphere. It is chemically stable at 20 °C, according to laboratory tests, but can be slowly attacked by concentrated acid solutions with rising temperatures. TiN has infrared (IR) reflectivity properties, reflecting in a spectrum similar to elemental gold (Au), which gives it a yellowish color. Depending on the substrate material and surface finish, TiN will have a coefficient of friction ranging from 0.4 to 0.9 against another TiN surface (non-lubricated). The typical TiN formation has a crystal structure of NaCl-type with a roughly 1:1 stoichiometry; TiNx compounds with x ranging from 0.6 to 1.2 are, however, thermodynamically stable. A thin film of TiN was chilled to near absolute zero, converting it into the first known superinsulator, with resistance suddenly increasing by a factor of 100,000. Uses A well-known use for TiN coating is for edge retention and corrosion resistance on machine tooling, such as drill bits and milling cutters, often improving their lifetime by a factor of three or more. Because of TiN's metallic gold color, it is used to coat costume jewelry and automotive trim for decorative purposes. TiN is also widely used as a top-layer coating, usually with nickel (Ni) or chromium (Cr) plated substrates, on consumer plumbing fixtures and door hardware. As a coating it is used in aerospace and military applications and to protect the sliding surfaces of suspension forks of bicycles and motorcycles as well as the shock shafts of radio controlled cars. TiN is non-toxic, meets FDA guidelines and has seen use in medical devices such as scalpel blades and orthopedic bone saw blades where sharpness and edge retention are important. TiN coatings have also been used in implanted prostheses (especially hip replacement implants) and other medical implants. Though less visible, thin films of TiN are also used in microelectronics, where they serve as a conductive connection between the active device and the metal contacts used to operate the circuit, while acting as a diffusion barrier to block the diffusion of the metal into the silicon. In this context, TiN is classified as a "barrier metal", even though it is clearly a ceramic from the perspective of chemistry or mechanical behavior. Recent chip design in t

  Titanium nitride  
  Titanium nitride – TiN-coated drill bit  
  Titanium nitride – Dark gray TiCN coating on a [Gerber](https://wikivisually.com/wiki/Gerber_Legendary_Blades) pocketknife  
  Titanium nitride – Titanium nitride (TiN) coated punches using cathodic arc deposition technique

17. [Magnesium oxide](https://wikivisually.com/wiki/Magnesium_oxide) – Magnesium oxide (MgO), or magnesia, is a white hygroscopic solid mineral that occurs naturally as periclase and is a source of magnesium (see also oxide). It has an empirical formula of MgO and consists of a lattice of Mg2+ ions and O2− ions held together by ionic bonding. Magnesium hydroxide forms in the presence of water (MgO + H2O → Mg(OH)2), but it can be reversed by heating it to separate moisture. Magnesium oxide was historically known as magnesia alba (literally, the white mineral from magnesia – other sources give magnesia alba as MgCO3), to differentiate it from magnesia negra, a black mineral containing what is now known as manganese. While "magnesium oxide" normally refers to MgO, magnesium peroxide MgO2 is also known as a compound. According to evolutionary crystal structure prediction, MgO2 is thermodynamically stable at pressures above 116 GPa (gigapascals), and a semiconducting suboxide Mg3O2 is thermodynamically stable above 500 GPa. Because of its stability, MgO is used as a model system for investigating vibrational properties of crystals. Production Magnesium oxide is produced by the calcination of magnesium carbonate or magnesium hydroxide. The latter is obtained by the treatment of magnesium chloride solutions, typically seawater, with lime. Mg2+ + Ca(OH)2 → Mg(OH)2 + Ca2+ Calcining at different temperatures produces magnesium oxide of different reactivity. High temperatures 1500 – 2000 °C diminish the available surface area and produces dead-burned (often called dead burnt) magnesia, an unreactive form used as a refractory. Calcining temperatures 1000 – 1500 °C produce hard-burned magnesia, which has limited reactivity and calcining at lower temperature, (700–1000 °C) produces light-burned magnesia, a reactive form, also known as caustic calcined magnesia. Although some decomposition of the carbonate to oxide occurs at temperatures below 700 °C, the resulting materials appears to reabsorpb carbon dioxide from the air. Applications MgO is prized as a refractory material, i.e. a solid that is physically and chemically stable at high temperatures. It has two useful attributes: high thermal conductivity and low electrical conductivity. "By far the largest consumer of magnesia worldwide is the refractory industry, which consumed about 56 % of the magnesia in the United States in 2004, the remaining 44 % being used in agricultural, chemical, construction, environmental, and other industrial applications." MgO is used as a basic refractory material for crucibles. It is a principal fireproofing ingredient in construction materials. As a construction material, magnesium oxide wallboards have several attractive characteristics: fire resistance, termite resistance, moisture resistance, mold and mildew resistance, and strength. Niche uses MgO is one of the components in Portland cement in dry process plants. Magnesium oxide is used extensively in the soil and groundwater remediation, wastewater treatment, drinking water treatment,

  Magnesium oxide  
  Magnesium oxide – Unpolished MgO crystal

18. [Aluminum](https://wikivisually.com/wiki/Aluminum) – Aluminium or aluminum is a chemical element with symbol Al and atomic number 13. It is a silvery-white, soft, nonmagnetic, ductile metal in the boron group. By mass, aluminium makes up about 8% of the Earth's crust; it is the third most abundant element after oxygen and silicon and the most abundant metal in the crust, though it is less common in the mantle below. Aluminium metal is so chemically reactive that native specimens are rare and limited to extreme reducing environments. Instead, it is found combined in over 270 different minerals. The chief ore of aluminium is bauxite. Aluminium is remarkable for the metal's low density and its ability to resist corrosion through the phenomenon of passivation. Aluminium and its alloys are vital to the aerospace industry and important in transportation and building industries, such as building facades and window frames. The oxides and sulfates are the most useful compounds of aluminium. Despite its prevalence in the environment, no known form of life uses aluminium salts metabolically, but aluminium is well tolerated by plants and animals. Because of these salts' abundance, the potential for a biological role for them is of continuing interest, and studies continue. Physical characteristics Aluminium is a relatively soft, durable, lightweight, ductile, and malleable metal with appearance ranging from silvery to dull gray, depending on the surface roughness. It is nonmagnetic and does not easily ignite. A fresh film of aluminium serves as a good reflector (approximately 92%) of visible light and an excellent reflector (as much as 98%) of medium and far infrared radiation. The yield strength of pure aluminium is 7–11 MPa, while aluminium alloys have yield strengths ranging from 200 MPa to 600 MPa. Aluminium has about one-third the density and stiffness of steel. It is easily machined, cast, drawn and extruded. Aluminium atoms are arranged in a face-centered cubic (fcc) structure. Aluminium has a stacking-fault energy of approximately 200 mJ/m2. Aluminium is a good thermal and electrical conductor, having 59% the conductivity of copper, both thermal and electrical, while having only 30% of copper's density. Aluminium is capable of superconductivity, with a superconducting critical temperature of 1.2 kelvin and a critical magnetic field of about 100 gauss (10 milliteslas). Aluminium is the most common material for the fabrication of superconducting qubits. Isotopes Aluminium has many known isotopes, with mass numbers range from 21 to 42; however, only 27Al (stable) and 26Al (radioactive, t1⁄2 = 7.2×105 years) occur naturally. 27Al has a natural abundance above 99.9%. 26Al is produced from argon in the atmosphere by spallation caused by cosmic-ray protons. Aluminium isotopes are useful in dating marine sediments, manganese nodules, glacial ice, quartz in rock exposures, and meteorites. The ratio of 26Al to 10Be has been used to study transport, deposition, sediment storage, burial times, and erosion on

  Aluminum – "[Bauxite tailings](https://wikivisually.com/wiki/Bauxite_tailings)" storage facility in [Stade](https://wikivisually.com/wiki/Stade), Germany. The aluminium industry generates about 70 million tons of this waste annually.  
  Aluminum – The statue of [Anteros](https://wikivisually.com/wiki/Anteros) in [Piccadilly Circus](https://wikivisually.com/wiki/Piccadilly_Circus), London, was made in 1893 and is one of the first statues cast in aluminium.  
  Aluminum – Bauxite, a major aluminium ore. The red-brown color is due to the presence of [iron](https://wikivisually.com/wiki/Iron)minerals.  
  Aluminum – Etched surface from a high purity (99.9998%) aluminium bar, size 55×37 mm

19. [Copper](https://wikivisually.com/wiki/Copper) – Copper is a chemical element with symbol Cu (from Latin: cuprum) and atomic number 29. It is a soft, malleable, and ductile metal with very high thermal and electrical conductivity. A freshly exposed surface of pure copper has a reddish-orange color. Copper is used as a conductor of heat and electricity, as a building material, and as a constituent of various metal alloys, such as sterling silver used in jewelry, cupronickel used to make marine hardware and coins, and constantan used in strain gauges and thermocouples for temperature measurement. Copper is one of the few metals that occur in nature in directly usable metallic form (native metals) as opposed to needing extraction from an ore. This led to very early human use, from c. 8000 BC. It was the first metal to be smelted from its ore, c. 5000 BC, the first metal to be cast into a shape in a mold, c. 4000 BC and the first metal to be purposefully alloyed with another metal, tin, to create bronze, c. 3500 BC. In the Roman era, copper was principally mined on Cyprus, the origin of the name of the metal, from aes сyprium (metal of Cyprus), later corrupted to сuprum, from which the words copper (English), cuivre (French), Koper (Dutch) and Kupfer (German) are all derived. The commonly encountered compounds are copper(II) salts, which often impart blue or green colors to such minerals as azurite, malachite, and turquoise, and have been used widely and historically as pigments. Copper used in buildings, usually for roofing, oxidizes to form a green verdigris (or patina). Copper is sometimes used in decorative art, both in its elemental metal form and in compounds as pigments. Copper compounds are used as bacteriostatic agents, fungicides, and wood preservatives. Copper is essential to all living organisms as a trace dietary mineral because it is a key constituent of the respiratory enzyme complex cytochrome c oxidase. In molluscs and crustaceans, copper is a constituent of the blood pigment hemocyanin, replaced by the iron-complexed hemoglobin in fish and other vertebrates. In humans, copper is found mainly in the liver, muscle, and bone. The adult body contains between 1.4 and 2.1 mg of copper per kilogram of body weight. Characteristics Physical Copper, silver, and gold are in group 11 of the periodic table; these three metals have one s-orbital electron on top of a filled d-electron shell and are characterized by high ductility, and electrical and thermal conductivity. The filled d-shells in these elements contribute little to interatomic interactions, which are dominated by the s-electrons through metallic bonds. Unlike metals with incomplete d-shells, metallic bonds in copper are lacking a covalent character and are relatively weak. This observation explains the low hardness and high ductility of single crystals of copper. At the macroscopic scale, introduction of extended defects to the crystal lattice, such as grain boundaries, hinders flow of the material under applied stress, thereb

  Copper – A copper disc (99.95% pure) made by [continuous casting](https://wikivisually.com/wiki/Continuous_casting); [etched](https://wikivisually.com/wiki/Industrial_etching) to reveal [crystallite](https://wikivisually.com/wiki/Crystallite)s.  
  Copper – Copper just above its melting point keeps its pink luster color when enough light outshines the orange [incandescence](https://wikivisually.com/wiki/Incandescence) color.  
  Copper – Unoxidized copper wire (left) and oxidized copper wire (right).  
  Copper – The East Tower of the [Royal Observatory, Edinburgh](https://wikivisually.com/wiki/Royal_Observatory%2C_Edinburgh). The contrast between the refurbished copper installed in 2010 and the green color of the original 1894 copper is clearly seen.