Glass

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*This article is about the material. For other uses, see*[*Glass (disambiguation)*](https://en.wikipedia.org/wiki/Glass_(disambiguation))*.*

[](https://en.wikipedia.org/wiki/File:Fassade_Wilhelmstrasse_65,_Berlin-Mitte,_160417,_ako.jpg)

A glass building facade

**Glass** is a non-[crystalline](https://en.wikipedia.org/wiki/Crystallinity), often [transparent](https://en.wikipedia.org/wiki/Transparency_and_translucency) [amorphous solid](https://en.wikipedia.org/wiki/Amorphous_solid), that has widespread practical, technological, and decorative use in, for example, [window](https://en.wikipedia.org/wiki/Window) panes, [tableware](https://en.wikipedia.org/wiki/Tableware), and [optics](https://en.wikipedia.org/wiki/Optics). Glass is most often formed by rapid cooling ([quenching](https://en.wikipedia.org/wiki/Quenching)) of the molten form; some glasses such as [volcanic glass](https://en.wikipedia.org/wiki/Volcanic_glass) are naturally occurring. The most familiar, and historically the oldest, types of manufactured glass are "silicate glasses" based on the chemical compound [silica](https://en.wikipedia.org/wiki/Silicon_dioxide) (silicon dioxide, or [quartz](https://en.wikipedia.org/wiki/Quartz)), the primary constituent of [sand](https://en.wikipedia.org/wiki/Sand). Soda-lime glass, containing around 70% silica, account for around 90% of manufactured glass. The term *glass*, in popular usage, is often used to refer only to this type of material, although silica-free glasses often have desirable properties for applications in modern communications technology. Some objects, such as drinking glasses and eyeglasses, are so commonly made of silicate-based glass that they are simply called by the name of the material.

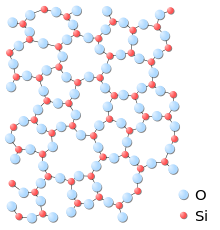
Although brittle, silicate glass is extremely durable, and many examples of glass fragments exist from early glass-making cultures. Archaeological evidence suggests glass-making dates back to at least 3,600 BCE in [Mesopotamia](https://en.wikipedia.org/wiki/Mesopotamia), [Egypt](https://en.wikipedia.org/wiki/Egypt), or [Syria](https://en.wikipedia.org/wiki/Syria). The earliest known glass objects were [beads](https://en.wikipedia.org/wiki/Beads), perhaps created accidentally during metal-working or the production of [faience](https://en.wikipedia.org/wiki/Faience). Due to its ease of [formability](https://en.wikipedia.org/wiki/Formability) into any shape, glass has been traditionally used for vessels: [bowls](https://en.wikipedia.org/wiki/Bowl_(vessel)), [vases](https://en.wikipedia.org/wiki/Vase), [bottles](https://en.wikipedia.org/wiki/Bottle), jars and drinking glasses. In its most solid forms, it has also been used for [paperweights](https://en.wikipedia.org/wiki/Paperweight_collecting) and [marbles](https://en.wikipedia.org/wiki/Marble_(toy)). Glass can be coloured by adding metal salts or painted and printed with [vitreous enamels](https://en.wikipedia.org/wiki/Vitreous_enamel), leading to its use in [stained glass](https://en.wikipedia.org/wiki/Stained_glass) windows and other [glass art](https://en.wikipedia.org/wiki/Glass_art) objects.

The [refractive](https://en.wikipedia.org/wiki/Refraction), [reflective](https://en.wikipedia.org/wiki/Reflection_(physics)) and [transmission](https://en.wikipedia.org/wiki/Transmission_coefficient#Optics) properties of glass make glass suitable for manufacturing [optical lenses](https://en.wikipedia.org/wiki/Lens_(optics)), [prisms](https://en.wikipedia.org/wiki/Prism), and [optoelectronics](https://en.wikipedia.org/wiki/Optoelectronics) materials. Extruded [glass fibres](https://en.wikipedia.org/wiki/Glass_fiber) have application as [optical fibres](https://en.wikipedia.org/wiki/Optical_fiber) in communications networks, thermal insulating material when matted as [glass wool](https://en.wikipedia.org/wiki/Glass_wool) so as to trap air, or in glass-fibre reinforced plastic ([fibreglass](https://en.wikipedia.org/wiki/Fiberglass)).

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Microscopic structure

[](https://en.wikipedia.org/wiki/File:Silica.svg)

The amorphous structure of glassy silica (SiO2) in two dimensions. No long-range order is present, although there is local ordering with respect to the [tetrahedral](https://en.wikipedia.org/wiki/Tetrahedral) arrangement of oxygen (O) atoms around the silicon (Si) atoms.

*Main article:*[*Structure of liquids and glasses*](https://en.wikipedia.org/wiki/Structure_of_liquids_and_glasses)

The standard definition of a *glass* (or vitreous solid) is a solid formed by rapid melt [quenching](https://en.wikipedia.org/wiki/Quenching).[[1]](https://en.wikipedia.org/wiki/Glass#cite_note-1)[[2]](https://en.wikipedia.org/wiki/Glass#cite_note-Zallen83-2)[[3]](https://en.wikipedia.org/wiki/Glass#cite_note-Cusack87-3)[[4]](https://en.wikipedia.org/wiki/Glass#cite_note-Horst_Scholze_1991-4) However, the term "glass" is often defined in a broader sense, to describe any non-crystalline ([amorphous](https://en.wikipedia.org/wiki/Amorphous_solid)) solid that exhibits a [glass transition](https://en.wikipedia.org/wiki/Glass_transition) when heated towards the liquid state.[[4]](https://en.wikipedia.org/wiki/Glass#cite_note-Horst_Scholze_1991-4)[[5]](https://en.wikipedia.org/wiki/Glass#cite_note-Elliot84-5)

Glass is an [amorphous solid](https://en.wikipedia.org/wiki/Amorphous_solid). Although the atomic-scale structure of glass shares characteristics of the structure of a [supercooled liquid](https://en.wikipedia.org/wiki/Supercooled_liquid), glass exhibits all the mechanical properties of a solid.[[6]](https://en.wikipedia.org/wiki/Glass#cite_note-6)[[7]](https://en.wikipedia.org/wiki/Glass#cite_note-Gibbs-7)[[8]](https://en.wikipedia.org/wiki/Glass#cite_note-8) As in other [amorphous solids](https://en.wikipedia.org/wiki/Amorphous_solid), the atomic structure of a glass lacks the long-range periodicity observed in [crystalline solids](https://en.wikipedia.org/wiki/Crystal_structure). Due to [chemical bonding](https://en.wikipedia.org/wiki/Chemical_bonding) constraints, glasses do possess a high degree of short-range order with respect to local atomic [polyhedra](https://en.wikipedia.org/wiki/Polyhedra).[[9]](https://en.wikipedia.org/wiki/Glass#cite_note-9) The notion that glass flows to an appreciable extent over extended periods of time is not supported by empirical research or theoretical analysis (see [viscosity in solids](https://en.wikipedia.org/wiki/Viscosity#In_solids)). Laboratory measurements of room temperature glass flow do show a motion consistent with a material viscosity on the order of 1017–1018 Pa s.[[5]](https://en.wikipedia.org/wiki/Glass#cite_note-Elliot84-5)[[10]](https://en.wikipedia.org/wiki/Glass#cite_note-10)

**Formation from a supercooled liquid**

*Main article:*[*Glass transition*](https://en.wikipedia.org/wiki/Glass_transition)

|  |  |
| --- | --- |
|  | **Unsolved problem in physics**:  *What is the nature of the*[*transition*](https://en.wikipedia.org/wiki/Glass_transition)*between a fluid or regular solid and a glassy phase? "The deepest and most interesting unsolved problem in solid state theory is probably the theory of the nature of glass and the glass transition." —*[*P.W. Anderson*](https://en.wikipedia.org/wiki/Philip_Warren_Anderson)[[11]](https://en.wikipedia.org/wiki/Glass#cite_note-11)  [(more unsolved problems in physics )](https://en.wikipedia.org/wiki/List_of_unsolved_problems_in_physics) |

For melt quenching, if the cooling is sufficiently rapid (relative to the characteristic [crystallization](https://en.wikipedia.org/wiki/Crystallization) time) then crystallization is prevented and instead the disordered atomic configuration of the [supercooled](https://en.wikipedia.org/wiki/Supercooled) liquid is frozen into the solid state at Tg. The tendency for a material to form a glass while quenched is called glass-forming ability. This ability can be predicted by the [rigidity theory](https://en.wikipedia.org/wiki/Rigidity_theory_(physics)).[[12]](https://en.wikipedia.org/wiki/Glass#cite_note-phillips1979-12) Generally, a glass exists in a structurally [metastable](https://en.wikipedia.org/wiki/Metastability_in_molecules) state with respect to its [crystalline](https://en.wikipedia.org/wiki/Crystallinity) form, although in certain circumstances, for example in [atactic](https://en.wikipedia.org/wiki/Atactic) polymers, there is no crystalline analogue of the amorphous phase.[[13]](https://en.wikipedia.org/wiki/Glass#cite_note-Folmer-13)

Glass is sometimes considered to be a liquid due to its lack of a first-order [phase transition](https://en.wikipedia.org/wiki/Phase_transition)[[7]](https://en.wikipedia.org/wiki/Glass#cite_note-Gibbs-7)[[14]](https://en.wikipedia.org/wiki/Glass#cite_note-14) where certain [thermodynamic](https://en.wikipedia.org/wiki/Thermodynamics) [variables](https://en.wikipedia.org/wiki/Thermodynamic_variable) such as [volume](https://en.wikipedia.org/wiki/Volume), [entropy](https://en.wikipedia.org/wiki/Entropy) and [enthalpy](https://en.wikipedia.org/wiki/Enthalpy) are discontinuous through the glass transition range. The [glass transition](https://en.wikipedia.org/wiki/Glass_transition) may be described as analogous to a second-order phase transition where the intensive thermodynamic variables such as the [thermal expansivity](https://en.wikipedia.org/wiki/Thermal_expansion) and [heat capacity](https://en.wikipedia.org/wiki/Heat_capacity) are discontinuous.[[2]](https://en.wikipedia.org/wiki/Glass#cite_note-Zallen83-2) Nonetheless, the equilibrium theory of phase transformations does not entirely hold for glass, and hence the glass transition cannot be classed as one of the classical equilibrium phase transformations in solids.[[4]](https://en.wikipedia.org/wiki/Glass#cite_note-Horst_Scholze_1991-4)[[5]](https://en.wikipedia.org/wiki/Glass#cite_note-Elliot84-5)

Occurrence in nature

*Main articles:*[*Volcanic glass*](https://en.wikipedia.org/wiki/Volcanic_glass)*,*[*Impactite*](https://en.wikipedia.org/wiki/Impactite)*, and*[*Fulgurite*](https://en.wikipedia.org/wiki/Fulgurite)

Glass can form naturally from volcanic magma. [Obsidian](https://en.wikipedia.org/wiki/Obsidian) is a common volcanic glass with high silica (SiO2) content formed when felsic lava extruded from a volcano cools rapidly.[[15]](https://en.wikipedia.org/wiki/Glass#cite_note-15) [Impactite](https://en.wikipedia.org/wiki/Impactite) is a form of glass formed by the impact of a [meteorite](https://en.wikipedia.org/wiki/Meteorite), where [Moldavite](https://en.wikipedia.org/wiki/Moldavite) (found in central and eastern Europe), and [Libyan desert glass](https://en.wikipedia.org/wiki/Libyan_desert_glass) (found in areas in the eastern [Sahara](https://en.wikipedia.org/wiki/Sahara), the [deserts of eastern Libya](https://en.wikipedia.org/wiki/Libyan_desert) and [western Egypt](https://en.wikipedia.org/wiki/Western_Desert_(Egypt))) are notable examples.[[16]](https://en.wikipedia.org/wiki/Glass#cite_note-16) [Vitrification](https://en.wikipedia.org/wiki/Vitrification) of [quartz](https://en.wikipedia.org/wiki/Quartz) can also occur when [lightning](https://en.wikipedia.org/wiki/Lightning) strikes [sand](https://en.wikipedia.org/wiki/Sand), forming hollow, [branching rootlike](https://en.wikipedia.org/wiki/Dendrite_(crystal)) structures called [fulgurites](https://en.wikipedia.org/wiki/Fulgurite).[[17]](https://en.wikipedia.org/wiki/Glass#cite_note-17) [Trinitite](https://en.wikipedia.org/wiki/Trinitite) is a glassy residue formed from the desert floor sand at the [Trinity](https://en.wikipedia.org/wiki/Trinity_test) [nuclear bomb test](https://en.wikipedia.org/wiki/Nuclear_testing) site.[[18]](https://en.wikipedia.org/wiki/Glass#cite_note-18) [Edeowie glass](https://en.wikipedia.org/wiki/Edeowie_glass), found in [South Australia](https://en.wikipedia.org/wiki/South_Australia), is proposed to originate from [Pleistocene](https://en.wikipedia.org/wiki/Pleistocene) grassland fires, [lightning](https://en.wikipedia.org/wiki/Lightning) strikes, or [hypervelocity impact](https://en.wikipedia.org/wiki/Hypervelocity_impact) by one or several [asteroids](https://en.wikipedia.org/wiki/Asteroids) or [comets](https://en.wikipedia.org/wiki/Comets).[[19]](https://en.wikipedia.org/wiki/Glass#cite_note-19)

* [](https://en.wikipedia.org/wiki/File:Lipari-Obsidienne_(5).jpg)

A piece of volcanic [obsidian](https://en.wikipedia.org/wiki/Obsidian) glass

* [](https://en.wikipedia.org/wiki/File:Moldavite_Besednice.jpg)

[Moldavite](https://en.wikipedia.org/wiki/Moldavite), a natural glass formed by [meteorite](https://en.wikipedia.org/wiki/Meteorite) impact, from [Besednice](https://en.wikipedia.org/wiki/Besednice), [Bohemia](https://en.wikipedia.org/wiki/Bohemia_proper)

* [](https://en.wikipedia.org/wiki/File:Fulgurites-algeria.jpg)

Tube [fulgurites](https://en.wikipedia.org/wiki/Fulgurites)

* [](https://en.wikipedia.org/wiki/File:Trinitite_from_Trinity_Site.jpg)

[Trinitite](https://en.wikipedia.org/wiki/Trinitite), a glass made by the [Trinity nuclear-weapon test](https://en.wikipedia.org/wiki/Trinity_(nuclear_test))

* [](https://en.wikipedia.org/wiki/File:Libyan_Desert_Glass.jpg)

[Libyan desert glass](https://en.wikipedia.org/wiki/Libyan_desert_glass)

History

*Main article:*[*History of glass*](https://en.wikipedia.org/wiki/History_of_glass)

[](https://en.wikipedia.org/wiki/File:Roman_diatretglas.jpg)

Roman [cage cup](https://en.wikipedia.org/wiki/Cage_cup) from the 4th century CE

Naturally occurring [obsidian](https://en.wikipedia.org/wiki/Obsidian) glass was used by [Stone Age](https://en.wikipedia.org/wiki/Stone_Age) societies as it fractures along very sharp edges, making it ideal for cutting tools and weapons.[[20]](https://en.wikipedia.org/wiki/Glass#cite_note-Harvey09-20)[[21]](https://en.wikipedia.org/wiki/Glass#cite_note-21) Glassmaking dates back to at least 6000 years, long before humans had discovered how to smelt iron.[[20]](https://en.wikipedia.org/wiki/Glass#cite_note-Harvey09-20) Archaeological evidence suggests that the first true synthetic glass was made in Lebanon and the coastal north Syria, [Mesopotamia](https://en.wikipedia.org/wiki/Mesopotamia) or [ancient Egypt](https://en.wikipedia.org/wiki/Ancient_Egypt).[[22]](https://en.wikipedia.org/wiki/Glass#cite_note-Henderson_ancient_glass-22)[[23]](https://en.wikipedia.org/wiki/Glass#cite_note-23) The earliest known glass objects, of the mid third millennium BCE, were beads, perhaps initially created as accidental by-products of [metal-working](https://en.wikipedia.org/wiki/Metalworking) ([slags](https://en.wikipedia.org/wiki/Slag)) or during the production of [faience](https://en.wikipedia.org/wiki/Egyptian_faience), a pre-glass vitreous material made by a process similar to [glazing](https://en.wikipedia.org/wiki/Ceramic_glaze).[[24]](https://en.wikipedia.org/wiki/Glass#cite_note-24) Early glass was rarely transparent and often contained impurities and imperfections.[[20]](https://en.wikipedia.org/wiki/Glass#cite_note-Harvey09-20) During the [Late Bronze Age](https://en.wikipedia.org/wiki/Late_Bronze_Age) there was a rapid growth in [glassmaking](https://en.wikipedia.org/wiki/Glassmaking) technology in [Egypt](https://en.wikipedia.org/wiki/Egypt) and [Western Asia](https://en.wikipedia.org/wiki/Western_Asia).[[22]](https://en.wikipedia.org/wiki/Glass#cite_note-Henderson_ancient_glass-22) Archaeological finds from this period include coloured glass [ingots](https://en.wikipedia.org/wiki/Ingots), vessels, and beads.[[22]](https://en.wikipedia.org/wiki/Glass#cite_note-Henderson_ancient_glass-22)[[25]](https://en.wikipedia.org/wiki/Glass#cite_note-25) Much early glass production relied on grinding techniques borrowed from stone working meaning that glass was ground and carved in a cold state.[[26]](https://en.wikipedia.org/wiki/Glass#cite_note-26)

The term *glass* developed in the late [Roman Empire](https://en.wikipedia.org/wiki/Roman_Empire). It was in the [Roman glassmaking](https://en.wikipedia.org/wiki/Roman_glass) centre at [Trier](https://en.wikipedia.org/wiki/Trier), now in modern Germany, that the [late-Latin](https://en.wikipedia.org/wiki/Late-Latin) term *glesum* originated, probably from a [Germanic](https://en.wikipedia.org/wiki/Germanic_languages) word for a [transparent](https://en.wikipedia.org/wiki/Transparent_materials), [lustrous](https://en.wikipedia.org/wiki/Lustrous) substance.[[27]](https://en.wikipedia.org/wiki/Glass#cite_note-douglas-27) Glass objects have been recovered across the Roman Empire[[28]](https://en.wikipedia.org/wiki/Glass#cite_note-28) in domestic, [funerary](https://en.wikipedia.org/wiki/Funerary),[[29]](https://en.wikipedia.org/wiki/Glass#cite_note-29) and industrial contexts.[[30]](https://en.wikipedia.org/wiki/Glass#cite_note-30) Examples of [Roman glass](https://en.wikipedia.org/wiki/Roman_glass) have been found outside of the former Roman Empire in [China](https://en.wikipedia.org/wiki/China),[[31]](https://en.wikipedia.org/wiki/Glass#cite_note-31) the [Baltics](https://en.wikipedia.org/wiki/Baltic_region), the [Middle East](https://en.wikipedia.org/wiki/Middle_East) and [India](https://en.wikipedia.org/wiki/India).[[32]](https://en.wikipedia.org/wiki/Glass#cite_note-32) The Romans perfected [Cameo glass](https://en.wikipedia.org/wiki/Cameo_glass), produced by etching and carving through fused layers of different colours to produce a design in relief on the glass object.[[33]](https://en.wikipedia.org/wiki/Glass#cite_note-britannica-glass-33)

[](https://en.wikipedia.org/wiki/File:Vitrail-Passion.jpg)

Windows in the choir of the [Basilica of Saint Denis](https://en.wikipedia.org/wiki/Basilica_of_Saint_Denis), one of the earliest uses of extensive areas of glass (early 13th-century architecture with restored glass of the 19th century)

Glass was used extensively during the [Middle Ages](https://en.wikipedia.org/wiki/Middle_Ages). [Anglo-Saxon glass](https://en.wikipedia.org/wiki/Anglo-Saxon_glass) has been found across England during archaeological excavations of both settlement and cemetery sites.[[34]](https://en.wikipedia.org/wiki/Glass#cite_note-34) From the 10th-century onwards, glass was employed in [stained glass](https://en.wikipedia.org/wiki/Stained_glass) windows of churches and [cathedrals](https://en.wikipedia.org/wiki/Cathedrals), with famous examples at [Chartres Cathedral](https://en.wikipedia.org/wiki/Chartres_Cathedral) and the [Basilica of Saint Denis](https://en.wikipedia.org/wiki/Basilica_of_Saint_Denis). By the 14th-century, architects were designing buildings with walls of stained glass such as [Sainte-Chapelle](https://en.wikipedia.org/wiki/Sainte-Chapelle), Paris, (1203–1248) and the East end of [Gloucester Cathedral](https://en.wikipedia.org/wiki/Gloucester_Cathedral). With the Renaissance, and a change in architectural style, the use of large stained glass windows became much less prevalent,[[35]](https://en.wikipedia.org/wiki/Glass#cite_note-35) although stained glass had a major revival with [Gothic Revival architecture](https://en.wikipedia.org/wiki/Gothic_Revival_architecture) in the 19th century.[[36]](https://en.wikipedia.org/wiki/Glass#cite_note-36)

During the 13th century, the island of [Murano](https://en.wikipedia.org/wiki/Murano), [Venice](https://en.wikipedia.org/wiki/Venice), became a centre for glass making, building on medieval techniques to produce colourful ornamental pieces in large quantities.[[33]](https://en.wikipedia.org/wiki/Glass#cite_note-britannica-glass-33) Murano glass makers developed the exceptionally clear colourless glass [cristallo](https://en.wikipedia.org/wiki/Cristallo), so called for its resemblance to natural crystal, and extensively used for windows, mirrors, ships' lanterns, and lenses.[[20]](https://en.wikipedia.org/wiki/Glass#cite_note-Harvey09-20) In the 13th, 14th, and 15th centuries, enamelling and gilding on glass vessels was perfected in Egypt and Syria.[[37]](https://en.wikipedia.org/wiki/Glass#cite_note-EB1911-incorp-37) Towards the end of the 17th century [Bohemia](https://en.wikipedia.org/wiki/Bohemia) became an important region for glass-production, remaining so until the start of the 20th century. By the 17th century, glass was also being produced in [England](https://en.wikipedia.org/wiki/England) in the Venetian tradition. In around 1675, [George Ravenscroft](https://en.wikipedia.org/wiki/George_Ravenscroft) invented [lead crystal](https://en.wikipedia.org/wiki/Lead_crystal) glass, with [cut glass](https://en.wikipedia.org/wiki/Cut_glass) becoming fashionable in the 18th century.[[33]](https://en.wikipedia.org/wiki/Glass#cite_note-britannica-glass-33) Ornamental glass objects became an important art medium during the [Art Nouveau](https://en.wikipedia.org/wiki/Art_Nouveau) period in the late 19th century.[[33]](https://en.wikipedia.org/wiki/Glass#cite_note-britannica-glass-33)

Throughout the 20th century, new mass production techniques led to the widespread availability and utility for bulk glass and its increased use as a building material and new applications of glass.[[38]](https://en.wikipedia.org/wiki/Glass#cite_note-38) In the 1920s a mould-etch process was developed, in which art was etched directly into the mould, so that each cast piece emerged from the mould with the image already on the surface of the glass. This reduced manufacturing costs and, combined with a wider use of coloured glass, led to cheap glassware in the 1930s, which later became known as [Depression glass](https://en.wikipedia.org/wiki/Depression_glass).[[39]](https://en.wikipedia.org/wiki/Glass#cite_note-39) In the 1950s, [Pilkington Bros.](https://en.wikipedia.org/wiki/Pilkington), [England](https://en.wikipedia.org/wiki/England), developed the [float glass](https://en.wikipedia.org/wiki/Float_glass) process, producing high-quality distortion free flat sheets of glass by floating on molten [tin](https://en.wikipedia.org/wiki/Tin).[[20]](https://en.wikipedia.org/wiki/Glass#cite_note-Harvey09-20) Modern multi-story buildings are frequently constructed with [curtain walls](https://en.wikipedia.org/wiki/Curtain_wall_(architecture)) made almost entirely of glass.[[40]](https://en.wikipedia.org/wiki/Glass#cite_note-40) Similarly, laminated glass has been widely applied to vehicles for windscreens.[[41]](https://en.wikipedia.org/wiki/Glass#cite_note-41) Optical glass for spectacles has been used since the Middle Ages.[[42]](https://en.wikipedia.org/wiki/Glass#cite_note-42) The production of lenses has become increasingly proficient, aiding astronomers[[43]](https://en.wikipedia.org/wiki/Glass#cite_note-43) as well as having other application in medicine and science.[[44]](https://en.wikipedia.org/wiki/Glass#cite_note-glassalliance-44) Glass is also employed as the aperture cover in many [solar energy](https://en.wikipedia.org/wiki/Solar_energy) collectors.[[45]](https://en.wikipedia.org/wiki/Glass#cite_note-45)

In the 21st century, glass manufacturers have developed different brands of chemically strengthened glass for widespread application in [touchscreens](https://en.wikipedia.org/wiki/Touchscreen) for [smartphones](https://en.wikipedia.org/wiki/Smartphone), [tablet computers](https://en.wikipedia.org/wiki/Tablet_computer), and many other types of [information appliances](https://en.wikipedia.org/wiki/Information_appliance). These include [Gorilla glass](https://en.wikipedia.org/wiki/Gorilla_glass), developed and manufactured by [Corning](https://en.wikipedia.org/wiki/Corning_Inc.), [AGC Inc.](https://en.wikipedia.org/wiki/AGC_Inc.)'s [Dragontrail](https://en.wikipedia.org/wiki/Dragontrail) and [Schott AG](https://en.wikipedia.org/wiki/Schott_AG)'s Xensation.[[46]](https://en.wikipedia.org/wiki/Glass#cite_note-46)[[47]](https://en.wikipedia.org/wiki/Glass#cite_note-47)[[48]](https://en.wikipedia.org/wiki/Glass#cite_note-gensix-48)

Physical properties

**Optical**

Glass is in widespread use in optical systems due to its ability to refract, reflect, and transmit light following [geometrical optics](https://en.wikipedia.org/wiki/Geometrical_optics). The most common and oldest applications of glass in optics are as [lenses](https://en.wikipedia.org/wiki/Lens_(optics)), [windows](https://en.wikipedia.org/wiki/Window), [mirrors](https://en.wikipedia.org/wiki/Mirror), and [prisms](https://en.wikipedia.org/wiki/Prism).[[49]](https://en.wikipedia.org/wiki/Glass#cite_note-Bach12-49) The key optical properties [refractive index](https://en.wikipedia.org/wiki/Refractive_index), [dispersion](https://en.wikipedia.org/wiki/Dispersion_(optics)), and [transmission](https://en.wikipedia.org/wiki/Transparency_and_translucency), of glass are strongly dependent on chemical composition and, to a lesser degree, its thermal history.[[49]](https://en.wikipedia.org/wiki/Glass#cite_note-Bach12-49) Optical glass typically has a refractive index of 1.4 to 2.4 and [Abbe number](https://en.wikipedia.org/wiki/Abbe_number), which characterises dispersion, of 15 to 100.[[49]](https://en.wikipedia.org/wiki/Glass#cite_note-Bach12-49) Refractive index may be modified by high-density (refractive index increases) or low-density (refractive index decreases) additives.[[50]](https://en.wikipedia.org/wiki/Glass#cite_note-50)

Glass transparency results from the absence of [grain boundaries](https://en.wikipedia.org/wiki/Grain_boundary) which [diffusely scatter light](https://en.wikipedia.org/wiki/Diffuse_reflection) in polycrystalline materials.[[51]](https://en.wikipedia.org/wiki/Glass#cite_note-Carter-Norton-51) Semi-opacity due to crystallization may be induced in many glasses by maintaining them for a long period at a temperature just insufficient to cause fusion. In this way, the crystalline, devitrified material, known as Réaumur's glass [porcelain](https://en.wikipedia.org/wiki/Porcelain) is produced.[[37]](https://en.wikipedia.org/wiki/Glass#cite_note-EB1911-incorp-37)[[52]](https://en.wikipedia.org/wiki/Glass#cite_note-Mysen05-52) Although generally transparent to visible light, glasses may be [opaque](https://en.wikipedia.org/wiki/Opacity_(optics)) to other [wavelengths of light](https://en.wikipedia.org/wiki/Electromagnetic_spectrum). While silicate glasses are generally opaque to [infrared](https://en.wikipedia.org/wiki/Infrared) wavelengths with a transmission cut-off at 4 μm, heavy-metal [fluoride](https://en.wikipedia.org/wiki/Fluoride_glass) and [chalcogenide](https://en.wikipedia.org/wiki/Chalcogenide_glass) glasses are transparent to infrared wavelengths of 7 to 18 μm, respectively.[[53]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-industrial-53) The addition of metallic oxides results in different coloured glasses as the metallic ions will absorb wavelengths of light corresponding to specific colours.[[53]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-industrial-53)

**Other**

*See also:*[*List of physical properties of glass*](https://en.wikipedia.org/wiki/List_of_physical_properties_of_glass)*,*[*Corrosion § Corrosion of glass*](https://en.wikipedia.org/wiki/Corrosion#Corrosion_of_glass)*, and*[*Strength of glass*](https://en.wikipedia.org/wiki/Strength_of_glass)

In the manufacturing process, glasses can be poured, formed, extruded and moulded into forms ranging from flat sheets to highly intricate shapes.[[54]](https://en.wikipedia.org/wiki/Glass#cite_note-54) The finished product is brittle and will fracture, unless [laminated](https://en.wikipedia.org/wiki/Laminated_glass) or [tempered](https://en.wikipedia.org/wiki/Tempered_glass) to enhance durability.[[55]](https://en.wikipedia.org/wiki/Glass#cite_note-55)[[56]](https://en.wikipedia.org/wiki/Glass#cite_note-56) Glass is typically inert, resistant to chemical attack, and can mostly withstand the action of water, making it an ideal material for the manufacture of containers for foodstuffs and most chemicals.[[20]](https://en.wikipedia.org/wiki/Glass#cite_note-Harvey09-20)[[57]](https://en.wikipedia.org/wiki/Glass#cite_note-:3-57)[[58]](https://en.wikipedia.org/wiki/Glass#cite_note-58) Nevertheless, although usually highly resistant to chemical attack, glass will corrode or dissolve under some conditions.[[57]](https://en.wikipedia.org/wiki/Glass#cite_note-:3-57)[[59]](https://en.wikipedia.org/wiki/Glass#cite_note-Bengisu_2013-59) The materials that make up a particular glass composition have an effect on how quickly the glass corrodes. Glasses containing a high proportion of [alkali](https://en.wikipedia.org/wiki/Alkali_metal) or [alkaline earth](https://en.wikipedia.org/wiki/Alkaline_earth_element) elements are more susceptible to corrosion than other glass compositions.[[60]](https://en.wikipedia.org/wiki/Glass#cite_note-60)[[61]](https://en.wikipedia.org/wiki/Glass#cite_note-Chawla93-61)

The density of glass varies with chemical composition with values ranging from 2.2 grams per cubic centimetre (2,200 kg/m3) for [fused silica](https://en.wikipedia.org/wiki/Fused_quartz) to 7.2 grams per cubic centimetre (7,200 kg/m3) for dense flint glass.[[62]](https://en.wikipedia.org/wiki/Glass#cite_note-62) Glass is stronger than most metals, with a theoretical [tensile strength](https://en.wikipedia.org/wiki/Tensile_strength) estimated at 14 gigapascals (2,000,000 psi) to 35 gigapascals (5,100,000 psi) due to its ability to undergo reversible compression without fracture. However, the presence of scratches, bubbles, and other microscopic flaws lead to a typical range of 14 megapascals (2,000 psi) to 175 megapascals (25,400 psi) in most commercial glasses.[[53]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-industrial-53) Several processes such as [toughening](https://en.wikipedia.org/wiki/Toughened_glass) can increase the strength of glass.[[63]](https://en.wikipedia.org/wiki/Glass#cite_note-63) Carefully drawn flawless [glass fibres](https://en.wikipedia.org/wiki/Glass_fibre) can be produced with strength of up to 11.5 gigapascals (1,670,000 psi).[[53]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-industrial-53)

**Reputed flow**

The observation that old windows are sometimes found to be thicker at the bottom than at the top is often offered as supporting evidence for the view that glass flows over a timescale of centuries, the assumption being that the glass has exhibited the liquid property of flowing from one shape to another.[[64]](https://en.wikipedia.org/wiki/Glass#cite_note-64) This assumption is incorrect, as once solidified, glass stops flowing. Instead, glass manufacturing processes in the past produced sheets of non-uniform thickness leading to observed sagging and ripples in old windows.[[7]](https://en.wikipedia.org/wiki/Glass#cite_note-Gibbs-7)

Types

**Silicate**

[](https://en.wikipedia.org/wiki/File:Quartz_sand.jpg)

[Quartz sand](https://en.wikipedia.org/wiki/Sand) (silica) is the main raw material in commercial glass production

[Silicon dioxide](https://en.wikipedia.org/wiki/Silicon_dioxide) (SiO2) is a common fundamental constituent of glass. [Fused quartz](https://en.wikipedia.org/wiki/Fused_quartz) is a glass made from chemically-pure silica.[[61]](https://en.wikipedia.org/wiki/Glass#cite_note-Chawla93-61) It has very low thermal expansion and excellent resistance to [thermal shock](https://en.wikipedia.org/wiki/Thermal_shock), being able to survive immersion in water while red hot, resists high temperatures (1000–1500 °C) and chemical weathering, and is very hard. It is also transparent to a wider spectral range than ordinary glass, extending from the visible further into both the [UV](https://en.wikipedia.org/wiki/UV) and [IR](https://en.wikipedia.org/wiki/Infrared) ranges, and is sometimes used where transparency to these wavelengths is necessary. Fused quartz is used for high-temperature applications such as furnace tubes, lighting tubes, melting crucibles, etc.[[65]](https://en.wikipedia.org/wiki/Glass#cite_note-:2-65) However, its high melting temperature (1723°C) and viscosity make it difficult to work with. Therefore, normally, other substances (fluxes) are added to lower the melting temperature and simplify glass processing.[[66]](https://en.wikipedia.org/wiki/Glass#cite_note-Chemistry-explained-66)

**Soda-lime**

[Sodium carbonate](https://en.wikipedia.org/wiki/Sodium_carbonate) (Na2CO3, "soda") is a common additive and acts to lowers the glass-transition temperature. However, [Sodium silicate](https://en.wikipedia.org/wiki/Sodium_silicate) is water-soluble, so [lime](https://en.wikipedia.org/wiki/Lime_(mineral)) (CaO, [calcium oxide](https://en.wikipedia.org/wiki/Calcium_oxide), generally obtained from [limestone](https://en.wikipedia.org/wiki/Limestone)), some [magnesium oxide](https://en.wikipedia.org/wiki/Magnesium_oxide) (MgO) and [aluminium oxide](https://en.wikipedia.org/wiki/Aluminium_oxide) (Al2O3) are other common components added to improve chemical durability. Soda-lime glasses (Na2O) + lime (CaO) + magnesia (MgO) + alumina (Al2O3) account for over 75% of manufactured glass, containing about 70 to 74% silica by weight.[[61]](https://en.wikipedia.org/wiki/Glass#cite_note-Chawla93-61)[[67]](https://en.wikipedia.org/wiki/Glass#cite_note-ullmann-67) Soda-lime-silicate glass is transparent, easily formed, and most suitable for window glass and tableware.[[68]](https://en.wikipedia.org/wiki/Glass#cite_note-:4-68) However, it has a high thermal expansion and poor resistance to heat.[[68]](https://en.wikipedia.org/wiki/Glass#cite_note-:4-68) Soda-lime glass is typically used for [windows](https://en.wikipedia.org/wiki/Window), [bottles](https://en.wikipedia.org/wiki/Bottle), [light bulbs](https://en.wikipedia.org/wiki/Light_bulb), and [jars](https://en.wikipedia.org/wiki/Jar).[[66]](https://en.wikipedia.org/wiki/Glass#cite_note-Chemistry-explained-66)

**Borosilicate**

[](https://en.wikipedia.org/wiki/File:Measuring_cup.jpg)

A Pyrex [borosilicate glass](https://en.wikipedia.org/wiki/Borosilicate_glass) [measuring jug](https://en.wikipedia.org/wiki/Measuring_jug)

[Borosilicate glasses](https://en.wikipedia.org/wiki/Borosilicate_glass) (e.g. [Pyrex](https://en.wikipedia.org/wiki/Pyrex), [Duran](https://en.wikipedia.org/wiki/Duran_(glass))) typically contain 5–13% [boron trioxide](https://en.wikipedia.org/wiki/Boron_trioxide) (B2O3).[[66]](https://en.wikipedia.org/wiki/Glass#cite_note-Chemistry-explained-66) Borosilicate glasses have fairly low [coefficients of thermal expansion](https://en.wikipedia.org/wiki/Coefficient_of_thermal_expansion) (7740 Pyrex CTE is 3.25×10−6/°C[[69]](https://en.wikipedia.org/wiki/Glass#cite_note-69) as compared to about 9×10−6/°C for a typical soda-lime glass[[70]](https://en.wikipedia.org/wiki/Glass#cite_note-70)). They are, therefore, less subject to [stress](https://en.wikipedia.org/wiki/Stress_(mechanics)) caused by [thermal expansion](https://en.wikipedia.org/wiki/Thermal_expansion) and thus less vulnerable to [cracking](https://en.wikipedia.org/wiki/Crack_propagation) from [thermal shock](https://en.wikipedia.org/wiki/Thermal_shock). They are commonly used for e.g. [labware](https://en.wikipedia.org/wiki/Labware), [household cookware](https://en.wikipedia.org/wiki/Cookware), and sealed beam car [head lamps](https://en.wikipedia.org/wiki/Head_lamp).[[66]](https://en.wikipedia.org/wiki/Glass#cite_note-Chemistry-explained-66)

**Lead**

The addition of [lead(II) oxide](https://en.wikipedia.org/wiki/Lead(II)_oxide) into silicate glass lowers melting point and [viscosity](https://en.wikipedia.org/wiki/Viscosity) of the melt.[[71]](https://en.wikipedia.org/wiki/Glass#cite_note-71) The high density of [Lead glass](https://en.wikipedia.org/wiki/Lead_glass) (silica + lead oxide (PbO) + potassium oxide (K2O) + soda (Na2O) + zinc oxide (ZnO) + alumina) results in a high electron density, and hence high refractive index, making the look of glassware more brilliant and causing noticeably more [specular reflection](https://en.wikipedia.org/wiki/Specular_reflection) and increased [optical dispersion](https://en.wikipedia.org/wiki/Dispersion_(optics)).[[61]](https://en.wikipedia.org/wiki/Glass#cite_note-Chawla93-61)[[72]](https://en.wikipedia.org/wiki/Glass#cite_note-:5-72) Lead glass has a high elasticity, making the glassware more workable and giving rise to a clear "ring" sound when struck. However, lead glass cannot withstand high temperatures well.[[65]](https://en.wikipedia.org/wiki/Glass#cite_note-:2-65) Lead oxide also facilitates solubility of other metal oxides and is used in colored glass. The viscosity decrease of lead glass melt is very significant (roughly 100 times in comparison with soda glass); this allows easier removal of bubbles and working at lower temperatures, hence its frequent use as an additive in [vitreous enamels](https://en.wikipedia.org/wiki/Vitreous_enamel) and [glass solders](https://en.wikipedia.org/wiki/Glass_solder). The high [ionic radius](https://en.wikipedia.org/wiki/Ionic_radius) of the Pb2+ ion renders it highly immobile and hinders the movement of other ions; lead glasses therefore have high electrical resistance, about two orders of magnitude higher than soda-lime glass (108.5 vs 106.5 Ω⋅cm, [DC](https://en.wikipedia.org/wiki/Direct_current) at 250 °C).[[73]](https://en.wikipedia.org/wiki/Glass#cite_note-73)

**Aluminosilicate**

Aluminosilicate glass typically contains 5-10% [alumina](https://en.wikipedia.org/wiki/Alumina) (Al2O3). Aluminosilicate glass tends to be more difficult to melt and shape compared to borosilicate compositions, but has excellent thermal resistance and durability.[[66]](https://en.wikipedia.org/wiki/Glass#cite_note-Chemistry-explained-66) Aluminosilicate glass is extensively used for [fiberglass](https://en.wikipedia.org/wiki/Fiberglass),[[74]](https://en.wikipedia.org/wiki/Glass#cite_note-:1-74) used for making glass-reinforced plastics (boats, fishing rods, etc.), top-of-stove cookware, and halogen bulb glass.[[65]](https://en.wikipedia.org/wiki/Glass#cite_note-:2-65)[[66]](https://en.wikipedia.org/wiki/Glass#cite_note-Chemistry-explained-66)

**Other oxide additives**

The addition of [barium](https://en.wikipedia.org/wiki/Barium) also increases the refractive index. [Thorium oxide](https://en.wikipedia.org/wiki/Thorium_oxide) gives glass a high refractive index and low dispersion and was formerly used in producing high-quality lenses, but due to its [radioactivity](https://en.wikipedia.org/wiki/Radioactivity) has been replaced by [lanthanum oxide](https://en.wikipedia.org/wiki/Lanthanum_oxide) in modern eyeglasses.[[75]](https://en.wikipedia.org/wiki/Glass#cite_note-75) Iron can be incorporated into glass to absorb [infrared](https://en.wikipedia.org/wiki/Infrared) radiation, for example in heat-absorbing filters for movie projectors, while [cerium(IV) oxide](https://en.wikipedia.org/wiki/Cerium(IV)_oxide) can be used for glass that absorbs [ultraviolet](https://en.wikipedia.org/wiki/Ultraviolet) wavelengths.[[76]](https://en.wikipedia.org/wiki/Glass#cite_note-76) [Fluorine](https://en.wikipedia.org/wiki/Fluorine) lowers the [dielectric constant](https://en.wikipedia.org/wiki/Dielectric_constant) of glass. Fluorine is highly [electronegative](https://en.wikipedia.org/wiki/Electronegative) and lowers the polarizability of the material. Fluoride silicate glasses are used in manufacture of [integrated circuits](https://en.wikipedia.org/wiki/Integrated_circuit) as an insulator.[[77]](https://en.wikipedia.org/wiki/Glass#cite_note-77)

**Glass-ceramics**

*Main article:*[*Glass-ceramic*](https://en.wikipedia.org/wiki/Glass-ceramic)

[](https://en.wikipedia.org/wiki/File:Ceranfeld.jpg)

A high-strength glass-ceramic cooktop with negligible [thermal expansion](https://en.wikipedia.org/wiki/Thermal_expansion).

[Glass-ceramic](https://en.wikipedia.org/wiki/Glass-ceramic) materials contain both non-crystalline glass and [crystalline](https://en.wikipedia.org/wiki/Crystallinity) [ceramic](https://en.wikipedia.org/wiki/Ceramic) phases. They are formed by controlled nucleation and partial crystallisation of a base glass by heat treatment.[[78]](https://en.wikipedia.org/wiki/Glass#cite_note-Holand-glass-ceramics-78) Crystalline grains are often embedded within a non-crystalline intergranular phase of [grain boundaries](https://en.wikipedia.org/wiki/Grain_boundary). Glass-ceramics exhibit advantageous thermal, chemical, biological, and dielectric properties as compared to metals or organic polymers.[[78]](https://en.wikipedia.org/wiki/Glass#cite_note-Holand-glass-ceramics-78)

The most commercially important property of glass-ceramics is their imperviousness to thermal shock. Thus, glass-ceramics have become extremely useful for countertop cooking and industrial processes. The negative [thermal expansion](https://en.wikipedia.org/wiki/Thermal_expansion) coefficient (CTE) of the crystalline ceramic phase can be balanced with the positive CTE of the glassy phase. At a certain point (~70% crystalline) the glass-ceramic has a net CTE near zero. This type of [glass-ceramic](https://en.wikipedia.org/wiki/Glass-ceramic) exhibits excellent mechanical properties and can sustain repeated and quick temperature changes up to 1000 °C.[[79]](https://en.wikipedia.org/wiki/Glass#cite_note-MOD-79)[[78]](https://en.wikipedia.org/wiki/Glass#cite_note-Holand-glass-ceramics-78)

**Fibreglass**

*Main articles:*[*Fiberglass*](https://en.wikipedia.org/wiki/Fiberglass)*and*[*Glass wool*](https://en.wikipedia.org/wiki/Glass_wool)

[Fibreglass](https://en.wikipedia.org/wiki/Fibreglass) (also called glass fibre reinforced plastic, GRP) is a [composite material](https://en.wikipedia.org/wiki/Composite_material) made by reinforcing a plastic [resin](https://en.wikipedia.org/wiki/Resin) with [glass fibres](https://en.wikipedia.org/wiki/Glass_fibre). It is made by melting glass and stretching the glass into fibres. These fibres are woven together into a cloth and left to set in a plastic resin.[[80]](https://en.wikipedia.org/wiki/Glass#cite_note-Parkyn-80)[[81]](https://en.wikipedia.org/wiki/Glass#cite_note-81)[[82]](https://en.wikipedia.org/wiki/Glass#cite_note-propertiesofmatter-82) Fibreglass has the properties of being lightweight and corrosion resistant, and is a good [insulator](https://en.wikipedia.org/wiki/Insulator_(electricity)) enabling its use as building insulation material and for electronic housing for consumer products. Fibreglass was originally used in the United Kingdom and United States during [World War II](https://en.wikipedia.org/wiki/World_War_II) to manufacture [radomes](https://en.wikipedia.org/wiki/Radome). Uses of fibreglass include building and construction materials, boat hulls, car body parts, and aerospace composite materials.[[83]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-fibreglass-83)[[80]](https://en.wikipedia.org/wiki/Glass#cite_note-Parkyn-80)[[82]](https://en.wikipedia.org/wiki/Glass#cite_note-propertiesofmatter-82)

[Glass-fibre wool](https://en.wikipedia.org/wiki/Glass_wool) is an excellent [thermal](https://en.wikipedia.org/wiki/Thermal_insulation) and [sound](https://en.wikipedia.org/wiki/Sound_insulation) insulation material, commonly used in buildings (e.g. [attic](https://en.wikipedia.org/wiki/Attic) and [cavity wall](https://en.wikipedia.org/wiki/Cavity_wall_insulation) insulation), and plumbing (e.g. [pipe insulation](https://en.wikipedia.org/wiki/Pipe_insulation)), and [soundproofing](https://en.wikipedia.org/wiki/Soundproofing).[[83]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-fibreglass-83) It is produced by forcing molten glass through a fine mesh by [centripetal force](https://en.wikipedia.org/wiki/Centripetal_force), and breaking the extruded glass fibres into short lengths using a stream of high-velocity air. The fibres are bonded with an adhesive spray and the resulting wool mat is cut and packed in rolls or panels.[[53]](https://en.wikipedia.org/wiki/Glass#cite_note-brittanica-industrial-53)

**Non-silicate**

[](https://en.wikipedia.org/wiki/File:CD-RW_bottom.jpg)

A [CD-RW](https://en.wikipedia.org/wiki/CD-RW) (CD). [Chalcogenide glass](https://en.wikipedia.org/wiki/Chalcogenide_glass) form the basis of rewritable CD and DVD solid-state memory technology.[[84]](https://en.wikipedia.org/wiki/Glass#cite_note-Greer05-84)

Besides common silica-based glasses many other [inorganic](https://en.wikipedia.org/wiki/Inorganic) and [organic](https://en.wikipedia.org/wiki/Organic_chemistry) materials may also form glasses, including [metals](https://en.wikipedia.org/wiki/Metallic_glass), [aluminates](https://en.wikipedia.org/wiki/Aluminate), [phosphates](https://en.wikipedia.org/wiki/Phosphate), [borates](https://en.wikipedia.org/wiki/Borate), [chalcogenides](https://en.wikipedia.org/wiki/Chalcogenide_glass), [fluorides](https://en.wikipedia.org/wiki/Fluoride), germanates (glasses based on [GeO2](https://en.wikipedia.org/wiki/Germanium_oxide)), tellurites (glasses based on TeO2), antimonates (glasses based on Sb2O3), arsenates (glasses based on As2O3), titanates (glasses based on TiO2), tantalates (glasses based on Ta2O5), [nitrates](https://en.wikipedia.org/wiki/Nitrate), [carbonates](https://en.wikipedia.org/wiki/Carbonate), [plastics](https://en.wikipedia.org/wiki/Plastics), [acrylic](https://en.wikipedia.org/wiki/Acrylic_glass), and many other substances.[[5]](https://en.wikipedia.org/wiki/Glass#cite_note-Elliot84-5) Some of these glasses (e.g. [Germanium dioxide](https://en.wikipedia.org/wiki/Germanium_dioxide) (GeO2, Germania), in many respects a structural analogue of silica, [fluoride](https://en.wikipedia.org/wiki/Fluoride_glass), [aluminate](https://en.wikipedia.org/wiki/Aluminate), [phosphate](https://en.wikipedia.org/wiki/Phosphate_glass), [borate](https://en.wikipedia.org/wiki/Borate_glass), and [chalcogenide](https://en.wikipedia.org/wiki/Chalcogenide_glass) glasses) have physico-chemical properties useful for their application in [fibre-optic](https://en.wikipedia.org/wiki/Optical_fiber) [waveguides](https://en.wikipedia.org/wiki/Waveguide) in communication networks and other specialized technological applications.[[85]](https://en.wikipedia.org/wiki/Glass#cite_note-85)[[86]](https://en.wikipedia.org/wiki/Glass#cite_note-86)

Silica-free glasses may often have poor glass forming tendencies. Novel techniques, including containerless processing by [aerodynamic levitation](https://en.wikipedia.org/wiki/Aerodynamic_levitation) (cooling the melt whilst it floats on a gas stream) or [splat quenching](https://en.wikipedia.org/wiki/Splat_quenching) (pressing the melt between two metal anvils or rollers), may be used increase cooling rate, or reduce crystal nucleation triggers.[[87]](https://en.wikipedia.org/wiki/Glass#cite_note-87)[[88]](https://en.wikipedia.org/wiki/Glass#cite_note-88)[[89]](https://en.wikipedia.org/wiki/Glass#cite_note-89)

**Amorphous metals**

*Main article:*[*Amorphous metal*](https://en.wikipedia.org/wiki/Amorphous_metal)

[](https://en.wikipedia.org/wiki/File:Bulk_Metallic_Glass_Sample.jpg)

Samples of amorphous metal, with millimeter scale

In the past, small batches of [amorphous metals](https://en.wikipedia.org/wiki/Amorphous_metal) with high surface area configurations (ribbons, wires, films, etc.) have been produced through the implementation of extremely rapid rates of cooling. Amorphous metal wires have been produced by sputtering molten metal onto a spinning metal disk. More recently a number of alloys have been produced in layers with thickness exceeding 1 millimeter. These are known as bulk metallic glasses (BMG). [Liquidmetal Technologies](https://en.wikipedia.org/wiki/Liquidmetal) sell a number of zirconium-based BMGs. Batches of amorphous steel have also been produced that demonstrate mechanical properties far exceeding those found in conventional steel alloys.[[90]](https://en.wikipedia.org/wiki/Glass#cite_note-90)[[91]](https://en.wikipedia.org/wiki/Glass#cite_note-91)[[92]](https://en.wikipedia.org/wiki/Glass#cite_note-92)

Experimental evidence indicates that the system Al-Fe-Si may undergo a *first-order transition* to an amorphous form (dubbed "q-glass") on rapid cooling from the melt. [Transmission electron microscopy](https://en.wikipedia.org/wiki/Transmission_electron_microscopy) (TEM) images indicate that q-glass nucleates from the melt as discrete particles with a uniform spherical growth in all directions. While [x-ray diffraction](https://en.wikipedia.org/wiki/X-ray_diffraction) reveals the isotropic nature of q-glass, a [nucleation](https://en.wikipedia.org/wiki/Nucleation) barrier exists implying an interfacial discontinuity (or internal surface) between the glass and melt phases.[[93]](https://en.wikipedia.org/wiki/Glass#cite_note-93)[[94]](https://en.wikipedia.org/wiki/Glass#cite_note-94)

**Polymers**

Important polymer glasses include amorphous and glassy pharmaceutical compounds. These are useful because the solubility of the compound is greatly increased when it is amorphous compared to the same crystalline composition. Many emerging pharmaceuticals are practically insoluble in their crystalline forms.[[95]](https://en.wikipedia.org/wiki/Glass#cite_note-95) Many polymer [thermoplastics](https://en.wikipedia.org/wiki/Thermoplastic) familiar from everyday use are glasses. For many applications, like [glass bottles](https://en.wikipedia.org/wiki/Glass_bottles) or [eyewear](https://en.wikipedia.org/wiki/Eyewear), polymer glasses ([acrylic glass](https://en.wikipedia.org/wiki/Acrylic_glass), [polycarbonate](https://en.wikipedia.org/wiki/Polycarbonate) or [polyethylene terephthalate](https://en.wikipedia.org/wiki/Polyethylene_terephthalate)) are a lighter alternative to traditional glass.[[96]](https://en.wikipedia.org/wiki/Glass#cite_note-Carraher-polymer-96)

**Molecular liquids and molten salts**

Molecular liquids, [electrolytes](https://en.wikipedia.org/wiki/Electrolyte), [molten salts](https://en.wikipedia.org/wiki/Molten_salt), and [aqueous solutions](https://en.wikipedia.org/wiki/Aqueous_solution) are mixtures of different [molecules](https://en.wikipedia.org/wiki/Molecules) or [ions](https://en.wikipedia.org/wiki/Ion) that do not form a covalent network but interact only through weak [van der Waals forces](https://en.wikipedia.org/wiki/Van_der_Waals_force) or through transient [hydrogen bonds](https://en.wikipedia.org/wiki/Hydrogen_bond). In a mixture of three or more ionic species of dissimilar size and shape, crystallization can be so difficult that the liquid can easily be supercooled into a glass.[[97]](https://en.wikipedia.org/wiki/Glass#cite_note-97)[[98]](https://en.wikipedia.org/wiki/Glass#cite_note-98) Examples include LiCl:*R*H2O (a solution of [lithium chloride](https://en.wikipedia.org/wiki/Lithium_chloride) salt and water molecules) in the composition range 4<*R*<8.[[99]](https://en.wikipedia.org/wiki/Glass#cite_note-99) [sugar glass](https://en.wikipedia.org/wiki/Sugar_glass),[[100]](https://en.wikipedia.org/wiki/Glass#cite_note-100) or Ca0.4K0.6(NO3)1.4.[[101]](https://en.wikipedia.org/wiki/Glass#cite_note-101) Glass electrolytes in the form of Ba-doped Li-glass and Ba-doped Na-glass have been proposed as solutions to problems identified with organic liquid electrolytes used in modern lithium-ion battery cells.[[102]](https://en.wikipedia.org/wiki/Glass#cite_note-102)

Production

*Main articles:*[*Glass production*](https://en.wikipedia.org/wiki/Glass_production)*,*[*Float glass*](https://en.wikipedia.org/wiki/Float_glass)*, and*[*Glassblowing*](https://en.wikipedia.org/wiki/Glassblowing)

[](https://en.wikipedia.org/wiki/File:Float_Glass_Unloading.jpg)

Robotized float glass unloading

Following the [glass batch](https://en.wikipedia.org/wiki/Glass_batch) preparation and mixing, the raw materials are transported to the furnace. [Soda-lime glass](https://en.wikipedia.org/wiki/Soda-lime_glass) for [mass production](https://en.wikipedia.org/wiki/Mass_production) is melted in [gas fired units](https://en.wikipedia.org/wiki/Glass_production#Furnace). Smaller scale furnaces for specialty glasses include electric melters, pot furnaces, and day tanks.[[67]](https://en.wikipedia.org/wiki/Glass#cite_note-ullmann-67) After melting, homogenization and [refining](https://en.wikipedia.org/wiki/Refining_(glass)) (removal of bubbles), the glass is [formed](https://en.wikipedia.org/wiki/Template:Glass_forming). [Flat glass](https://en.wikipedia.org/wiki/Flat_glass) for windows and similar applications is formed by the [float glass](https://en.wikipedia.org/wiki/Float_glass) process, developed between 1953 and 1957 by Sir [Alastair Pilkington](https://en.wikipedia.org/wiki/Alastair_Pilkington) and Kenneth Bickerstaff of the UK's Pilkington Brothers, who created a continuous ribbon of glass using a molten tin bath on which the molten glass flows unhindered under the influence of gravity. The top surface of the glass is subjected to nitrogen under pressure to obtain a polished finish.[[103]](https://en.wikipedia.org/wiki/Glass#cite_note-103) [Container glass](https://en.wikipedia.org/wiki/Container_glass) for common bottles and jars is formed by [blowing and pressing](https://en.wikipedia.org/wiki/Glass_container_production#Forming_process) methods.[[104]](https://en.wikipedia.org/wiki/Glass#cite_note-104) This glass is often slightly modified chemically (with more alumina and calcium oxide) for greater water resistance.[[105]](https://en.wikipedia.org/wiki/Glass#cite_note-105)

[](https://en.wikipedia.org/wiki/File:Skansen,_Stockholm,_Sweden_(Unsplash).jpg)

Glass blowing

Once the desired form is obtained, glass is usually [annealed](https://en.wikipedia.org/wiki/Annealing_(glass)) for the removal of stresses and to increase the glass's hardness and durability.[[106]](https://en.wikipedia.org/wiki/Glass#cite_note-EB1911-106) Surface treatments, coatings or [lamination](https://en.wikipedia.org/wiki/Lamination) may follow to improve the chemical durability ([glass container coatings](https://en.wikipedia.org/wiki/Glass_production#Coatings), [glass container internal treatment](https://en.wikipedia.org/wiki/Glass_production#Internal_treatment)), strength ([toughened glass](https://en.wikipedia.org/wiki/Toughened_glass), [bulletproof glass](https://en.wikipedia.org/wiki/Bulletproof_glass), [windshields](https://en.wikipedia.org/wiki/Windshield)[[107]](https://en.wikipedia.org/wiki/Glass#cite_note-107)), or optical properties ([insulated glazing](https://en.wikipedia.org/wiki/Insulated_glazing), [anti-reflective coating](https://en.wikipedia.org/wiki/Anti-reflective_coating)).[[108]](https://en.wikipedia.org/wiki/Glass#cite_note-108)

New chemical glass compositions or new treatment techniques can be initially investigated in small-scale laboratory experiments. The raw materials for laboratory-scale glass melts are often different from those used in mass production because the cost factor has a low priority. In the laboratory mostly pure [chemicals](https://en.wikipedia.org/wiki/Chemical) are used. Care must be taken that the raw materials have not reacted with moisture or other chemicals in the environment (such as [alkali](https://en.wikipedia.org/wiki/Alkali_metal) or [alkaline earth metal](https://en.wikipedia.org/wiki/Alkaline_earth_metal) oxides and hydroxides, or [boron oxide](https://en.wikipedia.org/wiki/Boron_trioxide)), or that the impurities are quantified (loss on ignition).[[109]](https://en.wikipedia.org/wiki/Glass#cite_note-pnnl-109) Evaporation losses during glass melting should be considered during the selection of the raw materials, e.g., [sodium selenite](https://en.wikipedia.org/wiki/Sodium_selenite) may be preferred over easily evaporating [selenium dioxide](https://en.wikipedia.org/wiki/Selenium_dioxide) (SeO2). Also, more readily reacting raw materials may be preferred over relatively [inert](https://en.wikipedia.org/wiki/Chemically_inert) ones, such as [aluminum hydroxide](https://en.wikipedia.org/wiki/Aluminium_hydroxide) (Al(OH)3) over [alumina](https://en.wikipedia.org/wiki/Aluminium_oxide) (Al2O3). Usually, the melts are carried out in platinum crucibles to reduce contamination from the crucible material. Glass [homogeneity](https://en.wikipedia.org/wiki/Homogeneous_(chemistry)) is achieved by homogenizing the raw materials mixture ([glass batch](https://en.wikipedia.org/wiki/Glass_batch)), by stirring the melt, and by crushing and re-melting the first melt. The obtained glass is usually [annealed](https://en.wikipedia.org/wiki/Annealing_(glass)) to prevent breakage during processing.[[109]](https://en.wikipedia.org/wiki/Glass#cite_note-pnnl-109)[[110]](https://en.wikipedia.org/wiki/Glass#cite_note-110)

**Colour**

*Main article:*[*Glass coloring and color marking*](https://en.wikipedia.org/wiki/Glass_coloring_and_color_marking)

Colour in glass may be obtained by addition of homogenously distributed electrically charged ions (or [colour centres](https://en.wikipedia.org/wiki/Transparent_materials#Absorption_of_light_in_solids)). While ordinary [soda-lime glass](https://en.wikipedia.org/wiki/Soda-lime_glass) appears colourless in thin section, [iron(II) oxide](https://en.wikipedia.org/wiki/Iron(II)_oxide) (FeO) impurities produce a green tint in thick sections.[[111]](https://en.wikipedia.org/wiki/Glass#cite_note-Mukherjee13-111) [Manganese dioxide](https://en.wikipedia.org/wiki/Manganese_dioxide) (MnO2), which gives glass a purple colour, may be added to remove the green tint given by FeO.[[112]](https://en.wikipedia.org/wiki/Glass#cite_note-112) FeO and [chromium(III) oxide](https://en.wikipedia.org/wiki/Chromium(III)_oxide) (Cr2O3) additives are used in the production of green bottles.[[111]](https://en.wikipedia.org/wiki/Glass#cite_note-Mukherjee13-111) [Iron (III) oxide](https://en.wikipedia.org/wiki/Iron_(III)_oxide), on the other-hand, produces yellow or yellow-brown glass.[[113]](https://en.wikipedia.org/wiki/Glass#cite_note-Langhamer03-113) Low concentrations (0.025 to 0.1%) of [cobalt oxide](https://en.wikipedia.org/wiki/Cobalt_oxide) (CoO) produces rich, deep blue [cobalt glass](https://en.wikipedia.org/wiki/Cobalt_glass).[[114]](https://en.wikipedia.org/wiki/Glass#cite_note-114) [Chromium](https://en.wikipedia.org/wiki/Chromium) is a very powerful colourising agent, yielding dark green.[[115]](https://en.wikipedia.org/wiki/Glass#cite_note-115) [Sulphur](https://en.wikipedia.org/wiki/Sulphur) combined with [carbon](https://en.wikipedia.org/wiki/Carbon) and iron salts produces amber glass ranging from yellowish to almost black.[[116]](https://en.wikipedia.org/wiki/Glass#cite_note-116) A glass melt can also acquire an amber colour from a reducing combustion atmosphere.[[117]](https://en.wikipedia.org/wiki/Glass#cite_note-117) [Cadmium sulfide](https://en.wikipedia.org/wiki/Cadmium_sulfide) produces imperial [red](https://en.wikipedia.org/wiki/Red), and combined with selenium can produce shades of yellow, orange, and red.[[111]](https://en.wikipedia.org/wiki/Glass#cite_note-Mukherjee13-111)[[113]](https://en.wikipedia.org/wiki/Glass#cite_note-Langhamer03-113) The additive [Copper(II) oxide](https://en.wikipedia.org/wiki/Copper(II)_oxide) (CuO) produces a [turquoise](https://en.wikipedia.org/wiki/Turquoise_(color)) colour in glass, in contrast to [Copper(I) oxide](https://en.wikipedia.org/wiki/Copper(I)_oxide) (Cu2O) which gives a dull brown-red colour.[[118]](https://en.wikipedia.org/wiki/Glass#cite_note-Nicholson00-118)

* [](https://en.wikipedia.org/wiki/File:Bottle,_wine_(AM_1997.80.28-1).jpg)

[Iron(II) oxide](https://en.wikipedia.org/wiki/Iron(II)_oxide) and [chromium(III) oxide](https://en.wikipedia.org/wiki/Chromium(III)_oxide) additives are often used in the production of green bottles.[[111]](https://en.wikipedia.org/wiki/Glass#cite_note-Mukherjee13-111)

* [](https://en.wikipedia.org/wiki/File:Bristol.blue.glass.arp.750pix.jpg)

[Cobalt oxide](https://en.wikipedia.org/wiki/Cobalt_oxide) produces rich, [deep blue glass](https://en.wikipedia.org/wiki/Cobalt_glass), such as [Bristol blue glass](https://en.wikipedia.org/wiki/Bristol_blue_glass).

* [](https://en.wikipedia.org/wiki/File:Colour_Eclipse,_Danny_Lane.jpg)

Different oxide additives produce the different colours in glass: [turquoise](https://en.wikipedia.org/wiki/Turquoise_(color)) ([Copper(II) oxide](https://en.wikipedia.org/wiki/Copper(II)_oxide)),[[118]](https://en.wikipedia.org/wiki/Glass#cite_note-Nicholson00-118) purple ([Manganese dioxide](https://en.wikipedia.org/wiki/Manganese_dioxide)),[[111]](https://en.wikipedia.org/wiki/Glass#cite_note-Mukherjee13-111) and red ([Cadmium sulfide](https://en.wikipedia.org/wiki/Cadmium_sulfide)).[[111]](https://en.wikipedia.org/wiki/Glass#cite_note-Mukherjee13-111)

* Red glass bottle with yellow glass overlay

* [](https://en.wikipedia.org/wiki/File:Glass_ornaments.JPG)

Amber-coloured glass

* [](https://en.wikipedia.org/wiki/File:Glass_garland_bowl_MET_DP122006.jpg)

Four-colour Roman glass bowl, manufactured circa 1st century B.C.

Uses

[](https://en.wikipedia.org/wiki/File:The_Shard_from_the_Sky_Garden_2015.jpg)

[The Shard](https://en.wikipedia.org/wiki/The_Shard) glass skyscraper, in [London](https://en.wikipedia.org/wiki/London).

**Architecture and windows**

*Main articles:*[*Architectural glass*](https://en.wikipedia.org/wiki/Architectural_glass)*and*[*Window*](https://en.wikipedia.org/wiki/Window)

Soda-lime [sheet glass](https://en.wikipedia.org/wiki/Plate_glass) is typically used as transparent [glazing](https://en.wikipedia.org/wiki/Glazing_in_architecture) material, typically as [windows](https://en.wikipedia.org/wiki/Window) in external walls of buildings. Float or rolled sheet glass products is cut to size either by [scoring](https://en.wikipedia.org/wiki/Scoring_(industrial_process)) and snapping the material, [laser cutting](https://en.wikipedia.org/wiki/Laser_cutting), [water jets](https://en.wikipedia.org/wiki/Water_jet_cutter), or [diamond bladed](https://en.wikipedia.org/wiki/Diamond_blade) saw. The glass may be thermally or chemically [tempered](https://en.wikipedia.org/wiki/Tempered_glass) (strengthened) for safety and bent or curved during heating. Surface coatings may be added for specific functions such as scratch resistance, blocking specific wavelengths of light (e.g. [infrared](https://en.wikipedia.org/wiki/Infrared) or [ultraviolet](https://en.wikipedia.org/wiki/Ultraviolet)), dirt-repellence (e.g. [self-cleaning glass](https://en.wikipedia.org/wiki/Self-cleaning_glass)), or switchable [electrochromic](https://en.wikipedia.org/wiki/Electrochromism) coatings.[[119]](https://en.wikipedia.org/wiki/Glass#cite_note-Weller12-119)

Structural glazing systems represent one of the most significant architectural innovations of modern times, where glass buildings now often dominate [skylines](https://en.wikipedia.org/wiki/Skyline) of many modern [cities](https://en.wikipedia.org/wiki/Cities).[[120]](https://en.wikipedia.org/wiki/Glass#cite_note-glass-times-120) These systems use stainless steel fittings countersunk into recesses in the corners of the glass panels allowing strengthened panes to appear unsupported creating a flush exterior.[[120]](https://en.wikipedia.org/wiki/Glass#cite_note-glass-times-120) Structural glazing systems have their roots in iron and [glass conservatories](https://en.wikipedia.org/wiki/Conservatory_(greenhouse)) of the nineteenth century[[121]](https://en.wikipedia.org/wiki/Glass#cite_note-Patterson-121)

**Tableware**

*Main articles:*[*Tableware*](https://en.wikipedia.org/wiki/Tableware)*and*[*List of glassware*](https://en.wikipedia.org/wiki/List_of_glassware)

Glass is an essential component of tableware and is typically used for water, [beer](https://en.wikipedia.org/wiki/Beer_glassware) and [wine](https://en.wikipedia.org/wiki/Wine_glass) drinking glasses.[[44]](https://en.wikipedia.org/wiki/Glass#cite_note-glassalliance-44) Wine glasses are typically [stemware](https://en.wikipedia.org/wiki/Stemware), i.e. goblets formed from a bowl, stem, and foot. Crystal or [Lead crystal](https://en.wikipedia.org/wiki/Lead_glass) glass may be cut and polished to produce decorative drinking glasses with gleaming facets.[[122]](https://en.wikipedia.org/wiki/Glass#cite_note-122)[[123]](https://en.wikipedia.org/wiki/Glass#cite_note-123) Other uses of glass in tableware include [decanters](https://en.wikipedia.org/wiki/Decanters), [jugs](https://en.wikipedia.org/wiki/Jug), [plates](https://en.wikipedia.org/wiki/Plate_(dishware)), and [bowls](https://en.wikipedia.org/wiki/Bowl).[[44]](https://en.wikipedia.org/wiki/Glass#cite_note-glassalliance-44)

* [](https://en.wikipedia.org/wiki/File:Jubilee_Campus_MMB_%C2%AB62_Melton_Hall_Christmas_Dinner.jpg)

Wine glasses and other glass tableware

* [](https://en.wikipedia.org/wiki/File:British_dimpled_glass_pint_jug_with_ale.jpg)

Dimpled glass beer pint jug

* [](https://en.wikipedia.org/wiki/File:Crystal_glass.jpg)

Cut [lead crystal glass](https://en.wikipedia.org/wiki/Lead_glass)

* [](https://en.wikipedia.org/wiki/File:Decanter_and_Stopper_LACMA_56.35.29a-b.jpg)

A glass [decanter](https://en.wikipedia.org/wiki/Decanter) and [stopper](https://en.wikipedia.org/wiki/Bung)

**Laboratories**

*Main article:*[*Laboratory glassware*](https://en.wikipedia.org/wiki/Laboratory_glassware)

Glass is an important material in scientific laboratories for the manufacture of experimental apparatus because it is relatively cheap, readily formed into required shapes for experiment, easy to keep clean, can withstand heat and cold treatment, is generally non-reactive with many [reagents](https://en.wikipedia.org/wiki/Reagent), and its transparency allows for the observation of chemical reactions and processes.[[124]](https://en.wikipedia.org/wiki/Glass#cite_note-Zumdahl-124)[[125]](https://en.wikipedia.org/wiki/Glass#cite_note-125) [Laboratory glassware](https://en.wikipedia.org/wiki/Laboratory_glassware) applications include [flasks](https://en.wikipedia.org/wiki/Laboratory_flask), [petri dishes](https://en.wikipedia.org/wiki/Petri_dish), [test tubes](https://en.wikipedia.org/wiki/Test_tube), [pipettes](https://en.wikipedia.org/wiki/Pipette), [graduated cylinders](https://en.wikipedia.org/wiki/Graduated_cylinder), glass lined metallic containers for chemical processing, [fractionation columns](https://en.wikipedia.org/wiki/Fractionation_column), glass pipes, [Schlenk lines](https://en.wikipedia.org/wiki/Schlenk_line), [gauges](https://en.wikipedia.org/wiki/Gauge_(instrument)), and [thermometers](https://en.wikipedia.org/wiki/Thermometer).[[126]](https://en.wikipedia.org/wiki/Glass#cite_note-BASUDEB-126)[[124]](https://en.wikipedia.org/wiki/Glass#cite_note-Zumdahl-124) Although most standard laboratory glassware has been mass-produced since the 1920s, scientists still employ skilled [glassblowers](https://en.wikipedia.org/wiki/Glassblower) to manufacture bespoke glass apparatus for their experimental requirements.[[127]](https://en.wikipedia.org/wiki/Glass#cite_note-127)

* [](https://en.wikipedia.org/wiki/File:Vigreux_column_lab.jpg)

A Vigreux [column](https://en.wikipedia.org/wiki/Fractionating_column) in a laboratory setup

* [](https://en.wikipedia.org/wiki/File:Double_vac_line_front_view.jpg)

A [Schlenk line](https://en.wikipedia.org/wiki/Schlenk_line) with four ports

* [](https://en.wikipedia.org/wiki/File:Different_types_of_graduated_cylinder-_10ml,_25ml,_50ml_and_100_ml_graduated_cylinder.jpg)

[Graduated cylinders](https://en.wikipedia.org/wiki/Graduated_cylinder)

* [](https://en.wikipedia.org/wiki/File:250_mL_Erlenmeyer_flask.jpg)

Erlenmeyer [flask](https://en.wikipedia.org/wiki/Laboratory_flask)

**Optics**

Glass is a ubiquitous material in [optics](https://en.wikipedia.org/wiki/Optics) by virtue of its ability to [refract](https://en.wikipedia.org/wiki/Refraction), [reflect](https://en.wikipedia.org/wiki/Reflection_(physics)), and [transmit](https://en.wikipedia.org/wiki/Transmittance) light. These and other optical properties can be controlled by varying chemical compositions, thermal treatment, and manufacturing techniques. The many applications of glass in optics includes [glasses](https://en.wikipedia.org/wiki/Glasses) for eyesight correction, imaging optics (e.g. [lenses](https://en.wikipedia.org/wiki/Lens) and [mirrors](https://en.wikipedia.org/wiki/Mirror) in [telescopes](https://en.wikipedia.org/wiki/Telescope), [microscopes](https://en.wikipedia.org/wiki/Microscope), and [cameras](https://en.wikipedia.org/wiki/Camera)), [fibre optics](https://en.wikipedia.org/wiki/Fibre_optics) in [telecommunications](https://en.wikipedia.org/wiki/Telecommunications) technology, and [integrated optics](https://en.wikipedia.org/wiki/Photonic_integrated_circuit). [Microlenses](https://en.wikipedia.org/wiki/Microlens) and [gradient-index optics](https://en.wikipedia.org/wiki/Gradient-index_optics) (where the [refractive index](https://en.wikipedia.org/wiki/Refractive_index) is non-uniform) find application in e.g. reading [optical discs](https://en.wikipedia.org/wiki/Optical_disc), [laser printers](https://en.wikipedia.org/wiki/Laser_printer), [photocopiers](https://en.wikipedia.org/wiki/Photocopier), and [laser diodes](https://en.wikipedia.org/wiki/Laser_diode). [[49]](https://en.wikipedia.org/wiki/Glass#cite_note-Bach12-49)

**Art**

*Main articles:*[*Studio glass*](https://en.wikipedia.org/wiki/Studio_glass)*,*[*Art glass*](https://en.wikipedia.org/wiki/Art_glass)*, and*[*Glass art*](https://en.wikipedia.org/wiki/Glass_art)

The 19th century saw a revival in ancient glass-making techniques including [cameo glass](https://en.wikipedia.org/wiki/Cameo_glass), achieved for the first time since the Roman Empire, initially mostly for pieces in a [neo-classical](https://en.wikipedia.org/wiki/Neoclassicism) style. The [Art Nouveau](https://en.wikipedia.org/wiki/Art_Nouveau) movement made great use of glass, with [René Lalique](https://en.wikipedia.org/wiki/Ren%C3%A9_Lalique), [Émile Gallé](https://en.wikipedia.org/wiki/%C3%89mile_Gall%C3%A9), and [Daum of Nancy](https://en.wikipedia.org/wiki/Daum_(studio)) in the first French wave of the movement, producing coloured vases and similar pieces, often in cameo glass or in luster techniques.[[128]](https://en.wikipedia.org/wiki/Glass#cite_note-128) [Louis Comfort Tiffany](https://en.wikipedia.org/wiki/Louis_Comfort_Tiffany) in America specialized in stained glass, both secular and religious, in panels and his famous lamps. The early 20th-century saw the large-scale factory production of glass art by firms such as [Waterford](https://en.wikipedia.org/wiki/Waterford_Crystal) and [Lalique](https://en.wikipedia.org/wiki/Lalique). Small studios may hand-produce glass artworks. Techniques for producing glass art include [blowing](https://en.wikipedia.org/wiki/Glass_blowing), kiln-casting, fusing, slumping, pâté-de-verre, flame-working, hot-sculpting and cold-working. Cold work includes traditional stained glass work and other methods of shaping glass at room temperature. Objects made out of glass include vessels, [paperweights](https://en.wikipedia.org/wiki/Paperweight_collecting), [marbles](https://en.wikipedia.org/wiki/Marbles), [beads](https://en.wikipedia.org/wiki/Bead), sculptures and [installation art](https://en.wikipedia.org/wiki/Installation_art).[[129]](https://en.wikipedia.org/wiki/Glass#cite_note-V&A_A-Z-129)

* [](https://en.wikipedia.org/wiki/File:Gall%C3%A9_Cameo_glass_vase_with_clematis.jpg)

[Cameo glass](https://en.wikipedia.org/wiki/Cameo_glass) vase with clematis, by [art nouveau](https://en.wikipedia.org/wiki/Art_nouveau) artist [Émile Gallé](https://en.wikipedia.org/wiki/%C3%89mile_Gall%C3%A9)

* Glass vase by [art nouveau](https://en.wikipedia.org/wiki/Art_nouveau) artist [René Lalique](https://en.wikipedia.org/wiki/Ren%C3%A9_Lalique)

* [](https://en.wikipedia.org/wiki/File:Girl_with_Cherry_Blossoms_-_Tiffany_Glass_%26_Decorating_Company,_c._1890.JPG)

[Tiffany glass](https://en.wikipedia.org/wiki/Tiffany_glass) panel "Girl with Cherry Blossoms"

* [](https://en.wikipedia.org/wiki/File:Glass.sculpture.kewgardens.london.arp.jpg)

A glass sculpture by [Dale Chihuly](https://en.wikipedia.org/wiki/Dale_Chihuly), "The Sun" at the "Gardens of Glass" exhibition in Kew Gardens, London

* [](https://en.wikipedia.org/wiki/File:Modern_stained_glass_-_geograph.org.uk_-_921350.jpg)

Modern stained glass window

* [](https://en.wikipedia.org/wiki/File:JM_marbles_01.jpg)

Glass [marbles](https://en.wikipedia.org/wiki/Marbles)

* [](https://en.wikipedia.org/wiki/File:Ken_Rosenfeld_Lampwork_Orb_Paperweight.jpg)

A flower bouquet glass [paperweight](https://en.wikipedia.org/wiki/Paperweight)

See also

* [Caneworking](https://en.wikipedia.org/wiki/Caneworking)
* [Colloid](https://en.wikipedia.org/wiki/Colloid)
* [Fabrication and testing of optical components](https://en.wikipedia.org/wiki/Fabrication_and_testing_of_optical_components)
* [Fire glass](https://en.wikipedia.org/wiki/Fire_glass)
* [Glassy carbon](https://en.wikipedia.org/wiki/Glassy_carbon)
* [Gorilla Glass](https://en.wikipedia.org/wiki/Gorilla_Glass)
* [Kimberley points](https://en.wikipedia.org/wiki/Kimberley_points)
* [Low-iron glass](https://en.wikipedia.org/wiki/Low-iron_glass)
* [Murrine](https://en.wikipedia.org/wiki/Murrine)
* [Millefiori](https://en.wikipedia.org/wiki/Millefiori)
* [Optical lens design](https://en.wikipedia.org/wiki/Optical_lens_design#Process)
* [Prince Rupert's drop](https://en.wikipedia.org/wiki/Prince_Rupert%27s_drop)
* [Smart glass](https://en.wikipedia.org/wiki/Smart_glass)
* [Superglass](https://en.wikipedia.org/wiki/Superglass)
* [Tektite](https://en.wikipedia.org/wiki/Tektite)

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