



Density

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The **density**, or more precisely, the **volumetric mass density**, of a substance is its mass per unit volume. The symbol most often used for density is ρ (the lower case Greek letter rho), although the Latin letter *D* can also be used. Mathematically, density is defined as mass divided by volume:^[1]

$$\rho = \frac{m}{V},$$

where ρ is the density, m is the mass, and V is the volume. In some cases (for instance, in the United States oil and gas industry), density is loosely defined as its weight per unit volume,^[2] although this is scientifically inaccurate – this quantity is more specifically called specific weight.

For a pure substance the density has the same numerical value as its mass concentration. Different materials usually have different densities, and density may be relevant to buoyancy, purity and packaging. Osmium and iridium are the densest known elements at standard conditions for temperature and pressure but certain chemical compounds may be denser.

To simplify comparisons of density across different systems of units, it is sometimes replaced by the dimensionless quantity "relative density" or "specific gravity", i.e. the ratio of the density of the material to that of a standard material, usually water. Thus a relative density less than one means that the substance floats in water.

The density of a material varies with temperature and pressure. This variation is typically small for solids and liquids but much greater for gases. Increasing the pressure on an object decreases the volume of the object and thus increases its density. Increasing the temperature of a substance (with a few exceptions) decreases its density by increasing its volume. In most materials, heating the bottom of a fluid results in convection of the heat from the bottom to the top, due to the decrease in the density of the heated fluid. This causes it to rise relative to more dense unheated material.

The reciprocal of the density of a substance is occasionally called its specific volume, a term sometimes used in thermodynamics. Density is an intensive property in that increasing the amount of a substance does not increase its density; rather it increases its mass.

Contents

- 1 History
- 2 Measurement of density
 - 2.1 Homogeneous materials
 - 2.2 Heterogeneous materials
 - 2.3 Non-compact materials
- 3 Changes of density
- 4 Density of solutions
- 5 Densities
 - 5.1 Water
 - 5.2 Air
 - 5.3 Various materials
 - 5.4 Others
- 6 Common units
- 7 See also
- 8 References
- 9 External links

<i>Density</i>	
Common symbols	ρ <i>D</i>
SI unit	kg/m ³



A graduated cylinder containing various coloured liquids with different densities.

History

In a well-known but probably apocryphal tale, Archimedes was given the task of determining whether King Hiero's goldsmith was embezzling gold during the manufacture of a golden wreath dedicated to the gods and replacing it with another, cheaper alloy.^[3] Archimedes knew that the irregularly shaped wreath could be crushed into a cube whose volume could be calculated easily and compared with the mass; but the king did not approve of this. Baffled, Archimedes is said to have taken an immersion bath and observed from the rise of the water upon entering that he could calculate the volume of the gold wreath through the displacement of the water. Upon this discovery, he leapt from his bath and ran naked through the streets shouting, "Eureka! Eureka!" (Εὕρηκα! Greek "I have found it"). As a result, the term "eureka" entered common parlance and is used today to indicate a moment of enlightenment.

The story first appeared in written form in Vitruvius' *books of architecture*, two centuries after it supposedly took place.^[4] Some scholars have doubted the accuracy of this tale, saying among other things that the method would have required precise measurements that would have been difficult to make at the time.^{[5][6]}

From the equation for density ($\rho = m / V$), mass density has units of mass divided by volume. As there are many units of mass and volume covering many different magnitudes there are a large number of units for mass density in use. The SI unit of kilogram per cubic metre (kg/m^3) and the cgs unit of gram per cubic centimetre (g/cm^3) are probably the most commonly used units for density. $1,000 \text{ kg/m}^3$ equals 1 g/cm^3 . (The cubic centimeter can be alternately called a *millilitre* or a *cc*.) In industry, other larger or smaller units of mass and or volume are often more practical and US customary units may be used. See below for a list of some of the most common units of density.

Measurement of density

Homogeneous materials

The density at all points of a homogeneous object equals its total mass divided by its total volume. The mass is normally measured with a scale or balance; the volume may be measured directly (from the geometry of the object) or by the displacement of a fluid. To determine the density of a liquid or a gas, a hydrometer, a dasymeter or a Coriolis flow meter may be used, respectively. Similarly, hydrostatic weighing uses the displacement of water due to a submerged object to determine the density of the object.

Heterogeneous materials

If the body is not homogeneous, then its density varies between different regions of the object. In that case the density around any given location is determined by calculating the density of a small volume around that location. In the limit of an infinitesimal volume the density of an inhomogeneous object at a point becomes: $\rho(\vec{r}) = \text{d}m/\text{d}V$, where $\text{d}V$ is an elementary volume at position r . The mass of the body then can be expressed as

$$m = \int_V \rho(\vec{r}) \text{d}V.$$

Non-compact materials

In practice, bulk materials such as sugar, sand, or snow contain voids. Many materials exist in nature as flakes, pellets, or granules.

Voids are regions which contain something other than the considered material. Commonly the void is air, but it could also be vacuum, liquid, solid, or a different gas or gaseous mixture.

The bulk volume of a material—inclusive of the void fraction—is often obtained by a simple measurement (e.g. with a calibrated measuring cup) or geometrically from known dimensions.

Mass divided by *bulk* volume determines bulk density. This is not the same thing as volumetric mass density.

To determine volumetric mass density, one must first discount the volume of the void fraction. Sometimes this can be determined by geometrical reasoning. For the close-packing of equal spheres the non-void fraction can be at most about 74%. It can also be determined empirically. Some bulk materials, however, such as sand, have a *variable* void fraction which depends on how the material is agitated or poured. It might be loose or compact, with more or less air space depending on handling.

In practice, the void fraction is not necessarily air, or even gaseous. In the case of sand, it could be water, which can be advantageous for measurement as the void fraction for sand saturated in water—once any air bubbles are thoroughly driven out—is potentially more consistent than dry sand measured with an air void.

In the case of non-compact materials, one must also take care in determining the mass of the material sample. If the material is under pressure (commonly ambient air pressure at the earth's surface) the determination of mass from a measured sample weight might need to account for buoyancy effects due to the density of the void constituent, depending on how the measurement was conducted. In the case of dry sand, sand is so much denser than air that the buoyancy effect is commonly neglected (less than one part in one thousand).

Mass change upon displacing one void material with another while maintaining constant volume can be used to estimate the void fraction, if the difference in density of the two voids materials is reliably known.

Changes of density

In general, density can be changed by changing either the pressure or the temperature. Increasing the pressure always increases the density of a material. Increasing the temperature generally decreases the density, but there are notable exceptions to this generalization. For example, the density of water increases between its melting point at 0 °C and 4 °C; similar behavior is observed in silicon at low temperatures.

The effect of pressure and temperature on the densities of liquids and solids is small. The compressibility for a typical liquid or solid is 10^{-6} bar^{-1} (1 bar = 0.1 MPa) and a typical thermal expansivity is 10^{-5} K^{-1} . This roughly translates into needing around ten thousand times atmospheric pressure to reduce the volume of a substance by one percent. (Although the pressures needed may be around a thousand times smaller for sandy soil and some clays.) A one percent expansion of volume typically requires a temperature increase on the order of thousands of degrees Celsius.

In contrast, the density of gases is strongly affected by pressure. The density of an ideal gas is

$$\rho = \frac{MP}{RT},$$

where M is the molar mass, P is the pressure, R is the universal gas constant, and T is the absolute temperature. This means that the density of an ideal gas can be doubled by doubling the pressure, or by halving the absolute temperature.

In the case of volumic thermal expansion at constant pressure and small intervals of temperature the temperature dependence of density is :

$$\rho = \frac{\rho_{T_0}}{1 + \alpha \cdot \Delta T}$$

where ρ_{T_0} is the density at a reference temperature, α is the thermal expansion coefficient of the material at temperatures close to T_0 .

Density of solutions

The density of a solution is the sum of mass (massic) concentrations of the components of that solution.

Mass (massic) concentration of each given component ρ_i in a solution sums to density of the solution.

$$\rho = \sum_i \rho_i$$

Expressed as a function of the densities of pure components of the mixture and their volume participation, it allows the determination of excess molar volumes:

$$\rho = \sum_i \rho_i \frac{V_i}{V} = \sum_i \rho_i \varphi_i = \sum_i \rho_i \frac{V_i}{\sum_i V_i + \sum_i V_i^E}$$

provided that there is no interaction between the components.

Knowing the relation between excess volumes and activity coefficients of the components, one can determine the activity coefficients.

$$\overline{V_i^E} = RT \frac{\partial (\ln(\gamma_i))}{\partial P}$$

Densities

Water

Density of liquid water at 1 atm pressure

Temp. (°C) ^[note 1]	Density (kg/m ³)
−30	983.854
−20	993.547
−10	998.117
0	999.8395
4	999.9720
10	999.7026
15	999.1026
20	998.2071
22	997.7735
25	997.0479
30	995.6502
40	992.2
60	983.2
80	971.8
100	958.4

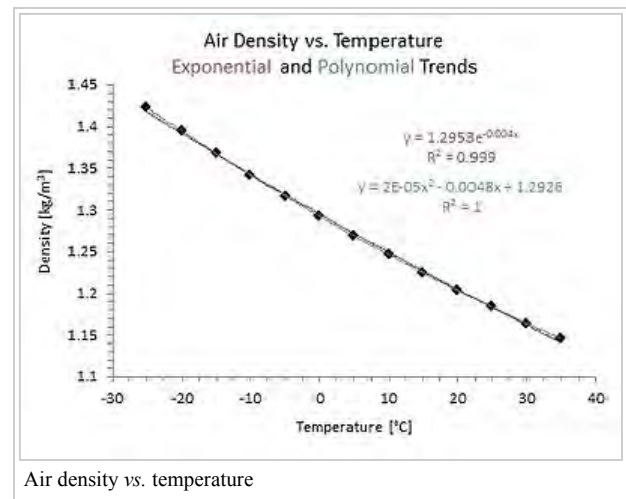
Notes:

1. Values below 0 °C refer to supercooled water.

Air

Density of air at 1 atm pressure

<i>T</i> (°C)	<i>ρ</i> (kg/m ³)
−25	1.423
−20	1.395
−15	1.368
−10	1.342
−5	1.316
0	1.293
5	1.269
10	1.247
15	1.225
20	1.204
25	1.184
30	1.164
35	1.146



Various materials

Densities of various materials covering a range of values

Material	ρ (kg/m ³) ^[note 1]	Notes
Helium	0.179	
Aerographite	0.2	^[note 2] ^[7] ^[8]
Metallic microlattice	0.9	^[note 2]
Aerogel	1.0	^[note 2]
Air	1.2	At sea level
Tungsten hexafluoride	12.4	One of the heaviest known gases at standard conditions
Liquid hydrogen	70	At approx. −255 °C
Styrofoam	75	Approx. ^[9]
Cork	240	Approx. ^[9]
Pine	373	^[10]
Lithium	535	
Wood	700	Seasoned, typical ^[11] ^[12]
Oak	710	^[10]
Potassium	860	^[13]
Ice	916.7	At temperature < 0 °C
Sodium	970	
Water (fresh)	1,000	At 4 °C, the temperature of its maximum density
Water (salt)	1,030	
Nylon	1,150	
Plastics	1,175	Approx.; for polypropylene and PETE/PVC
Tetrachloroethene	1,622	
Magnesium	1,740	
Beryllium	1,850	
Glycerol	1,261	^[14]
Concrete	2,000	^[15]
Silicon	2,330	
Aluminium	2,700	
Diiodomethane	3,325	Liquid at room temperature
Diamond	3,500	
Titanium	4,540	
Selenium	4,800	
Vanadium	6,100	
Antimony	6,690	
Zinc	7,000	
Chromium	7,200	
Tin	7,310	
Manganese	7,325	Approx.
Iron	7,870	
Niobium	8,570	
Brass	8,600	^[15]

Notes:

1. Unless otherwise noted, all densities given are at standard conditions for temperature and pressure, that is, 273.15 K (0.00 °C) and 100 kPa (0.987 atm).
2. Air contained in material excluded when calculating density

Material	ρ (kg/m ³) ^[note 1]	Notes
Cadmium	8,650	
Cobalt	8,900	
Nickel	8,900	
Copper	8,940	
Bismuth	9,750	
Molybdenum	10,220	
Silver	10,500	
Lead	11,340	
Thorium	11,700	
Rhodium	12,410	
Mercury	13,546	
Tantalum	16,600	
Uranium	18,800	
Tungsten	19,300	
Gold	19,320	
Plutonium	19,840	
Rhenium	21,020	
Platinum	21,450	
Iridium	22,420	
Osmium	22,570	

Notes:

- Unless otherwise noted, all densities given are at standard conditions for temperature and pressure, that is, 273.15 K (0.00 °C) and 100 kPa (0.987 atm).
- Air contained in material excluded when calculating density

Others

Entity	ρ (kg/m ³)	Notes
Interstellar medium	1×10^{-19}	Assuming 90% H, 10% He; variable T
The Earth	5,515	Mean density. ^[16]
The inner core of the Earth	13,000	Approx., as listed in Earth. ^[17]
The core of the Sun	33,000–160,000	Approx. ^[18]
Super-massive black hole	9×10^5	Density of a 4.5-million-solar-mass black hole Event horizon radius is 13.5 million km.
White dwarf star	2.1×10^9	Approx. ^[19]
Atomic nuclei	2.3×10^{17}	Does not depend strongly on size of nucleus ^[20]
Neutron star	1×10^{18}	
Stellar-mass black hole	1×10^{18}	Density of a 4-solar-mass black hole Event horizon radius is 12 km.

Common units

The SI unit for density is:

- kilograms per cubic meter (kg/m³)

Litres and metric tons are not part of the SI, but are acceptable for use with it, leading to the following units:

- kilograms per liter (kg/L)
- grams per milliliter (g/mL)
- metric tons per cubic meter (t/m³)

Densities using the following metric units all have exactly the same numerical value, one thousandth of the value in (kg/m³). Liquid water has a density of about 1 kg/dm³, making any of these SI units numerically convenient to use as most solids and liquids have densities between 0.1 and 20 kg/dm³.

- kilograms per cubic decimetre (kg/dm³)
- grams per cubic centimetre (g/cm³)
 - 1 gram/cm³ = 1000 kg/m³
- megagrams (metric tons) per cubic metre (Mg/m³)

In US customary units density can be stated in:

- Avoirdupois ounces per cubic inch (1 g/cc ≈ 0.578036672 oz/cu in)
- Avoirdupois ounces per fluid ounce (1 g/cc ≈ 1.04317556 oz/fl. oz = 1.04317556 lbs/pint)
- Avoirdupois pounds per cubic inch (1 g/cc ≈ 0.036127292 lb/cu in)
- pounds per cubic foot (1 g/cc ≈ 62.427961 lb/cu ft)
- pounds per cubic yard (1 g/cc ≈ 1685.5549 lb/cu yd)
- pounds per US liquid gallon (1 g/cc ≈ 8.34540445 lb/gal)
- pounds per US bushel (1 g/cc ≈ 77.6888513 lb/bu)
- slugs per cubic foot

Imperial units differing from the above (as the Imperial gallon and bushel differ from the US units) in practice are rarely used, though found in older documents. The Imperial gallon was based on the concept that an Imperial fluid ounce of water would have a mass of one Avoirdupois ounce, and indeed 1 g/cc ≈ 1.00224129 ounces per Imperial fluid ounce = 10.0224129 lbs per Imperial gallon. The density of precious metals could conceivably be based on Troy ounces and pounds, a possible cause of confusion.

See also

- List of elements by density
- Air density
- Area density
- Bulk density
- Buoyancy
- Charge density
- Density prediction by the Girolami method
- Dord
- Energy density
- Lighter than air
- Linear density
- Number density
- Orders of magnitude (density)
- Orthobaric density
- Paper density
- Specific weight
- Spice (oceanography)
- Standard temperature and pressure

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External links

- "Density". *Encyclopædia Britannica*. **8** (11th ed.). 1911.
- "Density". *The New Student's Reference Work*. 1914.
- Video: Density Experiment with Oil and Alcohol (<https://www.youtube.com/watch?v=eY-44iPSWIU>)
- Video: Density Experiment with Whiskey and Water (<https://www.youtube.com/watch?v=96NFH2Z7GSA>)
- Glass Density Calculation – Calculation of the density of glass at room temperature and of glass melts at 1000 – 1400°C (<http://glassproperties.com/density/room-temperature/>)
- List of Elements of the Periodic Table – Sorted by Density (<http://www.science.co.il/PTElements.asp?s=Density>)
- Calculation of saturated liquid densities for some components (<http://ddbonline.ddbst.de/DIPPR105DensityCalculation/DIPPR105CalculationCGI.exe>)
- Field density test (<http://www.denichsoiltest.com/field/field-density-test.html>)
- On-line calculator for densities and partial molar volumes of aqueous solutions of some common electrolytes and their mixtures, at temperatures up to 323.15 K. (http://www.aim.env.uea.ac.uk/aim/density/density_electrolyte.php)
- Water – Density and specific weight (http://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html)
- Temperature dependence of the density of water – Conversions of density units (<http://www.sengpielaudio.com/ConvDensi.htm>)
- A delicious density experiment (<http://www.adamequipment.com/education/Documents/EdExp1.pdf>)
- Water density calculator (<http://linkingweatherandclimate.com/ocean/waterdensitycalc.php>) Water density for a given salinity and temperature.
- Liquid density calculator (<http://www.enggcyclopedia.com/welcome-to-enggcyclopedia/calculators/liquid-density>) Select a liquid from the list and calculate density as a function of temperature.
- Gas density calculator (<http://www.enggcyclopedia.com/welcome-to-enggcyclopedia/thermodynamics/gas-density>) Calculate density of a gas for as a function of temperature and pressure.
- Densities of various materials. (<http://www.jaredzone.info/2010/09/densities.html>)
- Determination of Density of Solid (<http://amrita.olabs.co.in/?sub=1&brch=1&sim=2&cnt=9>), instructions for performing classroom experiment.
- density prediction (http://www.shd.org.rs/JSCS/Vol75/No2/13_4388_3960.pdf)
- density prediction (http://www.scielo.cl/scielo.php?pid=S0717-97072008000100015&script=sci_arttext)

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