Density and its uses

How heavy is this stuff? Will it float?

Dolphin and diver engage in a graceful dance while supported by the weight of the water they displace.

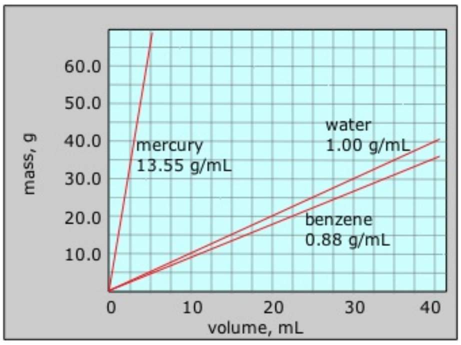
The density of an object is one of its most important and easily-measured physical properties. Densities are widely used to identify pure substances and to characterize and estimate the composition of many kinds of mixtures.

The purpose of this lesson is to show how densities are defined, measured, and utilized, and to make sure you understand the closely-related concepts of buoyancy and specific gravity, and the roles they play in our lives and the environment.

1 So what is *density*?

Most of us have long understood that "oil is lighter than water", or that iron is "heavier" than sugar. But in making such statements, we are implicitly comparing *equal volumes* of these substances: after all, we know that a cup of sugar will weigh more than a single ordinary steel nail.

Mass and volume, as we learned in the previous unit, are measures of the *quantity* of a substance, and as such are defined as *extensive* properties of matter. You will recall that the ratio of two extensive properties is always an *intensive* property — one that characterizes a particular kind of matter, independently of its size or mass. It is this ratio, (mass ÷ volume), that we are concerned with in this lesson.



These plots show how the masses of three liquids vary with their volumes. Notice that

- the plots all have the same origin of (0,0): if the mass is zero, so is the volume;
- the plots are all straight lines, which signify direct proportionality.

The only difference between these plots is their slopes. Denoting mass and volume by m and V respectively, we can write the equation of each line as $m = \rho V$, where the slope ρ (Greek lower-case *rho*) is the proportionality constant that relates mass to volume. This quantity ρ is known as the ***density***, which is usually defined as the mass per unit volume: $\rho = m/V$.

The volume units *milliliter* (mL) and *cubic centimeter* (cm^3) are almost identical and are commonly used interchangeably.

Density can be expressed in any combination of mass and volume units; the most commonly seen units are grams per mL ($g\ mL^{-1}$, $g\ cm^{-3}$), or kilograms per litre.

$$\mathbf{1\ kg\ m^{-3} = 1\ g\ L^{-1} = .0624\ lb\ ft^{-3}}$$

The general meaning of density is the amount of anything per unit volume. What we conventionally call the "density" is more precisely known as the "mass density".

Problem Example 1

Ordinary commercial nitric acid is a liquid having a density of 1.42 g mL^{-1}, and contains 69.8% HNO_3 by weight. *a)* Calculate the mass of HNO_3 in 800 ml of nitric acid. *b)* What volume of acid will contain 100 g of HNO_3?

Solution: The mass of 800 mL of the acid is (1.42 g mL^{-1}) × (800 mL) = 1140 g. The weight of acid that contains 100 g of HNO_3 is (100 g) / (0.698) = 143 g and will have a volume of (143 g) / (1.42 g mL^{-1}) = 101 mL.

Specific volume

It is sometimes more convenient to express the volume occupied by a unit mass of a substance. This is just the inverse of the density and is known as the ***specific volume***.

Problem Example 2

A glass bulb weighs 66.3915 g when evacuated, and 66.6539 g when filled with xenon gas at 25°C. The bulb can hold 50.0 mL of water. Find the density and specific volume of xenon under these conditions.

Solution: The mass of xenon is found by difference: (66.6539 – 66.3915)g = 0.2624 g. The density $\rho = m/V$ = (0.2624 g)/(0.050 L) = 5.248 g L^{-1}. The specific volume is 1/(5.248 g L^{-1} = 0.190 L g^{-1}.

Specific gravity

A quantity that is very closely related to density, and which is frequently used in its place, is specific gravity.

Specific gravity is the ratio of the mass of a material to that of an equal volume of water. Because the density of water is about 1.00 g mL^{-1}, the specific gravity is numerically very close to that of the density, but being a ratio, it is dimensionless.

The presence of "volume" in this definition introduces a slight complication: volumes are temperature-dependent owing to thermal expansion. At 4°C, water has its maximum density of almost exactly 1.000 g mL^{-1}, so if the equivalent volume of water is assumed to be at this temperature, then the density and specific gravity can be considered numerically identical. In making actual comparisons, however, the temperatures of both the material being measured and of the equivalent volume of water are frequently different, so in order to specify a specific gravity value unambiguously, it is necessary to state the temperatures of both the substance in question and of the water.

Thus if we find that a given volume of a substance at 20°C weighs 1.11 times as much as the same volume of water measured at 4°C, we would express its specific gravity as

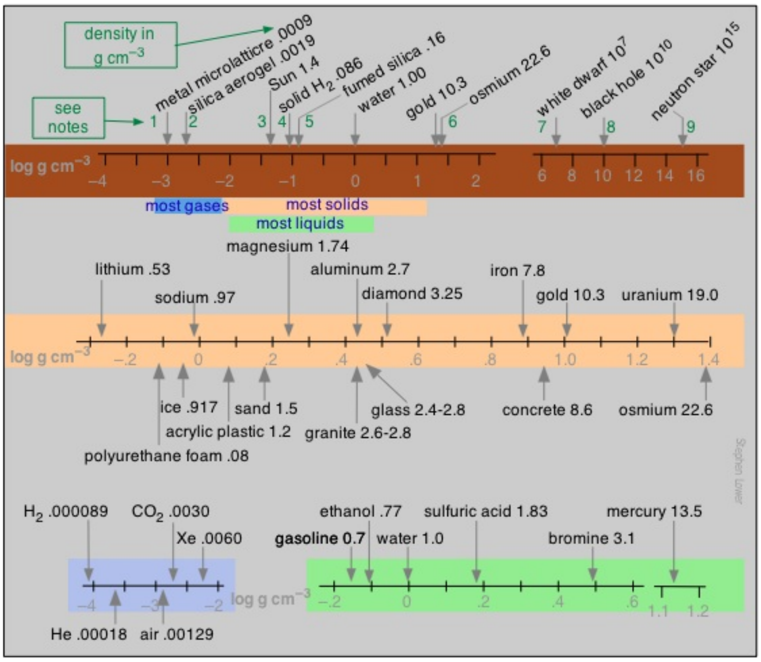
$$1.11\,\frac{20}{4}$$

Although most chemists find density to be more convenient to work with and consider "specific gravity" to be rather old-fashioned, the latter quantity is still widely used in many industrial and technical fields ranging from winemaking to urinalysis.

2 Densities of common substances

The range of densities encountered in the world spans a remarkably wide range, from essentially zero in outer space to the unimaginably huge values found in stellar bodies. These very high densities represent the ultimate limits of how much mass can be packed into a given volume.

The following chart will give you some feeling for the values of density found in nature generally (top), in common solids (middle), and in gases and liquids (bottom). Please note that in order to depict reasonably wide ranges of values in limited space, **the density scales are *logarithmic***; thus zero on these scales corresponds to the density of water (10^0 = 1 g cm^{-3}). Densities listed for ordinary substances (including gases) are mostly those at around 20° C.



The following notes are keyed to the **green numbers** immediately above the topmost (dark orange) bar of the chart →

1 The world's lowest-density class of solids, invented in 2011. More

2 Remove the water from a colloidal gel, and you get an aerogel, sometimes called "solid smoke". Besides its extremely low density, many aerogels exhibit remarkably low thermal conductivity. More

3 The Sun's very low average density may surprise you. But bear in mind that it is all very hot gas. The density at the Sun's center is estimated to be about 160 g/cm3. More

4 No surprise that the lightest element forms the lowest density solid of any pure substance. Melts at 14 K. First prepared by James Dewar in 1899.

5 This ultrafine form of SiO_2 is found in everything from toothpaste to coffee creamer. More

6 Osmium's density is just a hair greater than that of indium. Why do these elements win out over the heavier ones? Blame it on the lanthanide contraction.

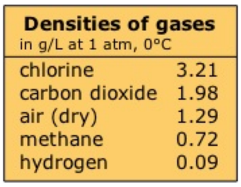
7 Squeeze the sun down into the size of the earth, and you get a white dwarf. This will eventually happen to the sun after it runs out of hydrogen fuel.

8 These exotic beasts concentrate their mass at a zero-radius point, so in a sense possess infinite density. The value given here assumes a volume defined by the event horizon. Don't ask! Black holes are the ultimate fate of the most massive stars.

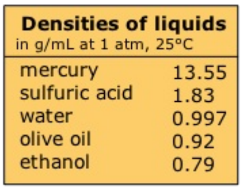
9 Collapse of stars between 1.4 and 2 times more massive than the sun squeezes electrons and protons into each other, rendering much of the star's matter into a ball of neutrons having a radius of only a few kilometers. More

Densities of solids, liquids and gases

In general, **gases** have the lowest densities, but these densities are highly dependent on the pressure and temperature which must always be specified. To the extent that a gas exhibits ideal behavior (low pressure, high temperature), the density of a gas is directly proportional to the masses of its component atoms, and thus to its molecular weight. Measurement of the density of a gas is a simple experimental way of estimating its molecular weight (more here)



Densities of gases in g/L at 1 atm, 0°C	
chlorine	3.21
carbon dioxide	1.98
air (dry)	1.29
methane	0.72
hydrogen	0.09



Densities of liquids in g/mL at 1 atm, 25°C	
mercury	13.55
sulfuric acid	1.83
water	0.997
olive oil	0.92
ethanol	0.79

Liquids encompass an intermediate range of densities. Mercury, being a liquid metal, is something of an outlier. Liquid densities are largely independent of pressure, but they are somewhat temperature-sensitive.

The density range of **solids** is quite wide. Metals, whose atoms pack together quite compactly, have the highest densities, although that of lithium, the highest metallic element, is quite low. Composite materials such as wood and high-density polyurethane foam contain void spaces which reduce the average density.

How the temperature affects density

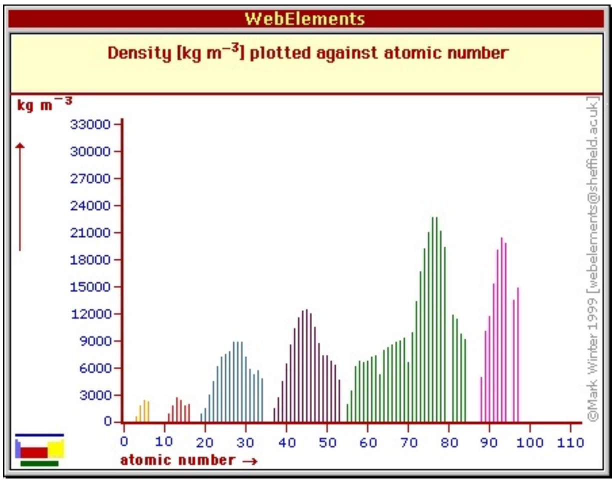
All substances tend to expand as they are heated, causing the same mass to occupy a greater volume, and thus lowering the density. For most solids, this expansion is relatively small, but it is far from negligible; for liquids, it is greater. The volumes of gases, as you may already know (see here for details), are highly temperature-sensitive, and so, of course, are their densities.

What is the cause of thermal expansion? As molecules acquire thermal energy, they move about more vigorously. In condensed phases (liquids and solids), this motion has the character of an irregular kind of bumping or jostling that causes the average distances between the molecules to increase, thus leading to increased volume and smaller density.

Densities of solids
in g/mL at 1 atm, 25°C

osmium	22.6
gold	19.3
iron	7.9
aluminum	2.70
sodium chloride	2.16
sugar	1.59
h.d. polyurethane	1.05
wood (pine)	.3 - .5
lithium	0.53

Densites of the elements



One might expect the densities of the chemical elements to increase uniformly with atomic weight, but this is not what happens; density depends on the volume as well as the mass, and the volume occupied by a given mass of an element, and these volumes can vary in a non-uniform way for two reasons:

The sizes (atomic radii) follow the zig-zag progression that characterizes the other periodic properties of the elements, with atomic volumes diminishing with increasing nuclear charge across each period (more here).

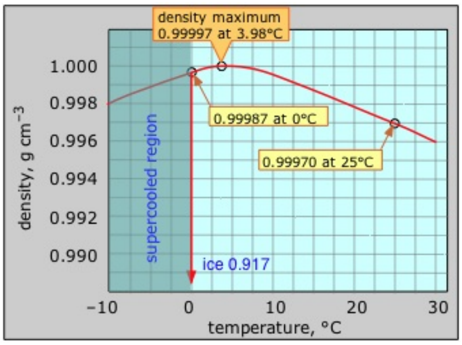
The plot is taken from the popular WebElements site.

Note that the volumes used to compute densities of the solid elements depend, in part, on the geometrical structure of these solids, which vary from element to element. Also, non-metallic solids are often composed of molecules (rather than individual atoms) that are more spread out in space, and which have shapes that cannot be arranged as compactly. so they tend to form more open crystal lattices than do the metals, and therefore have lower densities.

For example, five solid elements, all semimetals, have lower densities in the solid state than in the molten state, and therefore will float in their own melts, just as ice does.

Element	Solid density	Liquid density	m.p. (°C)
Arsenic	4.70	5.22	817
Bismuth	9.80	10.1	271
Gallium	5.90	6.09	30
Germanium	5.32	5.60	940
Silicon	2.33	2.51	1410

Density of water

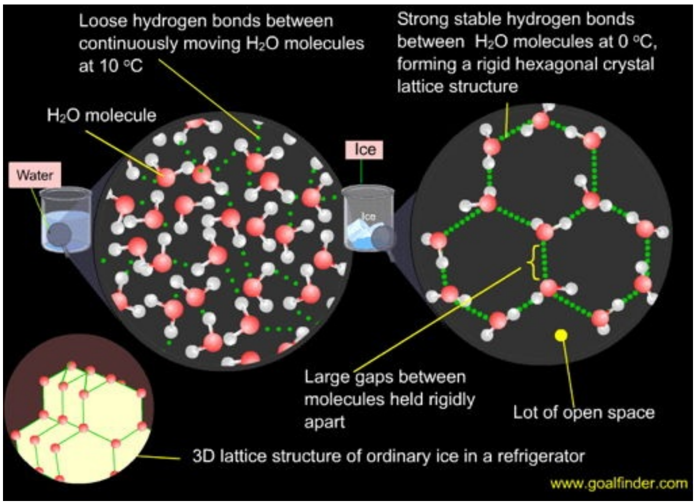


Nature has conveniently made the density of water at ordinary temperatures almost exactly 1.000 g/mL (1 kg/L). Water is subject to thermal expansion just as are all other liquids, and throughout most of its temperature range, the density of water diminishes with temperature. But water is famously exceptional over the temperature range 0-4° C, where raising the temperature causes the density to *increase*, reaching its greatest value at about 4°C.

The 4° density maximum is one of many "anomalous" behaviors of water. As you may know, the H_2O molecules in liquid and solid water are loosely joined together through a phenomenon known as *hydrogen bonding*. Any single water molecule can link up to four other H_2O molecules, but this occurs only when the molecules are locked into place within an ice crystal. This is what leads to a relatively open lattice arrangement, and thus to the relatively low density of ice.

Notice the greater openness of the ice structure which is necessary to ensure the strongest degree of hydrogen bonding in a uniform, extended crystal lattice. The more crowded and jumbled arrangement in liquid water can be sustained only by the greater amount thermal energy available above the freezing point.

When ice melts, thermal energy begins to overcome the hydrogen-bonding forces so



that each H_2O molecule, instead of being permanently connected to four neighbors, is now only linked to an average of three other molecules through hydrogen bonds that continually break and re-form. With fewer hydrogen bonds, the geometrical requirements that formerly mandated a more open structural arrangement now diminish, so the entire network tends to collapse, rendering the water more dense. As the temperature rises, the fraction of H_2O molecules that occupy ice-like clusters diminishes, contributing to the rise in density that is seen between 0° and 4°.

> Whenever a continuously varying quantity such as density passes through a maximum or a minimum value as the temperature or some other variable is changing, you know that two opposing effects are at work.
>
> The 4° density maximum of water corresponds to the temperature at which the breakup of ice-like clusters (leading to higher density) and thermal expansion (leading to lower density) achieve a balance.

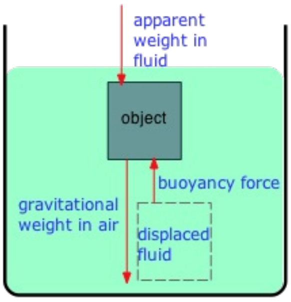
Problem Example 3

Suppose that you place 1000 mL of pure water at 25°C in the refrigerator and that it freezes, producing ice at 0C. What will be the volume of the ice?

Solution: From the graph above, the density of water at 25°C is 0.9997 kg L^{-1}, and that of ice at 0°C 0.917 g L^{-1}.

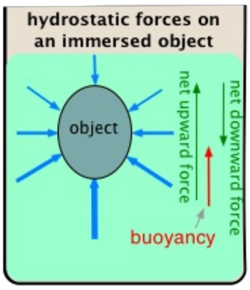
3 Buoyancy

What do an ice cube and a block of wood have in common? Throw either material into water, and it will float. Well, mostly; each object will have its bottom part immersed, but the upper part will ride high and dry. People often say that wood and ice float because they are "lighter than water", but this is true only if we compare the masses of *equal volumes* of the substances. In other words, we need to compare the masses-per-unit-volume, meaning the ***densities***, of each material with that of water. So we would more properly say that objects capable of floating in water must have densities smaller than that of water.



The “true” weight of an object is the downward force exerted by gravity on the object's mass. When the object is immersed in a fluid, this downward force is opposed by a net upward force (the ***buoyancy***) that results from the displacement of this fluid by the object. The magnitude of this upward force is equal to the weight of fluid displaced by the object. So the apparent weight of the object immersed in the fluid is its true weight minus its buoyancy.

The source of the upward “buoyancy force” produced by the displaced fluid is basically the force of gravity acting on the fluid itself. In a glass of water, for example, each tiny layer of the liquid presses down on, and adds it weight to the layers beneath it, creating a hydrostatic pressure gradient that increases with depth. If we now drop a solid object into the water, the object will experience not only the force of gravity acting on its own mass (which we call its “true weight”), but also the hydrostatic forcees due to the fluid pressing against each point on its surface.



> Because this hydrostatic pressure (indicated here by the length and weight of the blue arrows) increases with depth, there is more force exerted on the bottom of the object than on its top. The overall effect is to create a net upward “buoyancy force” that opposes the true weight of the object.The magnitude of this force is equal to the mass of liquid displaced by the object.

Problem Example 4

An object weighs 36 g in air and has a volume of 8.0 cm^3. What will be its apparent weight when immersed in water?

Solution: When immersed in water, the object is buoyed up by the mass of the water it displaces, which of course is the mass of 8 cm^3 of water. Taking the density of water as unity, the upward (buoyancy) force is just 8 g.

The apparent weight will be (36 g) – (8 g) = 28 g.

Air is of course a fluid, and buoyancy can be a problem when weighing a large object such as an empty flask. The following problem illustrates a more extreme case:

Problem Example 5

A balloon having a volume of 5.000 L is placed on a sensitive balance which registers a weight of 2.833 g. What is the "true weight" of the balloon if the density of the air is 1.294 g L^{-1}?

Solution: The mass of air displaced by the balloon exerts a buoyancy force of (5.000 L) × (1.294 g L^{-1}) = 6.470 g. Thus the true weight of the balloon is this much greater than the apparent weight: (2.833 + 6.470) g = 9.303 g.

Example 6

A piece of metal weighs 9.25 g in air, 8.20 g in water, and 8.36 g when immersed in gasoline. *a)* What is the density of the metal? *b)* What is the density of the gasoline?

Solution: When immersed in water, the metal object displaces (9.25 – 8.20) g = 1.05 g of water whose volume is (1.05 g) / (1.00 g cm^{-3}) = 1.05 cm^3. The density of the metal is thus (9.25 g) / (1.05 cm^3) = 8.81 g cm^{-3}.

The metal object displaces (9.25 - 8.36) g = 0.89 g of gasoline, whose density must therefore be (0.89 g) / (1.05 cm^3) = 0.85 g cm^{-3}.

Floating – "the tip of the iceberg"

When an object floats in a liquid, the portion of it that is immersed has a volume that depends on the mass of the same volume of displaced liquid.

Problem Example 7
A cube of ice that is 10 cm on each side floats in water. How many cm does the top of the cube extend above the water level? (Density of ice = 0.917 g cm^{-3}.)

Solution: The volume of the ice is $(10\ cm)^3$ = 1000 cm^3 and its mass is (1000 cm^3) x (0.917 g cm^{-3}) = 917 g. The ice is supported by an upward force equivalent to this mass of displaced water whose volume is (917 g) / (1.00 g cm^{-3}) = 917 cm^3 . Since the cross section of the ice cube is 100-cm^2, it must sink by 9.17 cm in order to displace 917 cm^3 of water. Thus the height of cube above the water is (10 cm – 9.17 cm) = 0.83 cm.

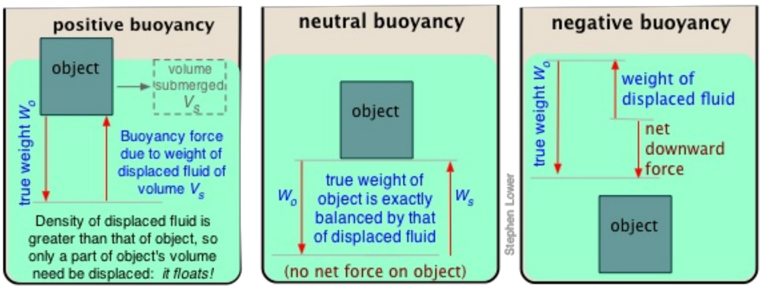
... hence the expression, “the tip of the iceberg”, implying that 90% of its volume is hidden under the surface of the water.

Positive, negative, and neutral buoyancy

An object (such as an iceberg) whose density is smaller than that of the water in which it is immersed, will float on the surface. This occurs because the volume *V* of the more dense fluid required to support the object is smaller than the volume of the object itself. Thus only that portion of the object having this same volume *V* need be submerged in order to counter the object's weight. This condition is known as *positive buoyancy*.

> It is interesting to note that it takes much less force to lift a sunken object such as a ship up to just under the water's surface, than it does to lift itcompletely out of the water, at which point the buoyancy force that reduces its apparent weight is no longer present.

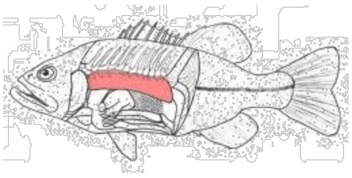
If the density of the object exceeds that of the fluid, the weight of fluid it displaces (the buoyant force) will be smaller than the object’s true weight, and thus unable to support it. In this condition of *negative buoyancy*, the object experiences a net downward force at any depth, so it will sink until it strikes the bottom.


positive buoyancy
object
volume submerged V_s
true weight W_o
Buoyancy force due to weight of displaced fluid of volume V_s
Density of displaced fluid is greater than that of object, so only a part of object's volume need be displaced: *it floats!*
neutral buoyancy
object
W_o
true weight of object is exactly balanced by that of displaced fluid
W_s
(no net force on object)
Stephen Lower
negative buoyancy
true weight W_o
weight of displaced fluid
net downward force
object

Neutral buoyancy and its control

If the density of an object is the same as that of the fluid, the upward and downward forces balance out to zero. In this condition of *neutral buoyancy*, the object "floats" within the fluid.

- Fish, marine mammals, scuba divers, and submarines must be able alter their average densities by switching between positive-, negative- and neutral buoyancy in order to ascend, descend, or maintain themselves at a constant depth under water.
- Mammals, including dolphins and humans, are naturally close to having neutral buoyancy, and use their appendages to move up or down.
- Most fish possess an organ known as a swim bladder whose degree of inflation enables them to switch buoyancy modes. These bladders are not connected to the mouth; they are inflated or deflated by oxygen gas that is extracted from (or returned to) the blood.



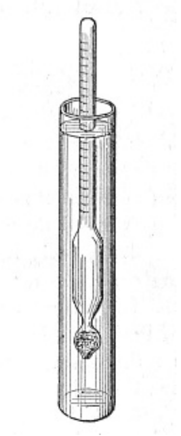
- Unclothed humans commonly tend to have a slight degree of positive buoyancy, enabling them to easily float on the water surface, especially if they possess generous amounts of body fat. People who are lean and more muscular will more likely be negatively buoyant. Scuba divers are trained to control their buoyancy by adjusting their lung inflation. The use of weight belts or external bladders (buoyancy compensators) provides additional flexibility.
- Submarines employ tanks that are filled with compressed air for surface cruising, or with seawater for under-water maneuvering.

4 How is density measured?

The most obvious way of finding the density of a material is to measure its mass and its volume. This is the only option we have for gases, but observing the mass of a fixed volume of a liquid is time-consuming and awkward, and measuring the volumes of solids whose shapes are irregular or which are finely divided is usually impractical.

Liquids: the hydrometer

The traditional hydrometer is a glass tube having a weighted bulb near the bottom. The hydrometer is lowered into a container of the liquid to be measured, and comes to a rest with the upper part protruding above the liquid surface at a height (read from a calibrated scale) that depends on the density of the liquid. This will only work, of course, if the overall density of the hydrometer itself is smaller than the density of the liquid to be measured. For this reason, hydrometers intended for general use come in sets. Because liquid densities are temperature dependent, hydrometers intended for precise measurements also contain an internal thermometer so that this information can be collected in the event that temperature corrections will be made.



Owing to the ease with which they can be observed, densities are widely employed to estimate the composition or quality of liquid mixtures or solutions, and in some cases determine their commercial value. This has given rise to many kinds of hydrometers that are specialized for specific uses:

- Saccharometer – used by winemakers and brewers to measure the sugar content of a liquid
- Alcoholometer – measures the alcoholic content of a liquid
- Salinometer – measures the "salinity" (salt content) of brine or seawater
- Lactometer - measures the specific gravity of milk products

Battery hydrometer - How it works

build-it-yourself drinking-straw hydrometer

Aquarium salinity hydrometer

A boat with depth markings on its body can be thought of as a gigantic hydrometer!

...for pressurized-liquids

Sugar and syrup hydrometer

Don't confuse them!

A ***hyd****rometer* measures the *density or specific gravity* of a liquid

a ***hyg****rometer* measures the *relative humidity* of the air

Hydrometer scales

Hydrometers for general purpose use are normally calibrated in units of specific gravity, but often defined at temperatures other than 25°C. A very common type of calibration is in "degrees" on various arbitrary scales, of which the best known are the Baumé scales. Special-purpose hydrometer scales can get quite esoteric; thus alcohol hydrometers may directly measure percentage alcohol by weight on a 0–100% scale, or "proof" (twice the volume-percent of alcohol) on a 0-200 scale.

Solids

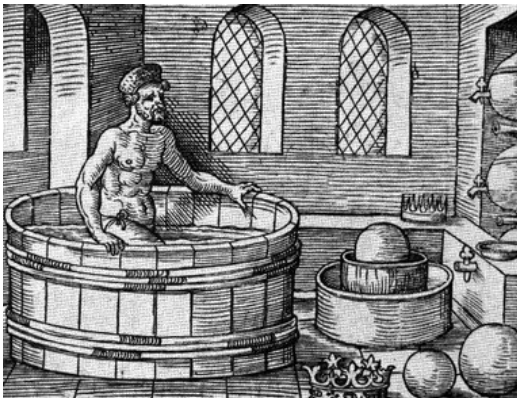
Measuring the density of a solid that is large enough to weigh accurately is largely a matter of determining its volume. For an irregular solid such as a rock, this is most easily done by observing the amount of water it displaces.

A small containerl having a precisely determined volume can be used to determine the density of powdered or granular samples. The vessel (known as a *pycnometer*) is weighed while empty, and again when filled; the density is found from the weight difference and the calibrated volume of the pycnometer. This method is also applicable to liquids and gases.

> In forensic work it is often necessary to determine the density of very small particles such as fibres, flakes of paint or metal, or grains of sand. Neither the weight nor volumes of such samples can be determined directly, so the simplest solution is to place the sample in a series of liquids of different densities, and see if it floats, sinks, or remains suspended within the liquid. A more sophisticated method is to layer two liquids in a vertical glass tube and allow them to slowly mix, creating a density gradient. When a particle is dropped into the tube, it sinks to a depth that matches its density.

5 Some applications of density

Archimedes' principle



The most famous application of buoyancy is due to Archimedes of Syracuse around 250 BCE. He was asked to determine whether the new crown that King Hiero II had commissioned contained all the gold that he had provided to the goldsmith for that purpose; apparently he suspected that the smith might have set aside some of the gold for himself and substituted less-valuable silver instead.

According to legend, Archimedes devised the principle of the “hydrostatic balance” after he noticed his own apparent loss in weight while sitting in his bath. The story goes that he was so enthused with his discovery that he jumped out of his bath and ran through the town, shouting "eureka" to the bemused populace.

Problem Example 8

If the weight of the crown when measured in air was 4.876 kg and its weight in water was 4.575 kg, what was the density of the crown?

Solution: The volume of the crown can be found from the mass of water it displaced, and thus from its buoyancy: (4876 – 4575) g / (1.00 g cm^{-3}) = 301 cm^{3}. The density is then

(4876 g) / (301 cm^{3}) = **16.2 g cm^{-3}**

The densities of the pure metals: silver = 10.5, gold = 19.3 g cm^{-3},

Estimating the size of an atom

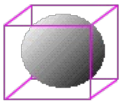
One of the delights of chemical science is to find a way of using the macroscopic properties of bulk matter to uncover information about the microscopic world at the atomic level. The following problem example is a good illustration of this.

Problem Example 9

Estimate the diameter of the neon atom from the following information:

Density of liquid neon: 1.204 g cm^{-3}; molar mass of neon: 20.18 g.

Solution: This problem can be divided into two steps.

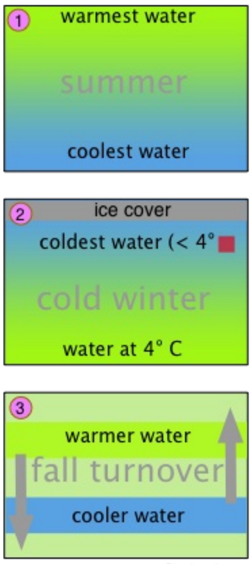


1 - *Estimate the volume occupied by each atom.* One mole (6.02E23 atoms) of neon occupy a volume of (20.18 g) / (1.204 g cm^{-3}) = 16.76 cm^3. If this space is divided up equally into tiny boxes, each just large enough to contain one atom, then the volume allocated to each atom is given by: (16.76 cm^3 mol^{-1}) / (6.02E23 atom mol^{-1}) = 2.78E–23 cm^3 atom^{-1}.

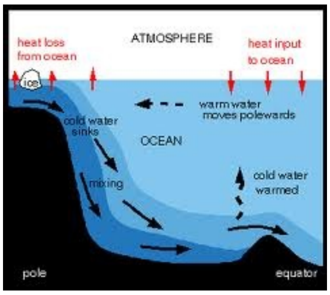
2 - *Find the length of each box, and thus the atomic diameter.* Each atom of neon has a volume of about 2.8E–23 cm^3. If we re-express this volume as 28E–24 cm^3 and fudge the “28” a bit, we can come up with a reasonably good approximation of the diameter of the neon atom without even using a calculator. Taking the volume as 27E–24 cm^3 allows us to find the cube root, 3.0E–8 cm = 3.0E–10 m = 300 pm, which corresponds to the length of the box and thus to the diameter of the atom it encloses.

The accepted [van der Waals] atomic radius of neon is 154 pm, corresponding to a diameter of about 310 pm. This estimate is surprisingly good, since the atoms of a liquid are not really confined to orderly little boxes in the liquid.

Seasonal stratification and turnover in lakes



Stephen Lower



Water's density maximum at 4°C has some interesting consequences in the aquatic ecology of lakes. In all but the most shallow lakes, the water tends to be stratified, so that for most of the year, the denser water remains near the bottom and mixes very little with the less-dense waters above. Because water has its density maximum at 4°C, the bottom waters of deep lakes (and of the oceans) usually stay around 4°C at all times of the year ①. In the summer this will be the coldest water, but in the winter ②, the surface waters lose heat to the atmosphere and if they cool below 4°, they will be colder than the more dense waters below.

When the weather turns cold in the fall, the surface waters lose heat and cool to 4°C ③. This more dense layer of water sinks to the bottom, displacing the water below, which rises to the surface and restores nutrients that were removed when dead algae sank to the bottom. This “*fall turnover*” renews the lake for the next season.

The global oceanic "conveyor belt": Thermohaline circulation

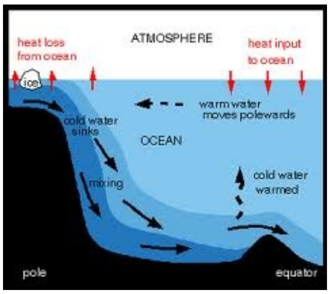
The density of water containing dissolved salts is greater than that of pure water, and the density increases with the salt concentration (*salinity*). This seemingly trivial fact exerts a profound effect on our planet, driving the circulation in the oceans and affecting the climate and oceanic productivity.

Two Oceans

The world's oceans consist of two huge reservoirs, one on top of the other. The upper *ocean comprises* about 5% of the total volume; owing to turbulence produced by wind and waves, its vertical profile is fairly uniform in composition and temperature. Its currents are driven mainly by surface winds which exert little effect below about 100 meters or so.

The remaining 95% of the ocean's volume resides in a deeper and colder layer. The temperature and density of this bottom ocean increase with depth, the coldest (4° C, and therefore the most dense) water being at the sea floor. So unlike the well-mixed upper ocean, the bottom one is *stratified*, similarly to that of lakes in cold winters.

Owing to this permanent stratification, mixing between the upper and lower oceans is very slow; only about 0.01% moves between the two layers per year. The mean residence time of a water molecule in the deep layer is about 1600 years. If it were not for cold polar winters, there would be very little movement of water in the bottom ocean.



But when seasonal ice begins to form in the polar regions,"holes" open up that allow water to drain from the upper ocean to the lower one. Because the salts dissolved in seawater cannot be accommodated within the ice structure, they are largely excluded from the new ice and remain in solution. This increases the salinity, and thus the density, of the surrounding unfrozen water, causing it to sink into the bottom ocean.

There are two major locations at which surface waters enter the deep ocean. The northern entry point is in the Norwegian Sea off Greenland; this water forms a mass known as the North Atlantic Deep Water (NADW) which flows southward across the equator.

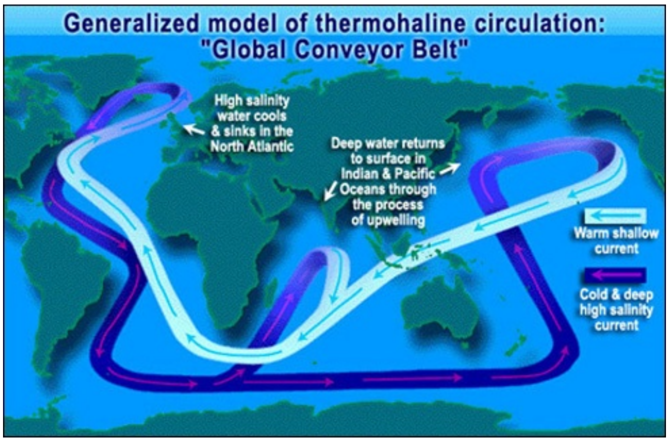
Most of the transport into the deep ocean takes place in the Weddell Sea off the coast of Antarctica. The highly saline water flows down the submerged Antarctic Slope to begin a 5000-year trip to the north across the bottom of the ocean. This is the major route by which dissolved CO_2 and O_2 (which are more soluble in this cold water) are transported into the deep ocean where it forms a water mass known as the Antarctic Bottom Water (AABW) which can be traced into all three oceans.

Deep ocean currents

As the cold water drains into the deep ocean. it spills over ridges and valleys, creating huge undersea cascades which rival the greatest terrestrial waterfalls in height and the largest rivers in volume. These deep water currents are much slower than the surface currents; estimated rates are of the order of kilometers per month, in contrast to the few kilometers per hour of surface waters.

Coastal upwelling

As the cold water begins to fill up the bottom ocean, it displaces the less dense bottom water, pushing it back up into the upper ocean. This recirculation occurs to a small extent in many regions, but is especially pronounced along continental coasts where prevailing winds tend to roll surface waters over.



[NASA]

The deep ocean contains few organisms to deplete the water of the nutrients it receives from the remains of the dead organisms raining down from above; this upwelled water is therefor exceptionally rich in nutrients, and strongly encourages the growth of new organisms that extend up the food chain to fish. For example, the upwelling that occurs off the west coast of South America is responsible for the Peruvian fishing and guano fertilizer industry.

About every seven years the prevailing winds that help drive upwelling disappear for a while, allowing warm equatorial waters to move in. This phenomenon is known as ***El Niño*** and it results in massive kills of plankton and fish. Decomposition of the dead organisms reduces the oxygen content of the water, causing the death of still more fish, and allowing reduced compounds such as hydrogen sulfide to accumulate.

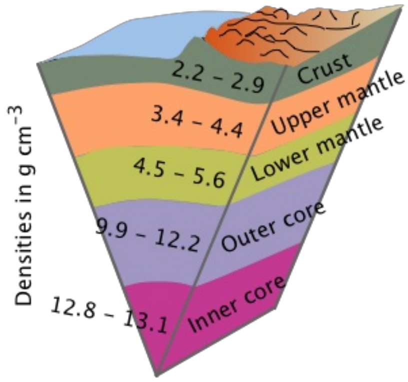
Density and the structure of the earth

The grandest scale in which density and buoyancy reveal themselves lies in the structure of the earth and its continents.

Formation and differentiation of the earth

The sun formed by gravitational attraction of the the massive amounts of interstellar atoms (mostly hydrogen and helium) that happened to be more concentrated in our part of the galaxy.

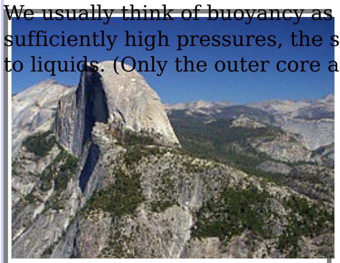
The remaining material probably formed a disk that rotated around the sun. As the temperature dropped to around 2000K, some of the more stable combinations of the elements began to condense out. These substances might have been calcium aluminum silicates, followed by the more volatile iron-nickel system, and then magnesium silicates. The further aggregation of these materials, together with the other constituents of the cooling disk, is now believed to be the origin of the planets. Density estimates indicate that the planets closest to the sun are predominantly rocky in nature, and probably condensed first. The outer planets (Uranus, Neptune and Pluto) appear to consist largely of water ice, methane, and ammonia, with a smaller rocky core.



Although the earth was formed from mostly solid materials, the heat produced by decay of radioactive elements brought about partial melting of the silicate rocks; these lower density molten materials migrated upward, leaving the more dense, iron-containing minerals below. This process, which took about 2 million years, was the first of several stages into which the chemical evolution of the earth is usually divided, and is primarily responsible for its layered structure of crust, mantle, and core.

Buoyancy at work in the earth

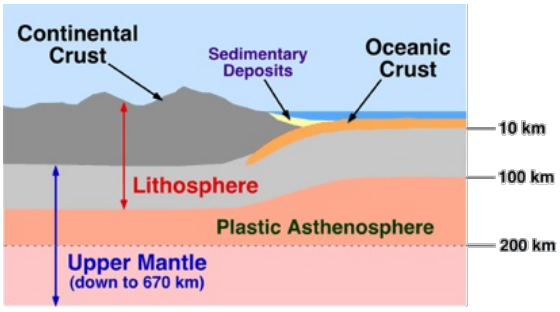
We usually think of buoyancy as something that happens in liquids, but under sufficiently high pressures, the solid crust and mantle can deform and flow similarly to liquids. (Only the outer core and portions of the upper mantle are liquids.)



Half-dome peak, in California's Yosemite National Park, is one of the most well known and widely visited batholiths. [Wikimedia]

Pop-up mountains. In the earth's early stages the stronger granitic rocks had not yet appeared, and the crust was mechanically weak. Upwelling flows of lava would cause the crust to subside. In some places, magma would solidify underground, forming low-density rock (*batholiths*) that would eventually rise by buoyancy and push up overlying crust. These mountain-building periods probably occurred in 6-8 major episodes, each lasting about 800 million years.

Continental and oceanic crusts float and slide on the lower lithosphere.
The earth's crust together with the upper part of the mantle (the *asthenosphere) are* collectively known as the lithosphere. It is in this region that the dynamics of geological change take place: continental drift, mountain building, earthquakes and volcanoes.



The crust itself comes in two varieties having different compositions and densities. The *continental* crust is thicker and less dense (2.7 g cm^{-3}) than the *oceanic* crust (3.0 g cm^{-3}) and therefore floats higher on the plastic material of the upper mantle. Both kinds of crust can slide along on the mantle in response to convection currents. When these motions cause the two kinds of crust to collide, the less-dense oceanic crust invariably loses the battle and undergoes subduction and melting.

Lava Lamps

Known more generically as "fluid motion lamps", these devices became popular in the 1970's and provide a nice, if somewhat mesmerizing illustration of density and buoyancy in action as the blobs of oozing goo move up and down in ever-changing shapes.

These lamps consist of a container of water in which is placed a colored organic oily liquid that does not mix with water, thus constituting a second phase. The composition of the oil phase is such that its density is slightly greater than that of water at room temperature, so it normally resides at the bottom of the container. When the lamp is turned on, a heat source (usually an incandescent light bulb) concealed in the base of the container heats the oil phase. This reduces its density to a value below that of the water, causing blobs of oil to rise to the top of the container. Being now far removed from the heat source, the blobs cool down and sink back to the bottom, where they repeat the cycle.

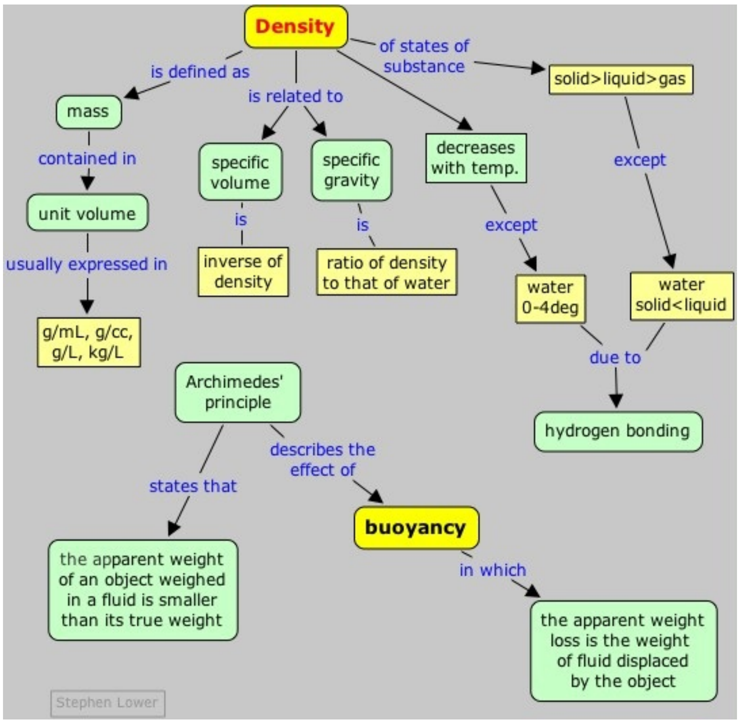
- Wikipedia article
- (4 min)

What you should be able to do

Make sure you thoroughly understand the following essential ideas which have been presented above. It is especially important that you know the precise meanings of all the highlighted terms in the context of this topic.

- Given two of the following values: mass - volume - density, find the value of the third.
- Define specific volume and specific gravity, and explain the significance of expressing the latter in a form such as $1.15^{25/4}$.
- Describe the two factors responsible for the 4°C density maximum of water.
- Explain why weighing a solid object suspended in a fluid yields a smaller value than its "true" weight. Be able to find this difference when given the volume of the solid and the density of the fluid.
- Describe the purpose of a hydrometer and explain how it works.

Concept Map


Density
is defined as
mass
contained in
unit volume
usually expressed in
g/mL, g/cc, g/L, kg/L
is related to
specific volume
is
inverse of density
specific gravity
is
ratio of density to that of water
decreases with temp.
except
water 0-4deg
of states of substance
solid>liquid>gas
except
water solid<liquid
due to
hydrogen bonding
Archimedes' principle
states that
the apparent weight of an object weighed in a fluid is smaller than its true weight
describes the effect of
buoyancy
in which
the apparent weight loss is the weight of fluid displaced by the object
Stephen Lower