[Template:About](/wiki/Template:About" \o "Template:About) [Template:Pp-semi-indef](/wiki/Template:Pp-semi-indef) [Template:Pp-move-indef](/wiki/Template:Pp-move-indef) [Template:Use mdy dates](/wiki/Template:Use_mdy_dates) [Template:Infobox oxygen](/wiki/Template:Infobox_oxygen) **Oxygen** is a [chemical element](/wiki/Chemical_element) with symbol **O** and [atomic number](/wiki/Atomic_number) 8. It is a member of the [chalcogen](/wiki/Chalcogen) [group](/wiki/Group_(periodic_table)) on the [periodic table](/wiki/Periodic_table) and is a highly [reactive](/wiki/Chemical_reaction) [nonmetal](/wiki/Nonmetal) and [oxidizing agent](/wiki/Oxidizing_agent) that readily forms [oxides](/wiki/Oxide) with most elements as well as other [compounds](/wiki/Chemical_compound).[[1]](#cite_note-1) By mass, oxygen is the third-[most abundant element](/wiki/Abundance_of_the_chemical_elements) in the universe, after [hydrogen](/wiki/Hydrogen) and [helium](/wiki/Helium).[[2]](#cite_note-2) At [standard temperature and pressure](/wiki/Standard_temperature_and_pressure), two atoms of the element [bind](/wiki/Chemical_bond) to form [dioxygen](/wiki/Allotropes_of_oxygen#Dioxygen), a colorless and odorless [diatomic](/wiki/Diatomic_molecule) [gas](/wiki/Gas) with the formula [Template:Chem](/wiki/Template:Chem). This is an important part of the [atmosphere](/wiki/Atmosphere_of_Earth) and diatomic oxygen gas constitutes 20.8% of the [Earth's atmosphere](/wiki/Earth's_atmosphere).[[3]](#cite_note-3) Additionally, as oxides the element also makes up almost half of the [Earth's crust](/wiki/Earth's_crust).[[4]](#cite_note-4) Oxygen is necessary to sustain most terrestrial life. Oxygen is used in [cellular respiration](/wiki/Cellular_respiration) and many major classes of [organic](/wiki/Organic_chemistry) molecules in living organisms contain oxygen, such as [proteins](/wiki/Protein), [nucleic acids](/wiki/Nucleic_acid), [carbohydrates](/wiki/Carbohydrate), and [fats](/wiki/Fat), as do the major constituent [inorganic compounds](/wiki/Inorganic_compound) of animal shells, teeth, and bone. Most of the mass of living organisms is oxygen as a component of water, the major constituent of lifeforms. Conversely, oxygen is continuously replenished by [photosynthesis](/wiki/Photosynthesis), which uses the energy of sunlight to produce oxygen from water and carbon dioxide. Oxygen is too chemically reactive to remain a free element in air without being continuously replenished by the photosynthetic action of living organisms. Another form ([allotrope](/wiki/Allotropes_of_oxygen)) of oxygen, [ozone](/wiki/Ozone) ([Template:Chem](/wiki/Template:Chem)), strongly absorbs ultraviolet [UVB](/wiki/UVB) radiation and the high-altitude [ozone layer](/wiki/Ozone_layer) helps protect the biosphere from [ultraviolet radiation](/wiki/Ultraviolet_radiation). But ozone is a pollutant near the surface where it is a by-product of [smog](/wiki/Smog). At [low earth orbit](/wiki/Low_earth_orbit) altitudes, sufficient atomic oxygen is present to cause [corrosion of spacecraft](/wiki/Corrosion_in_space).[[5]](#cite_note-5) Oxygen was discovered independently by [Carl Wilhelm Scheele](/wiki/Carl_Wilhelm_Scheele), in [Uppsala](/wiki/Uppsala), in 1773 or earlier, and [Joseph Priestley](/wiki/Joseph_Priestley) in [Wiltshire](/wiki/Wiltshire), in 1774, but Priestley is often given priority because his work was published first. The name *oxygen* was coined in 1777 by [Antoine Lavoisier](/wiki/Antoine_Lavoisier),[[6]](#cite_note-6) whose experiments with oxygen helped to discredit the then-popular [phlogiston theory](/wiki/Phlogiston_theory) of [combustion](/wiki/Combustion) and [corrosion](/wiki/Corrosion). Its name derives from the [Greek](/wiki/Greek_language) roots ὀξύς *oxys*, "acid", literally "sharp", referring to the [sour taste](/wiki/Taste#Sourness) of [acids](/wiki/Acid) and -γενής *-genes*, "producer", literally "begetter", because at the time of naming, it was mistakenly thought that all acids required oxygen in their composition.

Common use of oxygen includes residential [heating](/wiki/HVAC), [internal combustion engines](/wiki/Internal_combustion_engine), production of [steel](/wiki/Steel), [plastics](/wiki/Plastics) and [textiles](/wiki/Textiles), [brazing, welding and cutting](/wiki/Oxy-fuel_welding_and_cutting) of steels and other [metals](/wiki/Metals), [rocket propellant](/wiki/Rocket_propellant), [oxygen therapy](/wiki/Oxygen_therapy), and [life support systems](/wiki/Life_support_system) in [aircraft](/wiki/Aircraft), [submarines](/wiki/Submarines), [spaceflight](/wiki/Human_spaceflight) and [diving](/wiki/Underwater_diving).

## Contents

* 1 History[[edit](/index.php?title=(none)&action=edit&section=1)]
  + 1.1 Early experiments[[edit](/index.php?title=(none)&action=edit&section=2)]
  + 1.2 Phlogiston theory[[edit](/index.php?title=(none)&action=edit&section=3)]
  + 1.3 Discovery[[edit](/index.php?title=(none)&action=edit&section=4)]
  + 1.4 Lavoisier's contribution[[edit](/index.php?title=(none)&action=edit&section=5)]
  + 1.5 Later history[[edit](/index.php?title=(none)&action=edit&section=6)]
* 2 Characteristics[[edit](/index.php?title=(none)&action=edit&section=7)]
  + 2.1 Properties and molecular structure[[edit](/index.php?title=(none)&action=edit&section=8)]
  + 2.2 Allotropes[[edit](/index.php?title=(none)&action=edit&section=9)]
  + 2.3 Physical properties[[edit](/index.php?title=(none)&action=edit&section=10)]
  + 2.4 Isotopes and stellar origin[[edit](/index.php?title=(none)&action=edit&section=11)]
  + 2.5 Occurrence[[edit](/index.php?title=(none)&action=edit&section=12)]
  + 2.6 Analysis[[edit](/index.php?title=(none)&action=edit&section=13)]
* 3 Biological role of O<sub>2</sub>[[edit](/index.php?title=(none)&action=edit&section=14)]
  + 3.1 Photosynthesis and respiration[[edit](/index.php?title=(none)&action=edit&section=15)]
  + 3.2 Living organisms[[edit](/index.php?title=(none)&action=edit&section=16)]
  + 3.3 Build-up in the atmosphere[[edit](/index.php?title=(none)&action=edit&section=17)]
* 4 Industrial production[[edit](/index.php?title=(none)&action=edit&section=18)]
* 5 Storage[[edit](/index.php?title=(none)&action=edit&section=19)]
* 6 Applications[[edit](/index.php?title=(none)&action=edit&section=20)]
  + 6.1 Medical[[edit](/index.php?title=(none)&action=edit&section=21)]
  + 6.2 Life support and recreational use[[edit](/index.php?title=(none)&action=edit&section=22)]
  + 6.3 Industrial[[edit](/index.php?title=(none)&action=edit&section=23)]
* 7 Compounds[[edit](/index.php?title=(none)&action=edit&section=24)]
  + 7.1 Oxides and other inorganic compounds[[edit](/index.php?title=(none)&action=edit&section=25)]
  + 7.2 Organic compounds and biomolecules[[edit](/index.php?title=(none)&action=edit&section=26)]
* 8 Safety and precautions[[edit](/index.php?title=(none)&action=edit&section=27)]
  + 8.1 Toxicity[[edit](/index.php?title=(none)&action=edit&section=28)]
  + 8.2 Combustion and other hazards[[edit](/index.php?title=(none)&action=edit&section=29)]
* 9 See also[[edit](/index.php?title=(none)&action=edit&section=30)]
* 10 Notes[[edit](/index.php?title=(none)&action=edit&section=31)]
* 11 Citations[[edit](/index.php?title=(none)&action=edit&section=32)]
* 12 References[[edit](/index.php?title=(none)&action=edit&section=33)]
* 13 External links[[edit](/index.php?title=(none)&action=edit&section=34)]

## History[[edit](/index.php?title=(none)&action=edit&section=1)]

### Early experiments[[edit](/index.php?title=(none)&action=edit&section=2)]

[thumb|upright|](/wiki/File:Philos_experiment_of_the_burning_candle.PNG)[Philo's](/wiki/Philo_of_Byzantium) experiment inspired later [investigators](/wiki/Detective).|alt=Drawing of a burning candle enclosed in a glass bulb.

One of the first known experiments on the relationship between [combustion](/wiki/Combustion) and air was conducted by the 2nd century BCE [Greek](/wiki/Ancient_Greece) writer on mechanics, [Philo of Byzantium](/wiki/Philo_of_Byzantium). In his work *Pneumatica*, Philo observed that inverting a vessel over a burning candle and surrounding the vessel's neck with water resulted in some water rising into the neck.[[7]](#cite_note-7) Philo incorrectly surmised that parts of the air in the vessel were converted into the [classical element](/wiki/Classical_element) [fire](/wiki/Fire_(classical_element)) and thus were able to escape through pores in the glass. Many centuries later [Leonardo da Vinci](/wiki/Leonardo_da_Vinci) built on Philo's work by observing that a portion of air is consumed during combustion and [respiration](/wiki/Respiration_(physiology)).[[8]](#cite_note-8) In the late 17th century, [Robert Boyle](/wiki/Robert_Boyle) proved that air is necessary for combustion. English chemist [John Mayow](/wiki/John_Mayow) (1641–1679) refined this work by showing that fire requires only a part of air that he called *spiritus nitroaereus* or just *nitroaereus*.[[9]](#cite_note-9) In one experiment, he found that placing either a mouse or a lit candle in a closed container over water caused the water to rise and replace one-fourteenth of the air's volume before extinguishing the subjects.[[10]](#cite_note-10) From this he surmised that nitroaereus is consumed in both [respiration](/wiki/Respiration_(physiology)) and combustion.

Mayow observed that [antimony](/wiki/Antimony) increased in weight when heated, and inferred that the nitroaereus must have combined with it.[[9]](#cite_note-9) He also thought that the lungs separate nitroaereus from air and pass it into the blood and that animal heat and muscle movement result from the reaction of nitroaereus with certain substances in the body.[[9]](#cite_note-9) Accounts of these and other experiments and ideas were published in 1668 in his work *Tractatus duo* in the tract "De respiratione".[[10]](#cite_note-10)

### Phlogiston theory[[edit](/index.php?title=(none)&action=edit&section=3)]

[Template:Main article](/wiki/Template:Main_article) [thumb|left|upright|](/wiki/File:Georg_Ernst_Stahl.png)[Stahl](/wiki/Georg_Ernst_Stahl) helped develop and popularize the phlogiston theory.|alt=Old drawing of a man wearing a large curly wig and a mantle.

[Robert Hooke](/wiki/Robert_Hooke), [Ole Borch](/wiki/Ole_Borch), [Mikhail Lomonosov](/wiki/Mikhail_Lomonosov), and [Template:Ill](/wiki/Template:Ill) all produced oxygen in experiments in the 17th and the 18th century but none of them recognized it as a [chemical element](/wiki/Chemical_element).[[11]](#cite_note-11) This may have been in part due to the prevalence of the philosophy of [combustion](/wiki/Combustion) and [corrosion](/wiki/Corrosion) called the phlogiston theory, which was then the favored explanation of those processes.

Established in 1667 by the German alchemist [J. J. Becher](/wiki/J._J._Becher), and modified by the chemist [Georg Ernst Stahl](/wiki/Georg_Ernst_Stahl) by 1731,[[12]](#cite_note-12) phlogiston theory stated that all combustible materials were made of two parts. One part, called phlogiston, was given off when the substance containing it was burned, while the dephlogisticated part was thought to be its true form, or [calx](/wiki/Calx).[[8]](#cite_note-8) Highly combustible materials that leave little [residue](/wiki/Residue_(chemistry)), such as wood or coal, were thought to be made mostly of phlogiston; non-combustible substances that corrode, such as iron, contained very little. Air did not play a role in phlogiston theory, nor were any initial quantitative experiments conducted to test the idea; instead, it was based on observations of what happens when something burns, that most common objects appear to become lighter and seem to lose something in the process.[[8]](#cite_note-8) The fact that a substance like wood gains overall weight in burning was hidden by the buoyancy of the gaseous combustion products. Indeed, one of the first clues that the phlogiston theory was incorrect was that metals gain weight in rusting (when they were supposedly losing phlogiston). [Template:Clear](/wiki/Template:Clear)

### Discovery[[edit](/index.php?title=(none)&action=edit&section=4)]

[thumb|upright|](/wiki/File:Carl_Wilhelm_Scheele_from_Familj-Journalen1874.png)[Carl Wilhelm Scheele](/wiki/Carl_Wilhelm_Scheele) beat Priestley to the discovery but published afterwards.|alt=Profile drawing of a young men's head in an oval frame. Oxygen was first discovered by Swedish pharmacist [Carl Wilhelm Scheele](/wiki/Carl_Wilhelm_Scheele). He had produced oxygen gas by heating mercuric oxide and various [nitrates](/wiki/Nitrate) by about 1772.[[3]](#cite_note-3)[[8]](#cite_note-8) Scheele called the gas "fire air" because it was the only known supporter of combustion, and wrote an account of this discovery in a manuscript he titled *Treatise on Air and Fire*, which he sent to his publisher in 1775. That document was published in 1777.[[13]](#cite_note-13) [thumb|upright|left|](/wiki/File:PriestleyFuseli.jpg)[Joseph Priestley](/wiki/Joseph_Priestley) is usually given priority in the discovery.|alt=A drawing of an elderly man sitting by the table and facing parallel to the drawing. His left arm rests on a notebook, legs crossed

In the meantime, on August 1, 1774, an experiment conducted by the British clergyman [Joseph Priestley](/wiki/Joseph_Priestley) focused sunlight on [mercuric oxide](/wiki/Mercury(II)_oxide) (HgO) inside a glass tube, which liberated a gas he named "dephlogisticated air".[[3]](#cite_note-3) He noted that candles burned brighter in the gas and that a mouse was more active and lived longer while breathing it. After breathing the gas himself, he wrote: "The feeling of it to my lungs was not sensibly different from that of common air, but I fancied that my breast felt peculiarly light and easy for some time afterwards."[[11]](#cite_note-11) Priestley published his findings in 1775 in a paper titled "An Account of Further Discoveries in Air" which was included in the second volume of his book titled [*Experiments and Observations on Different Kinds of Air*](/wiki/Experiments_and_Observations_on_Different_Kinds_of_Air).[[8]](#cite_note-8)[[14]](#cite_note-14) Because he published his findings first, Priestley is usually given priority in the discovery.

The French chemist [Antoine Laurent Lavoisier](/wiki/Antoine_Lavoisier) later claimed to have discovered the new substance independently. Priestley visited Lavoisier in October 1774 and told him about his experiment and how he liberated the new gas. Scheele also posted a letter to Lavoisier on September 30, 1774 that described his discovery of the previously unknown substance, but Lavoisier never acknowledged receiving it (a copy of the letter was found in Scheele's belongings after his death).[[13]](#cite_note-13)[Template:Clear](/wiki/Template:Clear)

### Lavoisier's contribution[[edit](/index.php?title=(none)&action=edit&section=5)]

What Lavoisier did (although this was disputed at the time) was to conduct the first adequate quantitative experiments on [oxidation](/wiki/Oxidation) and give the first correct explanation of how combustion works.[[3]](#cite_note-3) He used these and similar experiments, all started in 1774, to discredit the phlogiston theory and to prove that the substance discovered by Priestley and Scheele was a [chemical element](/wiki/Chemical_element). [thumb|upright|left|](/wiki/File:Antoine_lavoisier.jpg)[Antoine Lavoisier](/wiki/Antoine_Lavoisier) discredited the phlogiston theory.|alt=A drawing of a young man facing towards the viewer, but looking on the side. He wear a white curly wig, dark suit and white scarf. In one experiment, Lavoisier observed that there was no overall increase in weight when [tin](/wiki/Tin) and air were heated in a closed container.[[3]](#cite_note-3) He noted that air rushed in when he opened the container, which indicated that part of the trapped air had been consumed. He also noted that the tin had increased in weight and that increase was the same as the weight of the air that rushed back in. This and other experiments on combustion were documented in his book *Sur la combustion en général*, which was published in 1777.[[3]](#cite_note-3) In that work, he proved that air is a mixture of two gases; 'vital air', which is essential to combustion and respiration, and *azote* (Gk. [*Template:Lang*](/wiki/Template:Lang) "lifeless"), which did not support either. *Azote* later became [*nitrogen*](/wiki/Nitrogen) in English, although it has kept the name in French and several other European languages.[[3]](#cite_note-3) Lavoisier renamed 'vital air' to *oxygène* in 1777 from the [Greek](/wiki/Ancient_Greek) roots [*Template:Lang*](/wiki/Template:Lang) *(oxys)* ([acid](/wiki/Acid), literally "sharp", from the taste of acids) and *-γενής (-genēs)* (producer, literally begetter), because he mistakenly believed that oxygen was a constituent of all acids.[[6]](#cite_note-6) Chemists (such as Sir [Humphry Davy](/wiki/Humphry_Davy) in 1812) eventually determined that Lavoisier was wrong in this regard (hydrogen forms the basis for acid chemistry), but by then the name was too well established.

*Oxygen* entered the English language despite opposition by English scientists and the fact that the Englishman Priestley had first isolated the gas and written about it. This is partly due to a poem praising the gas titled "Oxygen" in the popular book [*The Botanic Garden*](/wiki/The_Botanic_Garden) (1791) by [Erasmus Darwin](/wiki/Erasmus_Darwin), grandfather of [Charles Darwin](/wiki/Charles_Darwin).[[13]](#cite_note-13)[Template:Clear](/wiki/Template:Clear)

### Later history[[edit](/index.php?title=(none)&action=edit&section=6)]

[thumb|upright|](/wiki/File:Goddard_and_Rocket.jpg)[Robert H. Goddard](/wiki/Robert_H._Goddard) and a liquid oxygen-gasoline [rocket](/wiki/Rocket)|alt=A metal frame structure stands on the snow near a tree. A middle-aged man wearing a coat, boots, leather gloves and a cap stands by the structure and holds it with his right hand.

[John Dalton's](/wiki/John_Dalton) original [atomic hypothesis](/wiki/Atomic_theory#Earliest_empirical_evidence) presumed that all elements were monatomic and that the atoms in compounds would normally have the simplest atomic ratios with respect to one another. For example, Dalton assumed that water's formula was HO, giving the [atomic mass](/wiki/Atomic_mass) of oxygen was 8 times that of hydrogen, instead of the modern value of about 16.[[15]](#cite_note-15) In 1805, [Joseph Louis Gay-Lussac](/wiki/Joseph_Louis_Gay-Lussac) and [Alexander von Humboldt](/wiki/Alexander_von_Humboldt) showed that water is formed of two volumes of hydrogen and one volume of oxygen; and by 1811 [Amedeo Avogadro](/wiki/Amedeo_Avogadro) had arrived at the correct interpretation of water's composition, based on what is now called [Avogadro's law](/wiki/Avogadro's_law) and the diatomic elemental molecules in those gases.[[16]](#cite_note-16)<ref group=lower-alpha>These results were mostly ignored until 1860. Part of this rejection was due to the belief that atoms of one element would have no [chemical affinity](/wiki/Chemical_affinity) towards atoms of the same element, and part was due to apparent exceptions to Avogadro's law that were not explained until later in terms of dissociating molecules.</ref>

By the late 19th century scientists realized that air could be liquefied and its components isolated by compressing and cooling it. Using a [cascade](/wiki/Cascade_(chemical_engineering)) method, Swiss chemist and physicist [Raoul Pierre Pictet](/wiki/Raoul_Pictet) [evaporated](/wiki/Evaporation) liquid [sulfur dioxide](/wiki/Sulfur_dioxide) in order to liquefy carbon dioxide, which in turn was evaporated to cool oxygen gas enough to liquefy it. He sent a telegram on December 22, 1877 to the [French Academy of Sciences](/wiki/French_Academy_of_Sciences) in Paris announcing his discovery of [liquid oxygen](/wiki/Liquid_oxygen).[[17]](#cite_note-17) Just two days later, French physicist [Louis Paul Cailletet](/wiki/Louis_Paul_Cailletet) announced his own method of liquefying molecular oxygen.[[17]](#cite_note-17) Only a few drops of the liquid were produced in each case and no meaningful analysis could be conducted. Oxygen was liquified in a stable state for the first time on March 29, 1883 by Polish scientists from [Jagiellonian University](/wiki/Jagiellonian_University), [Zygmunt Wróblewski](/wiki/Zygmunt_Wróblewski) and [Karol Olszewski](/wiki/Karol_Olszewski).[[18]](#cite_note-18) In 1891 Scottish chemist [James Dewar](/wiki/James_Dewar) was able to produce enough liquid oxygen for study.[[19]](#cite_note-19) The first commercially viable process for producing liquid oxygen was independently developed in 1895 by German engineer [Carl von Linde](/wiki/Carl_von_Linde) and British engineer William Hampson. Both men lowered the temperature of air until it liquefied and then [distilled](/wiki/Distillation) the component gases by boiling them off one at a time and capturing them.[[20]](#cite_note-20) Later, in 1901, oxyacetylene [welding](/wiki/Welding) was demonstrated for the first time by burning a mixture of [acetylene](/wiki/Acetylene) and compressed [Template:Chem](/wiki/Template:Chem). This method of welding and cutting metal later became common.[[20]](#cite_note-20) In 1923, the American scientist [Robert H. Goddard](/wiki/Robert_H._Goddard) became the first person to develop a [rocket engine](/wiki/Rocket_engine) that burned liquid fuel; the engine used [gasoline](/wiki/Gasoline) for fuel and liquid oxygen as the [oxidizer](/wiki/Oxidizer). Goddard successfully flew a small liquid-fueled rocket 56 m at 97 km/h on March 16, 1926 in [Auburn, Massachusetts](/wiki/Auburn,_Massachusetts), US.[[20]](#cite_note-20)[[21]](#cite_note-21) Oxygen levels in the atmosphere are trending slightly downward globally, possibly because of fossil-fuel burning.[[22]](#cite_note-22)

## Characteristics[[edit](/index.php?title=(none)&action=edit&section=7)]

### Properties and molecular structure[[edit](/index.php?title=(none)&action=edit&section=8)]

[thumb|left|260 px|Orbital diagram, after Barrett (2002),<ref name=Barrett2002/> showing the participating atomic orbitals from each oxygen atom, the molecular orbitals that result from their overlap, and the](/wiki/File:Oxygen_molecule_orbitals_diagram.JPG) [Aufbau](/wiki/Aufbau_principle) filling of the orbitals with the 12 electrons, 6 from each O atom, beginning from the lowest energy orbitals, and resulting in covalent double bond character from filled orbitals (and cancelation of the contributions of the pairs of σ and σ\* and [Template:Pi](/wiki/Template:Pi) and [Template:Pi](/wiki/Template:Pi)\* orbital pairs). At [standard temperature and pressure](/wiki/Standard_temperature_and_pressure), oxygen is a colorless, odorless, and tasteless gas with the [molecular formula](/wiki/Molecular_formula) [Template:Chem](/wiki/Template:Chem), referred to as dioxygen.[[23]](#cite_note-23) As *dioxygen*, two oxygen atoms are [chemically bound](/wiki/Chemical_bond) to each other. The bond can be variously described based on level of theory, but is reasonably and simply described as a covalent [double bond](/wiki/Double_bond) that results from the filling of [molecular orbitals](/wiki/Molecular_orbitals) formed from the [atomic orbitals](/wiki/Atomic_orbital) of the individual oxygen atoms, the filling of which results in a [bond order](/wiki/Bond_order) of two. More specifically, the double bond is the result of sequential, low-to-high energy, or [Aufbau](/wiki/Aufbau_principle), filling of orbitals, and the resulting cancellation of contributions from the 2s electrons, after sequential filling of the low σ and σ\* orbitals; σ overlap of the two atomic 2p orbitals that lie along the O-O molecular axis and [Template:Pi](/wiki/Template:Pi) overlap of two pairs of atomic 2p orbitals perpendicular to the O-O molecular axis, and then cancellation of contributions from the remaining two of the six 2p electrons after their partial filling of the lowest [Template:Pi](/wiki/Template:Pi) and [Template:Pi](/wiki/Template:Pi)\* orbitals.<ref name=Barrett2002>Jack Barrett, 2002, "Atomic Structure and Periodicity, (Basic concepts in chemistry, Vol. 9 of Tutorial chemistry texts), Cambridge, U.K.:Royal Society of Chemistry, p. 153, ISBN 0854046577, see <https://books.google.com/books?isbn=0854046577> accessed January 31, 2015.</ref>

This combination of cancellations and σ and [Template:Pi](/wiki/Template:Pi) overlaps results in dioxygen's double bond character and reactivity, and a triplet electronic [ground state](/wiki/Ground_state). An [electron configuration](/wiki/Electron_configuration) with two unpaired electrons, as is found in dioxygen (see the filled [Template:Pi](/wiki/Template:Pi)\* orbitals in the diagram) orbitals that are of equal energy—i.e., [degenerate](/wiki/Degenerate_orbitals)—is a configuration termed a [spin triplet](/wiki/Spin_triplet) state. Hence, the ground state of the [Template:Chem](/wiki/Template:Chem) molecule is referred to as [triplet oxygen](/wiki/Triplet_oxygen).[[24]](#cite_note-24)<ref group=lower-alpha>An orbital is a concept from [quantum mechanics](/wiki/Quantum_mechanics) that models an electron as a [wave-like particle](/wiki/Wave–particle_duality) that has a spatial distribution about an atom or molecule.</ref> The highest energy, partially filled orbitals are [antibonding](/wiki/Antibonding), and so their filling weakens the bond order from three to two. Because of its unpaired electrons, triplet oxygen reacts only slowly with most organic molecules, which have paired electron spins; this prevents spontaneous combustion.[[25]](#cite_note-25) [thumb|left|upright|A trickle of liquid oxygen is deflected by a magnetic field, illustrating its paramagnetic property](/wiki/File:Paramagnetism_of_liquid_oxygen.jpeg) In the triplet form, [Template:Chem](/wiki/Template:Chem) molecules are [paramagnetic](/wiki/Paramagnetism). That is, they impart magnetic character to oxygen when it is in the presence of a magnetic field, because of the [spin](/wiki/Spin_(physics)) [magnetic moments](/wiki/Magnetic_moment) of the unpaired electrons in the molecule, and the negative [exchange energy](/wiki/Exchange_energy) between neighboring [Template:Chem](/wiki/Template:Chem) molecules.[[19]](#cite_note-19) Liquid oxygen is so [magnetic](/wiki/Magnet) that, in laboratory demonstrations, a bridge of liquid oxygen may be supported against its own weight between the poles of a powerful magnet.[[26]](#cite_note-26)[Template:Refn](/wiki/Template:Refn)

[Singlet oxygen](/wiki/Singlet_oxygen) is a name given to several higher-energy species of molecular [Template:Chem](/wiki/Template:Chem) in which all the electron spins are paired. It is much more reactive with common [organic molecules](/wiki/Organic_compound) than is molecular oxygen per se. In nature, singlet oxygen is commonly formed from water during photosynthesis, using the energy of sunlight.[[27]](#cite_note-27) It is also produced in the [troposphere](/wiki/Troposphere) by the photolysis of ozone by light of short wavelength,[[28]](#cite_note-28) and by the [immune system](/wiki/Immune_system) as a source of active oxygen.[[29]](#cite_note-29) [Carotenoids](/wiki/Carotenoid) in photosynthetic organisms (and possibly animals) play a major role in absorbing energy from [singlet oxygen](/wiki/Singlet_oxygen) and converting it to the unexcited ground state before it can cause harm to tissues.[[30]](#cite_note-30)

### Allotropes[[edit](/index.php?title=(none)&action=edit&section=9)]

[Template:Main article](/wiki/Template:Main_article) [thumb|upright|left|Ozone is a rare gas on Earth found mostly in the](/wiki/File:Ozone-1,3-dipole.png) [stratosphere](/wiki/Stratosphere).|alt=Central atom is positively charged and end atoms are negatively charged. [thumb|right|200px|](/wiki/File:Oxygen_molecule.png)[Space-filling model](/wiki/Space-filling_model) representation of dioxygen (O2) molecule The common [allotrope](/wiki/Allotropy) of elemental oxygen on Earth is called [dioxygen](/wiki/Dioxygen), [Template:Chem](/wiki/Template:Chem), the major part of the Earth's atmospheric oxygen (see [Occurrence](/wiki/#Occurrence)). O2 has a bond length of 121 [pm](/wiki/Picometre) and a bond energy of 498 [kJ·mol−1](/wiki/Joule_per_mole),[[31]](#cite_note-31) which is smaller than the energy of other double bonds or pairs of single bonds in the biosphere and responsible for the [exothermic](/wiki/Exothermic) reaction of O2 with any organic molecule.[[25]](#cite_note-25)[[32]](#cite_note-32) Due to its energy content, O2 is used by complex forms of life, such as animals, in cellular respiration (see [Biological role](/wiki/#Biological_role)). Other aspects of [Template:Chem](/wiki/Template:Chem) are covered in the remainder of this article.

Trioxygen ([Template:Chem](/wiki/Template:Chem)) is usually known as [ozone](/wiki/Ozone) and is a very reactive allotrope of oxygen that is damaging to lung tissue.[[33]](#cite_note-33) Ozone is produced in the [upper atmosphere](/wiki/Upper_atmosphere) when [Template:Chem](/wiki/Template:Chem) combines with atomic oxygen made by the splitting of [Template:Chem](/wiki/Template:Chem) by [ultraviolet](/wiki/Ultraviolet) (UV) radiation.[[6]](#cite_note-6) Since ozone absorbs strongly in the UV region of the [spectrum](/wiki/Electromagnetic_spectrum), the [ozone layer](/wiki/Ozone_layer) of the upper atmosphere functions as a protective radiation shield for the planet.[[6]](#cite_note-6) Near the Earth's surface, it is a [pollutant](/wiki/Air_pollution) formed as a by-product of automobile exhaust.[[33]](#cite_note-33) The [metastable](/wiki/Metastability_in_molecules) molecule [tetraoxygen](/wiki/Tetraoxygen) ([Template:Chem](/wiki/Template:Chem)) was discovered in 2001,[[34]](#cite_note-34)[[35]](#cite_note-35) and was assumed to exist in one of the six phases of [solid oxygen](/wiki/Solid_oxygen). It was proven in 2006 that this phase, created by pressurizing [Template:Chem](/wiki/Template:Chem) to 20 [GPa](/wiki/Pascal_(unit)), is in fact a [rhombohedral](/wiki/Rhombohedral) [Template:Chem](/wiki/Template:Chem) [cluster](/wiki/Cluster_chemistry).[[36]](#cite_note-36) This cluster has the potential to be a much more powerful [oxidizer](/wiki/Oxidizing_agent) than either [Template:Chem](/wiki/Template:Chem) or [Template:Chem](/wiki/Template:Chem) and may therefore be used in [rocket fuel](/wiki/Rocket_fuel).[[34]](#cite_note-34)[[35]](#cite_note-35) A metallic phase was discovered in 1990 when solid oxygen is subjected to a pressure of above 96 GPa[[37]](#cite_note-37) and it was shown in 1998 that at very low temperatures, this phase becomes [superconducting](/wiki/Superconductivity).[[38]](#cite_note-38)

### Physical properties[[edit](/index.php?title=(none)&action=edit&section=10)]

[thumb|Oxygen discharge (spectrum) tube. The green color is similar to the color of an](/wiki/File:Oxygen_discharge_tube.jpg) ["aurora borealis"](/wiki/Aurora) [Template:See also](/wiki/Template:See_also) Oxygen [dissolves](/wiki/Solubility) more readily in water than nitrogen, and in freshwater more readily than seawater. Water in equilibrium with air contains approximately 1 molecule of dissolved [Template:Chem](/wiki/Template:Chem) for every 2 molecules of [Template:Chem](/wiki/Template:Chem) (1:2), compared with an atmospheric ratio of approximately 1:4. The solubility of oxygen in water is temperature-dependent, and about twice as much (14.6 mg·L−1) dissolves at 0 °C than at 20 °C (7.6 mg·L−1).[[11]](#cite_note-11)[[39]](#cite_note-39) At 25 °C and [Template:Convert](/wiki/Template:Convert) of air, freshwater contains about 6.04 [milliliters](/wiki/Litre) (mL) of oxygen per [liter](/wiki/Liter), and [seawater](/wiki/Seawater) contains about 4.95 mL per liter.[[40]](#cite_note-40) At 5 °C the solubility increases to 9.0 mL (50% more than at 25 °C) per liter for water and 7.2 mL (45% more) per liter for sea water. {| class="wikitable" |+Oxygen gas dissolved in water at sealevel ! !5 °C !25 °C |- |Freshwater |9.0 mL |6.04 mL |- |Seawater |7.2 mL |4.95 mL |} Oxygen condenses at 90.20 [K](/wiki/Kelvin) (−182.95 °C, −297.31 °F), and freezes at 54.36 K (−218.79 °C, −361.82 °F).[[41]](#cite_note-41) Both [liquid](/wiki/Liquid_oxygen) and [solid](/wiki/Solid_oxygen) [Template:Chem](/wiki/Template:Chem) are clear substances with a light [sky-blue](/wiki/Diffuse_sky_radiation) color caused by absorption in the red (in contrast with the blue color of the sky, which is due to [Rayleigh scattering](/wiki/Rayleigh_scattering) of blue light). High-purity liquid [Template:Chem](/wiki/Template:Chem) is usually obtained by the [fractional distillation](/wiki/Fractional_distillation) of liquefied air.[[42]](#cite_note-42) Liquid oxygen may also be condensed from air using liquid nitrogen as a coolant.[[43]](#cite_note-43) Oxygen is a highly reactive substance and must be segregated from combustible materials.[[43]](#cite_note-43) The spectroscopy of molecular oxygen is associated with the atmospheric processes of [aurora](/wiki/Aurora), [airglow](/wiki/Airglow) and [nightglow](/wiki/Nightglow).[[44]](#cite_note-44) The absorption in the [Herzberg continuum](/wiki/Herzberg_continuum) and [Schumann–Runge bands](/wiki/Schumann–Runge_bands) in the ultraviolet produces atomic oxygen that is important in the chemistry of the middle atmosphere.[[45]](#cite_note-45) Excited state singlet molecular oxygen is responsible for red chemiluminescence in solution.[[46]](#cite_note-46)

### Isotopes and stellar origin[[edit](/index.php?title=(none)&action=edit&section=11)]

[Template:Main article](/wiki/Template:Main_article) [thumb|Late in a massive star's life, 16O concentrates in the O-shell, 17O in the H-shell and 18O in the He-shell.|alt=A concentric-sphere diagram, showing, from the core to the outer shell, iron, silicon, oxygen, neon, carbon, helium and hydrogen layers.](/wiki/File:Evolved_star_fusion_shells.svg) Naturally occurring oxygen is composed of three stable [isotopes](/wiki/Isotope), [16O](/wiki/Oxygen-16), [17O](/wiki/Oxygen-17), and [18O](/wiki/Oxygen-18), with 16O being the most abundant (99.762% [natural abundance](/wiki/Natural_abundance)).[[47]](#cite_note-47) Most 16O is [synthesized](/wiki/Nucleosynthesis) at the end of the [helium fusion](/wiki/Helium_fusion) process in massive [stars](/wiki/Star) but some is made in the [neon burning process](/wiki/Neon_burning_process).[[48]](#cite_note-48) 17O is primarily made by the burning of hydrogen into [helium](/wiki/Helium) during the [CNO cycle](/wiki/CNO_cycle), making it a common isotope in the hydrogen burning zones of stars.[[48]](#cite_note-48) Most 18O is produced when [14N](/wiki/Nitrogen-14) (made abundant from CNO burning) captures a [4He](/wiki/Helium-4) nucleus, making 18O common in the helium-rich zones of [evolved, massive stars](/wiki/Stellar_evolution#Massive_stars).[[48]](#cite_note-48) Fourteen [radioisotopes](/wiki/Radioisotope) have been characterized. The most stable are 15O with a [half-life](/wiki/Half-life) of 122.24 seconds and 14O with a half-life of 70.606 seconds.[[47]](#cite_note-47) All of the remaining [radioactive](/wiki/Radioactive_decay) isotopes have half-lives that are less than 27 s and the majority of these have half-lives that are less than 83 milliseconds.[[47]](#cite_note-47) The most common [decay mode](/wiki/Decay_mode) of the isotopes lighter than 16O is [β+ decay](/wiki/Positron_emission)[[49]](#cite_note-49)[[50]](#cite_note-50)[[51]](#cite_note-51) to yield nitrogen, and the most common mode for the isotopes heavier than 18O is [beta decay](/wiki/Beta_decay) to yield [fluorine](/wiki/Fluorine).[[47]](#cite_note-47)

### Occurrence[[edit](/index.php?title=(none)&action=edit&section=12)]

[Template:See also](/wiki/Template:See_also)

|  |  |  |  |
| --- | --- | --- | --- |
| Ten most common elements in the [Milky Way Galaxy](/wiki/Milky_Way_Galaxy) estimated spectroscopically[[52]](#cite_note-52) | | | |
| [**Z**](/wiki/Atomic_Number) | **Element** | **Mass fraction in parts per million** | |
| 1 | [Hydrogen](/wiki/Hydrogen) | 739,000 | 71 × mass of oxygen (red bar) | |
| 2 | [Helium](/wiki/Helium) | 240,000 | 23 × mass of oxygen (red bar) | |
| 8 | Oxygen | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 6 | [Carbon](/wiki/Carbon) | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 10 | [Neon](/wiki/Neon) | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 26 | [Iron](/wiki/Iron) | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 7 | [Nitrogen](/wiki/Nitrogen) | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 14 | [Silicon](/wiki/Silicon) | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 12 | [Magnesium](/wiki/Magnesium) | [Template:Bartable](/wiki/Template:Bartable) |  |  |
| 16 | [Sulfur](/wiki/Sulfur) | [Template:Bartable](/wiki/Template:Bartable) |  |  |

Oxygen is the most abundant chemical element by mass in the Earth's biosphere, air, sea and land. Oxygen is the third most abundant chemical element in the universe, after hydrogen and helium.[[2]](#cite_note-2) About 0.9% of the [Sun's](/wiki/Sun) mass is oxygen.[[3]](#cite_note-3) Oxygen constitutes 49.2% of the [Earth's crust](/wiki/Earth's_crust) by mass[[4]](#cite_note-4) as part of oxide compounds such as [silicon dioxide](/wiki/Silicon_dioxide) and is most abundant element by mass in the [Earth's crust](/wiki/Crust_(geology)#Earth's_crust_and_mantle). It is also the major component of the world's oceans (88.8% by mass).[[3]](#cite_note-3) Oxygen gas is the second most common component of the [Earth's atmosphere](/wiki/Earth's_atmosphere), taking up 20.8% of its volume and 23.1% of its mass (some 1015 tonnes).[[3]](#cite_note-3)[[53]](#cite_note-53)<ref group=lower-alpha>Figures given are for values up to [Template:Convert](/wiki/Template:Convert) above the surface</ref> Earth is unusual among the planets of the [Solar System](/wiki/Solar_System) in having such a high concentration of oxygen gas in its atmosphere: [Mars](/wiki/Mars) (with 0.1% [Template:Chem](/wiki/Template:Chem) by volume) and [Venus](/wiki/Venus) have much less. The [Template:Chem](/wiki/Template:Chem) surrounding those planets is produced solely by ultraviolet radiation on oxygen-containing molecules such as carbon dioxide.

The unusually high concentration of oxygen gas on Earth is the result of the [oxygen cycle](/wiki/Oxygen_cycle). This [biogeochemical cycle](/wiki/Biogeochemical_cycle) describes the movement of oxygen within and between its three main reservoirs on Earth: the atmosphere, the [biosphere](/wiki/Biosphere), and the [lithosphere](/wiki/Lithosphere). The main driving factor of the oxygen cycle is [photosynthesis](/wiki/Photosynthesis), which is responsible for modern Earth's atmosphere. Photosynthesis releases oxygen into the atmosphere, while [respiration](/wiki/Cellular_respiration), [decay](/wiki/Decomposition), and combustion remove it from the atmosphere. In the present equilibrium, production and consumption occur at the same rate of roughly 1/2000th of the entire atmospheric oxygen per year.

[thumb|right|Cold water holds more dissolved](/wiki/File:WOA09_sea-surf_O2_AYool.png) [Template:Chem](/wiki/Template:Chem).|alt=World map showing that the sea-surface oxygen is depleted around the equator and increases towards the poles.

Free oxygen also occurs in solution in the world's water bodies. The increased solubility of [Template:Chem](/wiki/Template:Chem) at lower temperatures (see [Physical properties](/wiki/#Physical_properties)) has important implications for ocean life, as polar oceans support a much higher density of life due to their higher oxygen content.[[54]](#cite_note-54) [Water polluted](/wiki/Water_pollution) with plant nutrients such as [nitrates](/wiki/Nitrate) or [phosphates](/wiki/Phosphate) may stimulate growth of algae by a process called [eutrophication](/wiki/Eutrophication) and the decay of these organisms and other biomaterials may reduce the [Template:Chem](/wiki/Template:Chem) content in eutrophic water bodies. Scientists assess this aspect of water quality by measuring the water's [biochemical oxygen demand](/wiki/Biochemical_oxygen_demand), or the amount of [Template:Chem](/wiki/Template:Chem) needed to restore it to a normal concentration.[[55]](#cite_note-55)

### Analysis[[edit](/index.php?title=(none)&action=edit&section=13)]

[thumb|left|250px|500 million years of](/wiki/File:Phanerozoic_Climate_Change.png) [climate change](/wiki/Climate_change) vs 18O|alt=Time evolution of oxygen-18 concentration on the scale of 500 million years showing many local peaks.

[Paleoclimatologists](/wiki/Paleoclimatology) measure the ratio of oxygen-18 and oxygen-16 in the [shells](/wiki/Animal_shell) and [skeletons](/wiki/Skeleton) of marine organisms to determine the climate millions of years ago (see [oxygen isotope ratio cycle](/wiki/Oxygen_isotope_ratio_cycle)). [Seawater](/wiki/Seawater) molecules that contain the lighter [isotope](/wiki/Isotope), oxygen-16, evaporate at a slightly faster rate than water molecules containing the 12% heavier oxygen-18, and this disparity increases at lower temperatures.[[56]](#cite_note-56) During periods of lower global temperatures, snow and rain from that evaporated water tends to be higher in oxygen-16, and the seawater left behind tends to be higher in oxygen-18. Marine organisms then incorporate more oxygen-18 into their skeletons and shells than they would in a warmer climate.[[56]](#cite_note-56) Paleoclimatologists also directly measure this ratio in the water molecules of [ice core](/wiki/Ice_core) samples as old as hundreds of thousands of years.

[Planetary geologists](/wiki/Geology_of_solar_terrestrial_planets) have measured the relative quantities of oxygen isotopes in samples from the [Earth](/wiki/Earth), the [Moon](/wiki/Moon), [Mars](/wiki/Mars), and [meteorites](/wiki/Meteorite), but were long unable to obtain reference values for the isotope ratios in the [Sun](/wiki/Sun), believed to be the same as those of the [primordial solar nebula](/wiki/Nebular_hypothesis). Analysis of a [silicon](/wiki/Silicon) wafer exposed to the [solar wind](/wiki/Solar_wind) in space and returned by the crashed [Genesis spacecraft](/wiki/Genesis_(spacecraft)) has shown that the Sun has a higher proportion of oxygen-16 than does the Earth. The measurement implies that an unknown process depleted oxygen-16 from the Sun's [disk of protoplanetary material](/wiki/Protoplanetary_disk) prior to the coalescence of dust grains that formed the Earth.[[57]](#cite_note-57) Oxygen presents two spectrophotometric [absorption bands](/wiki/Absorption_band) peaking at the wavelengths 687 and 760 [nm](/wiki/Nanometre). Some [remote sensing](/wiki/Remote_sensing) scientists have proposed using the measurement of the radiance coming from vegetation canopies in those bands to characterize plant health status from a [satellite](/wiki/Earth_observation_satellite) platform.[[58]](#cite_note-58) This approach exploits the fact that in those bands it is possible to discriminate the vegetation's [reflectance](/wiki/Reflectance) from its [fluorescence](/wiki/Fluorescence), which is much weaker. The measurement is technically difficult owing to the low [signal-to-noise ratio](/wiki/Signal-to-noise_ratio) and the physical structure of vegetation; but it has been proposed as a possible method of monitoring the [carbon cycle](/wiki/Carbon_cycle) from satellites on a global scale. [Template:Clear](/wiki/Template:Clear)

## Biological role of O<sub>2</sub>[[edit](/index.php?title=(none)&action=edit&section=14)]

[Template:Main article](/wiki/Template:Main_article)

### Photosynthesis and respiration[[edit](/index.php?title=(none)&action=edit&section=15)]

[thumb|Photosynthesis splits water to liberate](/wiki/File:Simple_photosynthesis_overview.svg) [Template:Chem](/wiki/Template:Chem) and fixes [Template:Chem](/wiki/Template:Chem) into sugar in what is called a [Calvin cycle](/wiki/Calvin_cycle).|alt=A diagram of photosynthesis processes, including income of water and carbon dioxide, illumination and release of oxygen. Reactions produce ATP and NADPH in a Calvin cycle with a sugar as a by product. In nature, free oxygen is produced by the [light-driven splitting](/wiki/Photolysis) of water during oxygenic [photosynthesis](/wiki/Photosynthesis). According to some estimates, [green algae](/wiki/Green_algae) and [cyanobacteria](/wiki/Cyanobacteria) in marine environments provide about 70% of the free oxygen produced on Earth, and the rest is produced by terrestrial plants.[[59]](#cite_note-59) Other estimates of the oceanic contribution to atmospheric oxygen are higher, while some estimates are lower, suggesting oceans produce ~45% of Earth's atmospheric oxygen each year.[[60]](#cite_note-60) A simplified overall formula for photosynthesis is:[[61]](#cite_note-61)

6 [Template:CO2](/wiki/Template:CO2) + 6 [Template:Chem](/wiki/Template:Chem) + [photons](/wiki/Photon) → [Template:Chem](/wiki/Template:Chem) + 6 [Template:Chem](/wiki/Template:Chem)

or simply

[carbon dioxide](/wiki/Carbon_dioxide) + water + sunlight → [glucose](/wiki/Glucose) + dioxygen

Photolytic [oxygen evolution](/wiki/Oxygen_evolution) occurs in the [thylakoid membranes](/wiki/Thylakoid_membrane) of photosynthetic organisms and requires the energy of four [photons](/wiki/Photon).<ref group=lower-alpha>Thylakoid membranes are part of [chloroplasts](/wiki/Chloroplast) in algae and plants while they simply are one of many membrane structures in cyanobacteria. In fact, chloroplasts are thought to have evolved from [cyanobacteria](/wiki/Cyanobacteria) that were once symbiotic partners with the progenerators of plants and algae.</ref> Many steps are involved, but the result is the formation of a [proton](/wiki/Proton) gradient across the thylakoid membrane, which is used to synthesize [adenosine triphosphate](/wiki/Adenosine_triphosphate) (ATP) via [photophosphorylation](/wiki/Photophosphorylation).[[62]](#cite_note-62) The [Template:Chem](/wiki/Template:Chem) remaining (after production of the water molecule) is released into the atmosphere.<ref group=lower-alpha>Water oxidation is catalyzed by a [manganese](/wiki/Manganese)-containing [enzyme](/wiki/Enzyme) complex known as the [oxygen evolving complex](/wiki/Oxygen_evolving_complex) (OEC) or water-splitting complex found associated with the lumenal side of thylakoid membranes. Manganese is an important [cofactor](/wiki/Cofactor_(biochemistry)), and [calcium](/wiki/Calcium) and [chloride](/wiki/Chloride) are also required for the reaction to occur. (Raven 2005)</ref>

Molecular dioxygen, [Template:Chem](/wiki/Template:Chem), is essential for cellular respiration in all [aerobic organisms](/wiki/Aerobic_organism). Oxygen is used in [mitochondria](/wiki/Mitochondrion) to generate ATP during [oxidative phosphorylation](/wiki/Oxidative_phosphorylation). The reaction for aerobic respiration is essentially the reverse of photosynthesis and is simplified as:

[Template:Chem](/wiki/Template:Chem) + 6 [Template:Chem](/wiki/Template:Chem) → 6 [Template:CO2](/wiki/Template:CO2) + 6 [Template:Chem](/wiki/Template:Chem) + 2880 kJ·mol−1

In [vertebrates](/wiki/Vertebrate), [Template:Chem](/wiki/Template:Chem) [diffuses](/wiki/Diffusion) through membranes in the lungs and into [red blood cells](/wiki/Red_blood_cell). [Hemoglobin](/wiki/Hemoglobin) binds [Template:Chem](/wiki/Template:Chem), changing color from bluish red to bright red[[33]](#cite_note-33) ([Template:Chem](/wiki/Template:Chem) is released from another part of hemoglobin through the [Bohr effect](/wiki/Bohr_effect)). Other animals use [hemocyanin](/wiki/Hemocyanin) ([molluscs](/wiki/Mollusca) and some [arthropods](/wiki/Arthropod)) or [hemerythrin](/wiki/Hemerythrin) ([spiders](/wiki/Spider) and [lobsters](/wiki/Lobster)).[[53]](#cite_note-53) A liter of blood can dissolve 200 cm3 of [Template:Chem](/wiki/Template:Chem).[[53]](#cite_note-53) Until the discovery of [anaerobic](/wiki/Anaerobic_organism) [metazoa](/wiki/Metazoa),[[63]](#cite_note-63) oxygen was thought to be a requirement for all complex life.[[64]](#cite_note-64) [Reactive oxygen species](/wiki/Reactive_oxygen_species), such as [superoxide](/wiki/Superoxide) ion ([Template:Chem](/wiki/Template:Chem)) and [hydrogen peroxide](/wiki/Hydrogen_peroxide) ([Template:Chem](/wiki/Template:Chem)), are dangerous by-products of oxygen use in organisms.[[53]](#cite_note-53) Parts of the [immune system](/wiki/Immune_system) of higher organisms create peroxide, superoxide, and singlet oxygen to destroy invading microbes. Reactive oxygen species also play an important role in the [hypersensitive response](/wiki/Hypersensitive_response) of plants against pathogen attack.[[62]](#cite_note-62) Oxygen is toxic to [obligately anaerobic organisms](/wiki/Obligate_anaerobe), which were the dominant form of [early life](/wiki/Evolutionary_history_of_life) on Earth until [Template:Chem](/wiki/Template:Chem) began to accumulate in the [atmosphere](/wiki/Atmosphere_of_Earth) about 2.5 billion years ago during the [Great Oxygenation Event](/wiki/Great_Oxygenation_Event), about a billion years after the first appearance of these organisms.[[65]](#cite_note-65)[[66]](#cite_note-66) An adult human at rest [inhales](/wiki/Breathing) 1.8 to 2.4 grams of oxygen per minute.[[67]](#cite_note-67) This amounts to more than 6 billion tonnes of oxygen inhaled by humanity per year.<ref group=lower-alpha>(1.8 grams/min/person)×(60 min/h)×(24 h/day)×(365 days/year)×(6.6 billion people)/1,000,000 g/t=6.24 billion tonnes</ref>

### Living organisms[[edit](/index.php?title=(none)&action=edit&section=16)]

[Template:Anchor](/wiki/Template:Anchor)

|  |  |  |  |
| --- | --- | --- | --- |
| [Partial pressures](/wiki/Partial_pressure) of oxygen in the human body (PO2) | | | |
| **Unit** | **Alveolar** [**pulmonary gas pressures**](/wiki/Pulmonary_gas_pressures) | [**Arterial blood oxygen**](/wiki/Arterial_blood_gas#oxygen) | [**Venous**](/wiki/Vein) **blood gas** |
| [kPa](/wiki/KPa) | 14.2 | 11<ref name=mmHg>Derived from mmHg values using 0.133322 kPa/mmHg</ref>-13<ref name=mmHg/> | 4.0<ref name=mmHg/>-5.3<ref name=mmHg/> |
| [mmHg](/wiki/MmHg) | 107 | 75<ref name=southwest>[Normal Reference Range Table](http://pathcuric1.swmed.edu/PathDemo/nrrt.htm) from The University of Texas Southwestern Medical Center at Dallas. Used in Interactive Case Study Companion to Pathologic basis of disease.</ref>-100<ref name=southwest/> | 30<ref name=brookside/>-40<ref name=brookside>[The Medical Education Division of the Brookside Associates--> ABG (Arterial Blood Gas)](http://www.brooksidepress.org/Products/OperationalMedicine/DATA/operationalmed/Lab/ABG_ArterialBloodGas.htm) Retrieved on December 6, 2009</ref> |
|  |  |  |  |

The free oxygen [partial pressure](/wiki/Partial_pressure) in the body of a living vertebrate organism is highest in the [respiratory system](/wiki/Respiratory_system), and decreases along any [arterial system](/wiki/Arterial_system), peripheral tissues, and [venous system](/wiki/Venous_system), respectively. Partial pressure is the pressure that oxygen would have if it alone occupied the volume.[[68]](#cite_note-68)

### Build-up in the atmosphere[[edit](/index.php?title=(none)&action=edit&section=17)]

[Template:Main article](/wiki/Template:Main_article)

[thumb|left|300px|](/wiki/File:Oxygenation-atm.svg)[Template:Chem](/wiki/Template:Chem) build-up in Earth's atmosphere: 1) no [Template:Chem](/wiki/Template:Chem) produced; 2) [Template:Chem](/wiki/Template:Chem) produced, but absorbed in oceans & seabed rock; 3) [Template:Chem](/wiki/Template:Chem) starts to gas out of the oceans, but is absorbed by land surfaces and formation of ozone layer; 4–5) [Template:Chem](/wiki/Template:Chem) sinks filled and the gas accumulates|alt=A graph showing time evolution of oxygen pressure on Earth; the pressure increases from zero to 0.2 atmospheres.

Free oxygen gas was almost nonexistent in [Earth's atmosphere](/wiki/Earth's_atmosphere) before photosynthetic [archaea](/wiki/Archaea) and [bacteria](/wiki/Bacteria) evolved, probably about 3.5 billion years ago. Free oxygen first appeared in significant quantities during the [Paleoproterozoic](/wiki/Paleoproterozoic) eon (between 3.0 and 2.3 billion years ago).[[69]](#cite_note-69) For the first billion years, any free oxygen produced by these organisms combined with dissolved [iron](/wiki/Iron) in the oceans to form [banded iron formations](/wiki/Banded_iron_formation). When such oxygen sinks became saturated, free oxygen began to [outgas](/wiki/Outgassing) from the oceans 3–2.7 billion years ago, reaching 10% of its present level around 1.7 billion years ago.[[69]](#cite_note-69)[[70]](#cite_note-70) The presence of large amounts of dissolved and free oxygen in the oceans and atmosphere may have driven most of the extant [anaerobic organisms](/wiki/Anaerobic_organism) to [extinction](/wiki/Extinction) during the [Great Oxygenation Event](/wiki/Great_Oxygenation_Event) (*oxygen catastrophe*) about 2.4 billion years ago. [Cellular respiration](/wiki/Cellular_respiration) using [Template:Chem](/wiki/Template:Chem) enables [aerobic organisms](/wiki/Aerobic_organism) to produce much more [ATP](/wiki/Adenosine_triphosphate) than [anaerobic organisms](/wiki/Anaerobic_organism).[[71]](#cite_note-71) Cellular respiration of [Template:Chem](/wiki/Template:Chem) occurs in all [eukaryotes](/wiki/Eukaryote), including all complex multicellular organisms such as plants and animals.

Since the beginning of the [Cambrian](/wiki/Cambrian) period 540 million years ago, atmospheric [Template:Chem](/wiki/Template:Chem) levels have fluctuated between 15% and 30% by volume.[[72]](#cite_note-72) Towards the end of the [Carboniferous](/wiki/Carboniferous) period (about 300 million years ago) atmospheric [Template:Chem](/wiki/Template:Chem) levels reached a maximum of 35% by volume,[[72]](#cite_note-72) which may have contributed to the large size of insects and amphibians at this time.<ref name=Butterfield2009>[Template:Cite journal](/wiki/Template:Cite_journal)</ref>

Variations of oxygen shaped the climates of the past. When oxygen declined, atmospheric density dropped and this in turn increased surface evaporation, and led to precipitation increases and warmer temperatures.[[73]](#cite_note-73) At the current rate of photosynthesis it would take about 2,000 years to regenerate the entire [Template:Chem](/wiki/Template:Chem) in the present atmosphere.[[74]](#cite_note-74)[Template:Clear](/wiki/Template:Clear)

## Industrial production[[edit](/index.php?title=(none)&action=edit&section=18)]

[thumb|](/wiki/File:Hofmann_voltameter_fr.svg)[Hofmann electrolysis apparatus](/wiki/Hofmann_voltameter) used in electrolysis of water.|alt=A drawing of three vertical pipes connected at the bottom and filled with oxygen (left pipe), water (middle) and hydrogen (right). Anode and cathode electrodes are inserted into the left and right pipes and externally connected to a battery. [Template:See also](/wiki/Template:See_also)

One hundred million tonnes of [Template:Chem](/wiki/Template:Chem) are extracted from air for industrial uses annually by two primary methods.[[13]](#cite_note-13) The most common method is [fractional distillation](/wiki/Fractional_distillation) of liquefied air, with [Template:Chem](/wiki/Template:Chem) [distilling](/wiki/Distillation) as a vapor while [Template:Chem](/wiki/Template:Chem) is left as a liquid.[[13]](#cite_note-13) The other primary method of producing [Template:Chem](/wiki/Template:Chem) is passing a stream of clean, dry air through one bed of a pair of identical [zeolite](/wiki/Zeolite) molecular sieves, which absorbs the nitrogen and delivers a gas stream that is 90% to 93% [Template:Chem](/wiki/Template:Chem).[[13]](#cite_note-13) Simultaneously, nitrogen gas is released from the other nitrogen-saturated zeolite bed, by reducing the chamber operating pressure and diverting part of the oxygen gas from the producer bed through it, in the reverse direction of flow. After a set cycle time the operation of the two beds is interchanged, thereby allowing for a continuous supply of gaseous oxygen to be pumped through a pipeline. This is known as [pressure swing adsorption](/wiki/Pressure_swing_adsorption). Oxygen gas is increasingly obtained by these non-[cryogenic](/wiki/Cryogenics) technologies (see also the related [vacuum swing adsorption](/wiki/Vacuum_swing_adsorption)).[[75]](#cite_note-75) Oxygen gas can also be produced through [electrolysis of water](/wiki/Electrolysis_of_water) into molecular oxygen and hydrogen. DC electricity must be used: if AC is used, the gases in each limb consist of hydrogen and oxygen in the explosive ratio 2:1. Contrary to popular belief, the 2:1 ratio observed in the DC electrolysis of acidified water does not prove that the empirical formula of water is H2O unless certain assumptions are made about the molecular formulae of hydrogen and oxygen themselves. A similar method is the electrocatalytic [Template:Chem](/wiki/Template:Chem) evolution from oxides and [oxoacids](/wiki/Oxoacid). Chemical catalysts can be used as well, such as in [chemical oxygen generators](/wiki/Chemical_oxygen_generator) or oxygen candles that are used as part of the life-support equipment on submarines, and are still part of standard equipment on commercial airliners in case of depressurization emergencies. Another air separation method is forcing air to dissolve through [ceramic](/wiki/Ceramic) membranes based on [zirconium dioxide](/wiki/Zirconium_dioxide) by either high pressure or an electric current, to produce nearly pure [Template:Chem](/wiki/Template:Chem) gas.[[55]](#cite_note-55) In large quantities, the price of liquid oxygen in 2001 was approximately $0.21/kg.[[76]](#cite_note-76) Since the primary cost of production is the energy cost of liquefying the air, the production cost will change as energy cost varies.

## Storage[[edit](/index.php?title=(none)&action=edit&section=19)]

[Oxygen storage](/wiki/Oxygen_storage) methods include high pressure [oxygen tanks](/wiki/Oxygen_tank), cryogenics and chemical compounds. For reasons of economy, oxygen is often transported in bulk as a liquid in specially insulated tankers, since one [liter](/wiki/Litre) of liquefied oxygen is equivalent to 840 liters of gaseous oxygen at atmospheric pressure and [Template:Convert](/wiki/Template:Convert).[[13]](#cite_note-13) Such tankers are used to refill bulk liquid oxygen storage containers, which stand outside hospitals and other institutions that need large volumes of pure oxygen gas. Liquid oxygen is passed through [heat exchangers](/wiki/Heat_exchanger), which convert the cryogenic liquid into gas before it enters the building. Oxygen is also stored and shipped in smaller cylinders containing the compressed gas; a form that is useful in certain portable medical applications and [oxy-fuel welding and cutting](/wiki/Oxy-fuel_welding_and_cutting).[[13]](#cite_note-13)[Template:Clear](/wiki/Template:Clear)

## Applications[[edit](/index.php?title=(none)&action=edit&section=20)]

[Template:See also](/wiki/Template:See_also)

### Medical[[edit](/index.php?title=(none)&action=edit&section=21)]

[thumb|upright|left|An](/wiki/File:Home_oxygen_concentrator.jpg) [oxygen concentrator](/wiki/Oxygen_concentrator) in an [emphysema](/wiki/Emphysema) patient's house|alt=A gray device with a label DeVILBISS LT4000 and some text on the front panel. A green plastic pipe is running from the device.

[Template:Main article](/wiki/Template:Main_article)

Uptake of [Template:Chem](/wiki/Template:Chem) from the air is the essential purpose of [respiration](/wiki/Respiration_(physiology)), so oxygen supplementation is used in [medicine](/wiki/Medicine). Treatment not only increases oxygen levels in the patient's blood, but has the secondary effect of decreasing resistance to blood flow in many types of diseased lungs, easing work load on the heart. [Oxygen therapy](/wiki/Oxygen_therapy) is used to treat [emphysema](/wiki/Emphysema), [pneumonia](/wiki/Pneumonia), some heart disorders ([congestive heart failure](/wiki/Congestive_heart_failure)), some disorders that cause increased [pulmonary artery pressure](/wiki/Pulmonary_artery_pressure), and any [disease](/wiki/Disease) that impairs the body's ability to take up and use gaseous oxygen.[[77]](#cite_note-77) Treatments are flexible enough to be used in hospitals, the patient's home, or increasingly by portable devices. [Oxygen tents](/wiki/Oxygen_tent) were once commonly used in oxygen supplementation, but have since been replaced mostly by the use of [oxygen masks](/wiki/Oxygen_mask) or [nasal cannulas](/wiki/Nasal_cannula).[[78]](#cite_note-78) [Hyperbaric](/wiki/Hyperbaric_medicine) (high-pressure) medicine uses special [oxygen chambers](/wiki/Hyperbaric_oxygen_chamber) to increase the [partial pressure](/wiki/Partial_pressure) of [Template:Chem](/wiki/Template:Chem) around the patient and, when needed, the medical staff.[[79]](#cite_note-79) [Carbon monoxide poisoning](/wiki/Carbon_monoxide_poisoning), [gas gangrene](/wiki/Gas_gangrene), and [decompression sickness](/wiki/Decompression_sickness) (the 'bends') are sometimes addressed with this therapy.[[80]](#cite_note-80) Increased [Template:Chem](/wiki/Template:Chem) concentration in the lungs helps to displace [carbon monoxide](/wiki/Carbon_monoxide) from the heme group of [hemoglobin](/wiki/Hemoglobin).[[81]](#cite_note-81)[[82]](#cite_note-82) Oxygen gas is poisonous to the [anaerobic bacteria](/wiki/Anaerobic_bacteria) that cause gas gangrene, so increasing its partial pressure helps kill them.[[83]](#cite_note-83)[[84]](#cite_note-84) Decompression sickness occurs in divers who decompress too quickly after a dive, resulting in bubbles of inert gas, mostly nitrogen and helium, forming in the blood. Increasing the pressure of [Template:Chem](/wiki/Template:Chem) as soon as possible helps to redissolve the bubbles back into the blood so that these excess gasses can be exhaled naturally through the lungs.[[77]](#cite_note-77)[[85]](#cite_note-85)[[86]](#cite_note-86) Oxygen is also used medically for patients who require [mechanical ventilation](/wiki/Mechanical_ventilation), often at concentrations above the 21% found in ambient air. [Template:Clear](/wiki/Template:Clear)

### Life support and recreational use[[edit](/index.php?title=(none)&action=edit&section=22)]

[thumb|Low pressure pure](/wiki/File:Wisoff_on_the_Arm_-_GPN-2000-001069.jpg) [Template:Chem](/wiki/Template:Chem) is used in [space suits](/wiki/Space_suit).

An application of [Template:Chem](/wiki/Template:Chem) as a low-pressure [breathing gas](/wiki/Breathing_gas) is in modern [space suits](/wiki/Space_suit), which surround their occupant's body with pressurized air. These devices use nearly pure oxygen at about one third normal pressure, resulting in a normal blood partial pressure of [Template:Chem](/wiki/Template:Chem).[[87]](#cite_note-87)[[88]](#cite_note-88) This trade-off of higher oxygen concentration for lower pressure is needed to maintain suit flexibility.

[Scuba divers](/wiki/Scuba_diving) and [submariners](/wiki/Submarine) also rely on artificially delivered [Template:Chem](/wiki/Template:Chem), but most often use normal pressure, and/or mixtures of oxygen and air. Pure or nearly pure [Template:Chem](/wiki/Template:Chem) use in diving at higher-than-sea-level pressures is usually limited to rebreather, decompression, or emergency treatment use at relatively shallow depths (~6 meters depth, or less).[[89]](#cite_note-89)[[90]](#cite_note-90) Deeper diving requires significant dilution of [Template:Chem](/wiki/Template:Chem) with other gases, such as nitrogen or helium, to prevent [oxygen toxicity](/wiki/Oxygen_toxicity).[[89]](#cite_note-89) People who climb mountains or fly in non-pressurized [fixed-wing aircraft](/wiki/Fixed-wing_aircraft) sometimes have supplemental [Template:Chem](/wiki/Template:Chem) supplies.<ref group=lower-alpha>The reason is that increasing the proportion of oxygen in the breathing gas at low pressure acts to augment the inspired [Template:Chem](/wiki/Template:Chem) partial pressure nearer to that found at sea-level.</ref> Pressurized commercial airplanes have an emergency supply of [Template:Chem](/wiki/Template:Chem) automatically supplied to the passengers in case of cabin depressurization. Sudden cabin pressure loss activates [chemical oxygen generators](/wiki/Chemical_oxygen_generator) above each seat, causing [oxygen masks](/wiki/Oxygen_mask) to drop. Pulling on the masks "to start the flow of oxygen" as cabin safety instructions dictate, forces iron filings into the [sodium chlorate](/wiki/Sodium_chlorate) inside the canister.[[55]](#cite_note-55) A steady stream of oxygen gas is then produced by the [exothermic](/wiki/Exothermic) reaction.

Oxygen, as a supposed mild [euphoric](/wiki/Euphoria), has a history of recreational use in [oxygen bars](/wiki/Oxygen_bar) and in [sports](/wiki/Sport). Oxygen bars are establishments found in Japan, [California](/wiki/California), and [Las Vegas](/wiki/Las_Vegas_Valley), [Nevada](/wiki/Nevada) since the late 1990s that offer higher than normal [Template:Chem](/wiki/Template:Chem) exposure for a fee.[[91]](#cite_note-91) Professional athletes, especially in [American football](/wiki/American_football), sometimes go off-field between plays to don oxygen masks to boost performance. The pharmacological effect is doubted; a [placebo](/wiki/Placebo) effect is a more likely explanation.[[91]](#cite_note-91) Available studies support a performance boost from enriched [Template:Chem](/wiki/Template:Chem) mixtures only if it is breathed *during* aerobic exercise.[[92]](#cite_note-92) Other recreational uses that do not involve breathing include [pyrotechnic](/wiki/Pyrotechnic) applications, such as [George Goble's](/wiki/George_Goble) five-second ignition of [barbecue](/wiki/Barbecue) grills.[[93]](#cite_note-93)

### Industrial[[edit](/index.php?title=(none)&action=edit&section=23)]

[thumb|Most commercially produced](/wiki/File:Clabecq_JPG01.jpg) [Template:Chem](/wiki/Template:Chem) is used to [smelt](/wiki/Smelting) [iron](/wiki/Iron) into [steel](/wiki/Steel).|alt=An elderly worker in a helmet is facing his side to the viewer in an industrial hall. The hall is dark but is illuminated yellow glowing splashes of a melted substance.

[Smelting](/wiki/Smelting) of [iron ore](/wiki/Iron_ore) into [steel](/wiki/Steel) consumes 55% of commercially produced oxygen.[[55]](#cite_note-55) In this process, [Template:Chem](/wiki/Template:Chem) is injected through a high-pressure lance into molten iron, which removes [sulfur](/wiki/Sulfur) impurities and excess [carbon](/wiki/Carbon) as the respective oxides, [Template:Chem](/wiki/Template:Chem) and [Template:Chem](/wiki/Template:Chem). The reactions are [exothermic](/wiki/Exothermic_reaction), so the temperature increases to 1,700 °[C](/wiki/Celsius).[[55]](#cite_note-55) Another 25% of commercially produced oxygen is used by the chemical industry.[[55]](#cite_note-55) [Ethylene](/wiki/Ethylene) is reacted with [Template:Chem](/wiki/Template:Chem) to create [ethylene oxide](/wiki/Ethylene_oxide), which, in turn, is converted into [ethylene glycol](/wiki/Ethylene_glycol); the primary feeder material used to manufacture a host of products, including [antifreeze](/wiki/Antifreeze) and [polyester](/wiki/Polyester) polymers (the precursors of many [plastics](/wiki/Plastic) and [fabrics](/wiki/Fabric)).[[55]](#cite_note-55) Most of the remaining 20% of commercially produced oxygen is used in medical applications, [metal cutting and welding](/wiki/Gas_welding), as an oxidizer in [rocket fuel](/wiki/Rocket_fuel), and in [water treatment](/wiki/Water_treatment).[[55]](#cite_note-55) Oxygen is used in [oxyacetylene welding](/wiki/Oxyacetylene_welding) burning [acetylene](/wiki/Acetylene) with [Template:Chem](/wiki/Template:Chem) to produce a very hot flame. In this process, metal up to 60 [cm](/wiki/Centimetre) thick is first heated with a small oxy-acetylene flame and then quickly cut by a large stream of [Template:Chem](/wiki/Template:Chem).[[94]](#cite_note-94)

## Compounds[[edit](/index.php?title=(none)&action=edit&section=24)]

[Template:Main article](/wiki/Template:Main_article) [thumb|upright|](/wiki/File:Stilles_Mineralwasser.jpg)[Water](/wiki/Water) ([Template:Chem](/wiki/Template:Chem)) is the most familiar oxygen compound.|alt=Water flowing from a bottle into a glass. The [oxidation state](/wiki/Oxidation_state) of oxygen is −2 in almost all known compounds of oxygen. The oxidation state −1 is found in a few compounds such as [peroxides](/wiki/Peroxide).[[95]](#cite_note-95) Compounds containing oxygen in other oxidation states are very uncommon: −1/2 ([superoxides](/wiki/Superoxide)), −1/3 ([ozonides](/wiki/Ozonide)), 0 ([elemental](/wiki/Allotropes_of_oxygen), [hypofluorous acid](/wiki/Hypofluorous_acid)), +1/2 ([dioxygenyl](/wiki/Dioxygenyl)), +1 ([dioxygen difluoride](/wiki/Dioxygen_difluoride)), and +2 ([oxygen difluoride](/wiki/Oxygen_difluoride)).

### Oxides and other inorganic compounds[[edit](/index.php?title=(none)&action=edit&section=25)]

[Water](/wiki/Water) ([Template:Chem](/wiki/Template:Chem)) is an oxide of [hydrogen](/wiki/Hydrogen) and the most familiar oxygen compound. Hydrogen atoms are [covalently bonded](/wiki/Covalent_bonding) to oxygen in a water molecule but also have an additional attraction (about 23.3 kJ·mol−1 per hydrogen atom) to an adjacent oxygen atom in a separate molecule.[[96]](#cite_note-96) These [hydrogen bonds](/wiki/Hydrogen_bond) between water molecules hold them approximately 15% closer than what would be expected in a simple liquid with just [van der Waals forces](/wiki/Van_der_Waals_force).[[97]](#cite_note-97)<ref group=lower-alpha>Also, since oxygen has a higher electronegativity than hydrogen, the charge difference makes it a [polar molecule](/wiki/Polar_molecule). The interactions between the different [dipoles](/wiki/Dipole) of each molecule cause a net attraction force.</ref>

[thumb|left|Oxides, such as](/wiki/File:Rust_screw.jpg) [iron oxide](/wiki/Iron_oxide) or [rust](/wiki/Rust), form when oxygen combines with other elements.|alt=A rusty piece of a bolt. Due to its [electronegativity](/wiki/Electronegativity), oxygen forms [chemical bonds](/wiki/Chemical_bond) with almost all other elements to give corresponding [oxides](/wiki/Oxide). The surface of most metals, such as [aluminium](/wiki/Aluminium) and [titanium](/wiki/Titanium), are oxidized in the presence of air and become coated with a thin film of oxide that [passivates](/wiki/Passivation_(chemistry)) the metal and slows further [corrosion](/wiki/Corrosion). Many oxides of the [transition metals](/wiki/Transition_metal) are [non-stoichiometric compounds](/wiki/Non-stoichiometric_compound), with slightly less metal than the [chemical formula](/wiki/Chemical_formula) would show. For example, the mineral [FeO](/wiki/Iron(II)_oxide) ([wüstite](/wiki/Wüstite)) is written as [Template:Chem](/wiki/Template:Chem), where *x* is usually around 0.05.[[98]](#cite_note-98) Oxygen is present in the atmosphere in trace quantities in the form of [carbon dioxide](/wiki/Carbon_dioxide) ([Template:Chem](/wiki/Template:Chem)). The [Earth's crustal](/wiki/Earth's_crust) [rock](/wiki/Rock_(geology)) is composed in large part of oxides of [silicon](/wiki/Silicon) ([silica](/wiki/Silicon_dioxide) [Template:Chem](/wiki/Template:Chem), as found in [granite](/wiki/Granite) and [quartz](/wiki/Quartz)), aluminium ([aluminium oxide](/wiki/Aluminium_oxide) [Template:Chem](/wiki/Template:Chem), in [bauxite](/wiki/Bauxite) and [corundum](/wiki/Corundum)), iron ([iron(III) oxide](/wiki/Iron(III)_oxide) [Template:Chem](/wiki/Template:Chem), in [hematite](/wiki/Hematite) and [rust](/wiki/Rust)), and [calcium carbonate](/wiki/Calcium_carbonate) (in [limestone](/wiki/Limestone)). The rest of the Earth's crust is also made of oxygen compounds, in particular various complex [silicates](/wiki/Silicate) (in [silicate minerals](/wiki/Silicate_minerals)). The Earth's mantle, of much larger mass than the crust, is largely composed of silicates of magnesium and iron.

Water-[soluble](/wiki/Solubility) silicates in the form of [Template:Chem](/wiki/Template:Chem), [Template:Chem](/wiki/Template:Chem), and [Template:Chem](/wiki/Template:Chem) are used as [detergents](/wiki/Detergent) and [adhesives](/wiki/Adhesive).[[99]](#cite_note-99) Oxygen also acts as a [ligand](/wiki/Ligand) for transition metals, forming [transition metal dioxygen complexes](/wiki/Transition_metal_dioxygen_complexes), which feature metal–[Template:Chem](/wiki/Template:Chem). This class of compounds includes the [heme](/wiki/Heme) proteins [hemoglobin](/wiki/Hemoglobin) and [myoglobin](/wiki/Myoglobin).[[100]](#cite_note-100) An exotic and unusual reaction occurs with [Template:Chem](/wiki/Template:Chem), which oxidizes oxygen to give O2+PtF6−.[[101]](#cite_note-101)

### Organic compounds and biomolecules[[edit](/index.php?title=(none)&action=edit&section=26)]

[thumb|](/wiki/File:Acetone-3D-vdW.png)[Acetone](/wiki/Acetone) is an important feeder material in the chemical industry. [Template:Legend](/wiki/Template:Legend) [Template:Legend](/wiki/Template:Legend) [Template:Legend](/wiki/Template:Legend) |alt=A ball structure of a molecule. Its backbone is a zig-zag chain of three carbon atoms connected in the center to an oxygen atom and on the end to 6 hydrogens. [thumb|left|Oxygen represents more than 40% of the](/wiki/File:ATP_structure.svg) [molecular mass](/wiki/Molecular_mass) of the [ATP](/wiki/Adenosine_triphosphate) molecule.|alt=Skeletal chemical structure with a linear chain of O-P-O bonds connected to three different carbon-nitrogen rings.

Among the most important classes of organic compounds that contain oxygen are (where "R" is an organic group): [alcohols](/wiki/Alcohol) (R-OH); [ethers](/wiki/Ether) (R-O-R); [ketones](/wiki/Ketone) (R-CO-R); [aldehydes](/wiki/Aldehyde) (R-CO-H); [carboxylic acids](/wiki/Carboxylic_acid) (R-COOH); [esters](/wiki/Ester) (R-COO-R); [acid anhydrides](/wiki/Acid_anhydride) (R-CO-O-CO-R); and [amides](/wiki/Amide) ([Template:Chem](/wiki/Template:Chem)). There are many important organic [solvents](/wiki/Solvent) that contain oxygen, including: [acetone](/wiki/Acetone), [methanol](/wiki/Methanol), [ethanol](/wiki/Ethanol), [isopropanol](/wiki/Isopropyl_alcohol), [furan](/wiki/Furan), [THF](/wiki/Tetrahydrofuran), [diethyl ether](/wiki/Diethyl_ether), [dioxane](/wiki/1,4-Dioxane), [ethyl acetate](/wiki/Ethyl_acetate), [DMF](/wiki/Dimethylformamide), [DMSO](/wiki/Dimethyl_sulfoxide), [acetic acid](/wiki/Acetic_acid), and [formic acid](/wiki/Formic_acid). Acetone ([Template:Chem](/wiki/Template:Chem)) and [phenol](/wiki/Phenol) ([Template:Chem](/wiki/Template:Chem)) are used as feeder materials in the synthesis of many different substances. Other important organic compounds that contain oxygen are: [glycerol](/wiki/Glycerol), [formaldehyde](/wiki/Formaldehyde), [glutaraldehyde](/wiki/Glutaraldehyde), [citric acid](/wiki/Citric_acid), [acetic anhydride](/wiki/Acetic_anhydride), and [acetamide](/wiki/Acetamide). [Epoxides](/wiki/Epoxide) are ethers in which the oxygen atom is part of a ring of three atoms.

Oxygen reacts spontaneously with many [organic](/wiki/Organic_chemistry) compounds at or below room temperature in a process called [autoxidation](/wiki/Autoxidation).[[102]](#cite_note-102) Most of the [organic compounds](/wiki/Organic_compound) that contain oxygen are not made by direct action of [Template:Chem](/wiki/Template:Chem). Organic compounds important in industry and commerce that are made by direct oxidation of a precursor include [ethylene oxide](/wiki/Ethylene_oxide) and [peracetic acid](/wiki/Peracetic_acid).[[99]](#cite_note-99) The element is found in almost all [biomolecules](/wiki/Biomolecule) that are important to (or generated by) life. Only a few common complex biomolecules, such as [squalene](/wiki/Squalene) and the [carotenes](/wiki/Carotene), contain no oxygen. Of the organic compounds with biological relevance, [carbohydrates](/wiki/Carbohydrate) contain the largest proportion by mass of oxygen. All [fats](/wiki/Fat), [fatty acids](/wiki/Fatty_acid), [amino acids](/wiki/Amino_acid), and [proteins](/wiki/Protein) contain oxygen (due to the presence of [carbonyl](/wiki/Carbonyl) groups in these acids and their ester residues). Oxygen also occurs in [phosphate](/wiki/Phosphate) ([Template:Chem](/wiki/Template:Chem)) groups in the biologically important energy-carrying molecules [ATP](/wiki/Adenosine_triphosphate) and [ADP](/wiki/Adenosine_diphosphate), in the backbone and the [purines](/wiki/Purine) (except [adenine](/wiki/Adenine)) and [pyrimidines](/wiki/Pyrimidine) of [RNA](/wiki/RNA) and [DNA](/wiki/DNA), and in bones as [calcium phosphate](/wiki/Calcium_phosphate) and [hydroxylapatite](/wiki/Hydroxylapatite).

## Safety and precautions[[edit](/index.php?title=(none)&action=edit&section=27)]

The [NFPA 704](/wiki/NFPA_704) standard rates compressed oxygen gas as nonhazardous to health, nonflammable and nonreactive, but an oxidizer. Refrigerated liquid oxygen (LOX) is given a health hazard rating of 3 (for increased risk of [hyperoxia](/wiki/Hyperoxia) from condensed vapors, and for hazards common to cryogenic liquids such as frostbite), and all other ratings are the same as the compressed gas form.

### Toxicity[[edit](/index.php?title=(none)&action=edit&section=28)]

[Template:Main article](/wiki/Template:Main_article) [thumb|left|300px|Main symptoms of oxygen toxicity](/wiki/File:Symptoms_of_oxygen_toxicity.png)[[103]](#cite_note-103)|alt=A diagraph showing a man torso and listing symptoms of oxygen toxicity: Eyes – visual field loss, near)sightedness, cataract formation, bleeding, fibrosis; Head – seizures; Muscles – twitching; Respiratory system – jerky breathing, irritation, coughing, pain, shortness of breath, tracheobronchitis, acute respiratory distress syndrome. [thumb|Oxygen toxicity occurs when the lungs take in](/wiki/File:Scuba-diving.jpg) [Template:Frac](/wiki/Template:Frac) higher than normal [Template:Chem](/wiki/Template:Chem) partial pressure, which can occur in deep [scuba diving](/wiki/Scuba_diving).|alt=Four divers, equipped with oxygen cylinders, at the see bottom.

Oxygen gas ([Template:Chem](/wiki/Template:Chem)) can be [toxic](/wiki/Oxygen_toxicity) at elevated [partial pressures](/wiki/Partial_pressure), leading to [convulsions](/wiki/Convulsion) and other health problems.[[89]](#cite_note-89)<ref group=lower-alpha>Since [Template:Chem's](/wiki/Template:Chem) partial pressure is the fraction of [Template:Chem](/wiki/Template:Chem) times the total pressure, elevated partial pressures can occur either from high [Template:Chem](/wiki/Template:Chem) fraction in breathing gas or from high breathing gas pressure, or a combination of both.</ref>[[104]](#cite_note-104) Oxygen toxicity usually begins to occur at partial pressures more than 50 kilo[pascals](/wiki/Pascal_(unit)) (kPa), equal to about 50% oxygen composition at standard pressure or 2.5 times the normal sea-level [Template:Chem](/wiki/Template:Chem) partial pressure of about 21 kPa. This is not a problem except for patients on [mechanical ventilators](/wiki/Mechanical_ventilator), since gas supplied through [oxygen masks](/wiki/Oxygen_mask) in medical applications is typically composed of only 30%–50% [Template:Chem](/wiki/Template:Chem) by volume (about 30 kPa at standard pressure).[[11]](#cite_note-11) (although this figure also is subject to wide variation, depending on type of mask).

At one time, [premature babies](/wiki/Premature_birth) were placed in incubators containing [Template:Chem](/wiki/Template:Chem)-rich air, but this practice was discontinued after some babies were blinded by the oxygen content being too high.[[11]](#cite_note-11) Breathing pure [Template:Chem](/wiki/Template:Chem) in space applications, such as in some modern space suits, or in early spacecraft such as [Apollo](/wiki/Apollo_spacecraft), causes no damage due to the low total pressures used.[[87]](#cite_note-87)[[105]](#cite_note-105) In the case of spacesuits, the [Template:Chem](/wiki/Template:Chem) partial pressure in the breathing gas is, in general, about 30 kPa (1.4 times normal), and the resulting [Template:Chem](/wiki/Template:Chem) partial pressure in the astronaut's arterial blood is only marginally more than normal sea-level [Template:Chem](/wiki/Template:Chem) partial pressure (for more information on this, see [space suit](/wiki/Space_suit) and [arterial blood gas](/wiki/Arterial_blood_gas)).

Oxygen toxicity to the lungs and [central nervous system](/wiki/Central_nervous_system) can also occur in deep [scuba diving](/wiki/Scuba_diving) and [surface supplied diving](/wiki/Surface_supplied_diving).[[11]](#cite_note-11)[[89]](#cite_note-89) Prolonged breathing of an air mixture with an [Template:Chem](/wiki/Template:Chem) partial pressure more than 60 kPa can eventually lead to permanent [pulmonary fibrosis](/wiki/Pulmonary_fibrosis).[[106]](#cite_note-106) Exposure to a [Template:Chem](/wiki/Template:Chem) partial pressures greater than 160 kPa (about 1.6 atm) may lead to convulsions (normally fatal for divers). Acute oxygen toxicity (causing seizures, its most feared effect for divers) can occur by breathing an air mixture with 21% [Template:Chem](/wiki/Template:Chem) at 66 m or more of depth; the same thing can occur by breathing 100% [Template:Chem](/wiki/Template:Chem) at only 6 m.[[106]](#cite_note-106)[[107]](#cite_note-107)[[108]](#cite_note-108)[[109]](#cite_note-109)

### Combustion and other hazards[[edit](/index.php?title=(none)&action=edit&section=29)]

[thumb|right|The interior of the](/wiki/File:Apollo_1_fire.jpg) [Apollo 1](/wiki/Apollo_1) Command Module. Pure [Template:Chem](/wiki/Template:Chem) at higher than normal pressure and a spark led to a fire and the loss of the [Apollo 1](/wiki/Apollo_1) crew.|alt=The inside of a small spaceship, charred and apparently destroyed. Highly concentrated sources of oxygen promote rapid combustion. [Fire](/wiki/Fire) and [explosion](/wiki/Explosion) hazards exist when concentrated oxidants and [fuels](/wiki/Fuel) are brought into close proximity; an ignition event, such as heat or a spark, is needed to trigger combustion.[[25]](#cite_note-25)[[110]](#cite_note-110) Oxygen is the oxidant, not the fuel, but nevertheless the source of most of the chemical energy released in combustion.[[25]](#cite_note-25)[[32]](#cite_note-32) Combustion hazards also apply to compounds of oxygen with a high oxidative potential, such as [peroxides](/wiki/Peroxide), [chlorates](/wiki/Chlorate), [nitrates](/wiki/Nitrate), [perchlorates](/wiki/Perchlorate), and [dichromates](/wiki/Dichromate) because they can donate oxygen to a fire.

Concentrated [Template:Chem](/wiki/Template:Chem) will allow combustion to proceed rapidly and energetically.[[110]](#cite_note-110) [Steel](/wiki/Steel) pipes and storage vessels used to store and transmit both gaseous and [liquid oxygen](/wiki/Liquid_oxygen) will act as a fuel; and therefore the design and manufacture of [Template:Chem](/wiki/Template:Chem) systems requires special training to ensure that ignition sources are minimized.[[110]](#cite_note-110) The fire that killed the [Apollo 1](/wiki/Apollo_1) crew in a launch pad test spread so rapidly because the capsule was pressurized with pure [Template:Chem](/wiki/Template:Chem) but at slightly more than atmospheric pressure, instead of the [Template:Frac](/wiki/Template:Frac) normal pressure that would be used in a mission.[Template:Refn](/wiki/Template:Refn)[[111]](#cite_note-111) Liquid oxygen spills, if allowed to soak into organic matter, such as [wood](/wiki/Wood), [petrochemicals](/wiki/Petrochemical), and [asphalt](/wiki/Asphalt) can cause these materials to [detonate](/wiki/Detonation) unpredictably on subsequent mechanical impact.[[110]](#cite_note-110) As with other [cryogenic](/wiki/Cryogenics) liquids, on contact with the human body it can cause [frostbites](/wiki/Frostbite) to the skin and the eyes. [Template:Clear](/wiki/Template:Clear)

## See also[[edit](/index.php?title=(none)&action=edit&section=30)]

[Template:Div col](/wiki/Template:Div_col)

* [Geological history of oxygen](/wiki/Geological_history_of_oxygen)
* [Hypoxia (environmental)](/wiki/Hypoxia_(environmental)) for [Template:Chem](/wiki/Template:Chem) depletion in aquatic ecology
* [Ocean deoxygenation](/wiki/Ocean_deoxygenation)
* [Hypoxia (medical)](/wiki/Hypoxia_(medical)), a lack of oxygen
* [Limiting oxygen concentration](/wiki/Limiting_oxygen_concentration)
* [Oxygen compounds](/wiki/Category:Oxygen_compounds)
* [Oxygen plant](/wiki/Oxygen_plant)
* [Oxygen sensor](/wiki/Oxygen_sensor)

[Template:Div col end](/wiki/Template:Div_col_end) [Template:Subject bar](/wiki/Template:Subject_bar)

## Notes[[edit](/index.php?title=(none)&action=edit&section=31)]

[Template:Reflist](/wiki/Template:Reflist)

## Citations[[edit](/index.php?title=(none)&action=edit&section=32)]

[Template:Reflist](/wiki/Template:Reflist)

## References[[edit](/index.php?title=(none)&action=edit&section=33)]

* [Template:Cite book](/wiki/Template:Cite_book)
* [Template:Cite book](/wiki/Template:Cite_book)
* [Template:Cite book](/wiki/Template:Cite_book)

## External links[[edit](/index.php?title=(none)&action=edit&section=34)]

[Template:Spoken Wikipedia](/wiki/Template:Spoken_Wikipedia)

* [Oxygen](http://www.periodicvideos.com/videos/008.htm) at [*The Periodic Table of Videos*](/wiki/The_Periodic_Table_of_Videos) (University of Nottingham)
* [Oxidizing Agents > Oxygen](http://www.organic-chemistry.org/chemicals/oxidations/oxygen.shtm)
* [Oxygen (O2) Properties, Uses, Applications](http://www.uigi.com/oxygen.html)
* [Roald Hoffmann article on "The Story of O"](http://www.americanscientist.org/issues/pub/the-story-of-o)
* [WebElements.com – Oxygen](http://www.webelements.com/webelements/elements/text/O/index.html)
* [Chemistry in its element podcast](http://www.rsc.org/chemistryworld/podcast/element.asp) (MP3) from the [Royal Society of Chemistry's](/wiki/Royal_Society_of_Chemistry) [Chemistry World](/wiki/Chemistry_World): [Oxygen](http://www.rsc.org/images/CIIE_oxygen_48k_tcm18-117681.mp3)
* [Template:In Our Time](/wiki/Template:In_Our_Time)
* [Scripps Institute: Atmospheric Oxygen has been dropping for 20 years](http://scrippso2.ucsd.edu/)

[Template:Diatomicelements](/wiki/Template:Diatomicelements) [Template:E number infobox 930-949](/wiki/Template:E_number_infobox_930-949) [Template:Compact periodic table](/wiki/Template:Compact_periodic_table) [Template:Molecules detected in outer space](/wiki/Template:Molecules_detected_in_outer_space) [Template:Featured article](/wiki/Template:Featured_article)

[Template:Authority control](/wiki/Template:Authority_control)

[Category:Biology and pharmacology of chemical elements](/wiki/Category:Biology_and_pharmacology_of_chemical_elements) [Category:Breathing gases](/wiki/Category:Breathing_gases) [Category:Chalcogens](/wiki/Category:Chalcogens) [Category:Chemical elements](/wiki/Category:Chemical_elements) [Category:Chemical substances for emergency medicine](/wiki/Category:Chemical_substances_for_emergency_medicine) [Category:Diatomic nonmetals](/wiki/Category:Diatomic_nonmetals) [Category:Oxidizing agents](/wiki/Category:Oxidizing_agents) [Category:Oxygen](/wiki/Category:Oxygen)