Carbon dioxide (chemical formula $\text{CO}_2$) is a naturally occurring chemical compound composed of two oxygen atoms covalently bonded to a single carbon atom. It is a gas at standard temperature and pressure and exists in Earth's atmosphere in this state, as a trace gas at a concentration of 0.039% by volume.

As part of the carbon cycle known as photosynthesis, plants, algae, and cyanobacteria absorb carbon dioxide, light, and water to produce carbohydrate energy for themselves and oxygen as a waste product. But in darkness photosynthesis cannot occur, and during the resultant respiration small amounts of carbon dioxide are produced. Carbon dioxide is also produced by combustion of coal or hydrocarbons, the fermentation of liquids and the breathing of humans and animals. In addition it is emitted from volcanoes, hot springs, geysers and other places where the earth’s crust is thin; and is freed from carbonate rocks by dissolution. CO$_2$ is also found in lakes at depth under the sea, and commingled with oil and gas deposits.

The environmental effects of carbon dioxide are of significant interest. In the earth’s atmosphere, it acts as a greenhouse gas which is believed to play a major role in global warming and anthropogenic climate change. Also a major source of ocean acidification is CO$_2$ which dissolves in water forming carbonic acid, which is a weak acid, because CO$_2$ molecule ionization in water is incomplete.

$$\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{H}_2\text{CO}_3$$

### Chemical and physical properties

#### Structure and bonding

The carbon dioxide molecule is linear and centrosymmetric. The two C-O bonds are equivalent and are short (116.3 pm), consistent with double bonding. Since it is centrosymmetric, the molecule has no electrical dipole. Consistent with this fact, only two vibrational bands are observed in the IR spectrum – an antisymmetric stretching mode at 2349 cm$^{-1}$ and a bending mode near 666 cm$^{-1}$. There is also a symmetric stretching mode at 1388 cm$^{-1}$ which is only observed in the Raman spectrum.

See also: Molecular orbital diagram#Carbon Dioxide MO Diagram

#### In aqueous solution

Carbon dioxide is soluble in water, in which it reversibly converts to H$_2$CO$_3$ (carbonic acid).

The hydration equilibrium constant $K_h$ (at 25 °C) of carbonic acid is $[\text{H}_2\text{CO}_3]/[\text{CO}_2] = 1.70 \times 10^{-3}$: Hence, the majority of the carbon dioxide is not converted into carbonic acid, but remains as CO$_2$ molecules not affecting the pH. It is an amphoteric substance that can act as an acid or as a base, depending on pH of the solution.

The relative concentrations of CO$_2$, H$_2$CO$_3$, and the deprotonated forms HCO$^-$ and CO$_2$–
3(carbonate) depend on the pH. In neutral or slightly alkaline water (pH > 6.5), the bicarbonate form predominates (>50%) becoming the most prevalent (>95%) at the pH of seawater. In very alkaline water (pH > 10.4), the predominant (>50%) form is carbonate. The oceans, being mildly alkaline with typical pH = 8.2 – 8.5, contain about 120 mg of bicarbonate per liter.

Being diprotic, carbonic acid has two acid dissociation constants, the first one for the dissociation into the bicarbonate (also called hydrogen carbonate) ion (HCO$_3^-$):

\[ \text{H}_2\text{CO}_3 \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \]
\[ K_{a1} = 2.5 \times 10^{-4}; \quad pK_{a1} = 3.6 \text{ at } 25^\circ\text{C} \text{.}^5 \]

At high pH, the bicarbonate ion dissociates significantly into the carbonate ion (CO$_3^{2-}$):

\[ \text{HCO}_3^- \rightleftharpoons \text{CO}_3^{2-} + \text{H}^+ \]
\[ K_{a2} = 4.69 \times 10^{-11}; \quad pK_{a2} = 10.329 \]

In organisms carbonic acid production is catalysed by the enzyme, carbonic anhydrase.

**Chemical reactions of CO$_2$**

Overall, CO$_2$ is a weak electrophile. Its reaction with basic water illustrates this property, in which case hydroxide is the nucleophile. Other nucleophiles react as well. For example, carbanions as provided by Grignard reagents and organolithium compounds react with CO$_2$ to give carboxylates:

\[ \text{MR} + \text{CO}_2 \rightarrow \text{RCO}_2\text{M} \quad (\text{where } \text{M} = \text{Li or MgBr and } \text{R} = \text{alkyl or aryl}) \]

In metal carbon dioxide complexes, CO$_2$ serves as a ligand, which can facilitate the conversion of CO$_2$ to other chemicals.\(^6\)

The reduction of CO$_2$ to CO is ordinarily a difficult and slow reaction:

\[ \text{CO}_2 + 2 \text{e}^- + 2\text{H}^+ \rightarrow \text{CO} + \text{H}_2\text{O} \]

The redox potential for this reaction near pH 7 is about −0.53 V vs NHE. The nickel-containing enzyme carbon monoxide dehydrogenase catalyses this process.\(^7\)

**Physical properties**
Carbon dioxide is colorless. At low concentrations, the gas is odorless. At higher concentrations it has a sharp, acidic odor.

At standard temperature and pressure, the density of carbon dioxide is around 1.98 kg/m³, about 1.5 times that of air.

Carbon dioxide has no liquid state at pressures below 5.1 standard atmospheres (520 kPa). At 1 atmosphere (near mean sea level pressure), the gas deposits directly to a solid at temperatures below −78.5 °C (−109.3 °F; 194.7 K) and the solid sublimes directly to a gas above −78.5 °C. In its solid state, carbon dioxide is commonly called dry ice.

Liquid carbon dioxide forms only at pressures above 5.1 atm; the triple point of carbon dioxide is about 518 kPa at −56.6 °C (see phase diagram, above). The critical point is 7.38 MPa at 31.1 °C.[8] Another form of solid carbon dioxide observed at high pressure is an amorphous glass-like solid.[9] This form of glass, called carbonia, is produced by supercooling heated CO₂ at extreme pressure (40–48 GPa or about 400,000 atmospheres) in a diamond anvil. This discovery confirmed the theory that carbon dioxide could exist in a glass state similar to other members of its elemental family, like silicon (silica glass) and germanium dioxide. Unlike silica and
germania glasses, however, carbonia glass is not stable at normal pressures and reverts to gas when pressure is released.

See also: Supercritical carbon dioxide and dry ice

**History**

![Crystal structure of dry ice](Image)

Carbon dioxide was one of the first gases to be described as a substance distinct from air. In the seventeenth century, the Flemish chemist Jan Baptist van Helmont observed that when he burned charcoal in a closed vessel, the mass of the resulting ash was much less than that of the original charcoal. His interpretation was that the rest of the charcoal had been transmuted into an invisible substance he termed a "gas" or "wild spirit" (spiritus sylvestre). [citation needed]

The properties of carbon dioxide were studied more thoroughly in the 1750s by the Scottish physician Joseph Black. He found that limestone (calcium carbonate) could be heated or treated with acids to yield a gas he called "fixed air." He observed that the fixed air was denser than air and supported neither flame nor animal life. Black also found that when bubbled through an aqueous solution of lime (calcium hydroxide), it would precipitate calcium carbonate. He used this phenomenon to illustrate that carbon dioxide is produced by animal respiration and microbial fermentation. In 1772, English chemist Joseph Priestley published a paper entitled Impregnating Water with Fixed Air in which he described a process of dripping sulfuric acid (or oil of vitriol as Priestley knew it) on chalk in order to produce carbon dioxide, and forcing the gas to dissolve by agitating a bowl of water in contact with the gas. [10] This was the invention of Soda water.

Carbon dioxide was first liquefied (at elevated pressures) in 1823 by Humphry Davy and Michael Faraday. [11] The earliest description of solid carbon dioxide was given by Charles Thilorier, who in 1834 opened a pressurized container of liquid carbon dioxide, only to find that the cooling produced by the rapid evaporation of the liquid yielded a "snow" of solid CO₂. [12]

**Isolation and production**
Carbon dioxide is mainly produced as an unrecovered side product of four technologies: combustion of fossil fuels, production of hydrogen by steam reforming, ammonia synthesis, and fermentation. The combustion of all carbon-containing fuels, such as methane (natural gas), petroleum distillates (gasoline, diesel, kerosene, propane), but also of coal and wood, will yield carbon dioxide and, in most cases, water. As an example the chemical reaction between methane and oxygen is given below.

\[
\text{CH}_4 + 2 \text{O}_2 \rightarrow \text{CO}_2 + 2 \text{H}_2\text{O}
\]

The production of quicklime (CaO), a compound that enjoys widespread use, involves the heating (calcining) of limestone at about 850 °C:

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2
\]

Iron is reduced from its oxides with coke in a blast furnace, producing pig iron and carbon dioxide:[13]

\[
\text{Fe}_2\text{O}_3 + 3 \text{CO} \rightarrow 2 \text{Fe} + 3 \text{CO}_2
\]

Yeast metabolizes sugar to produce carbon dioxide and ethanol, also known as alcohol, in the production of wines, beers and other spirits, but also in the production of bioethanol:

\[
\text{C}_6\text{H}_{12}\text{O}_6 \rightarrow 2 \text{CO}_2 + 2 \text{C}_2\text{H}_5\text{OH}
\]

All aerobic organisms produce CO2 when they oxidize carbohydrates, fatty acids, and proteins in the mitochondria of cells. The large number of reactions involved are exceedingly complex and not described easily. Refer to (cellular respiration, anaerobic respiration and photosynthesis). The equation for the respiration of glucose and other monosachharides is:

\[
\text{C}_6\text{H}_{12}\text{O}_6 + 6 \text{O}_2 \rightarrow 6 \text{CO}_2 + 6 \text{H}_2\text{O}
\]

Photoautotrophs (i.e. plants, cyanobacteria) use another modus operandi: Plants absorb CO2 from the air, and, together with water, react it to form carbohydrates:

\[
n\text{CO}_2 + n\text{H}_2\text{O} \rightarrow (\text{CH}_2\text{O})_n + n\text{O}_2
\]

**Industrial production**

Industrial carbon dioxide can be produced by several methods, many of which are practiced at various scales.[14] In its dominant route, carbon dioxide is produced as a side product of the industrial production of ammonia and hydrogen, and also extraction from flue gases in power plants and etc. Although carbon dioxide is not often recovered, carbon dioxide results from combustion of fossil fuels and wood as well fermentation of sugar in the brewing of beer, whisky and other alcoholic beverages. It also results from thermal decomposition of limestone, CaCO3, in the manufacture of lime (Calcium oxide, CaO). Directly from natural carbon dioxide springs, where it is produced by the action of acidified water on limestone or dolomite.
Uses

Carbon dioxide is used by the food industry, the oil industry, and the chemical industry.[14]

Precursor to chemicals

In the chemical industry, carbon dioxide is mainly consumed as an ingredient in the production of urea and methanol. Metal carbonates and bicarbonates, as well as some carboxylic acids derivatives (e.g., sodium salicylate) are prepared from CO₂.

Foods

Carbon dioxide is a food additive used as a propellant and acidity regulator in the food industry. It is approved for usage in the EU[16] (listed as E number E290), USA[17] and Australia and New Zealand[18] (listed by its INS number 290).

A candy called Pop Rocks is pressurized with carbon dioxide gas at about 40 bar (580 psi). When placed in the mouth, it dissolves (just like other hard candy) and releases the gas bubbles with an audible pop.

Leavening agents cause dough to rise by producing carbon dioxide. Baker's yeast produces carbon dioxide by fermentation of sugars within the dough, while chemical leaveners such as baking powder and baking soda release carbon dioxide when heated or if exposed to acids.

Beverages

Carbon dioxide is used to produce carbonated soft drinks and soda water. Traditionally, the carbonation in beer and sparkling wine came about through natural fermentation, but many manufacturers carbonate these drinks with carbon dioxide recovered from the fermentation process. In the case of bottled and kegged beer, recycled carbon dioxide carbonation is the most common method used. With the exception of British Real Ale, draught beer is usually transferred from kegs in a cold room or cellar to dispensing taps on the bar using pressurized carbon dioxide, sometimes mixed with nitrogen.
Inert gas

It is one of the most commonly used compressed gases for pneumatic (pressurized gas) systems in portable pressure tools. Carbon dioxide also finds use as an atmosphere for welding, although in the welding arc, it reacts to oxidize most metals. Use in the automotive industry is common despite significant evidence that welds made in carbon dioxide are more brittle than those made in more inert atmospheres, and that such weld joints deteriorate over time because of the formation of carbonic acid. It is used as a welding gas primarily because it is much less expensive than more inert gases such as argon or helium. When used for MIG welding, CO₂ use is sometimes referred to as MAG welding, for Metal Active Gas, as CO₂ can react at these high temperatures. It tends to produce a hotter puddle than truly inert atmospheres, improving the flow characteristics. Although, this may be due to atmospheric reactions occurring at the puddle site. This is usually the opposite of the desired effect when welding, as it tends to embrittle the site, but may not be a problem for general mild steel welding, where ultimate ductility is not a major concern.

It is used in many consumer products that require pressurized gas because it is inexpensive and nonflammable, and because it undergoes a phase transition from gas to liquid at room temperature at an attainable pressure of approximately 60 bar (870 psi, 59 atm), allowing far more carbon dioxide to fit in a given container than otherwise would. Life jackets often contain canisters of pressurized carbon dioxide for quick inflation. Aluminum capsules of CO₂ are also sold as supplies of compressed gas for airguns, paintball markers, inflating bicycle tires, and for making carbonated water. Rapid vaporization of liquid carbon dioxide is used for blasting in coal mines. High concentrations of carbon dioxide can also be used to kill pests. Liquid carbon dioxide is used in supercritical drying of some food products and technological materials, in the preparation of specimens for scanning electron microscopy and in the decaffeination of coffee beans.

Fire extinguisher

Carbon dioxide extinguishes flames, and some fire extinguishers, especially those designed for electrical fires, contain liquid carbon dioxide under pressure. Carbon dioxide extinguishers work well on small flammable liquid and electrical fires, but not on ordinary combustible fires, because although it excludes oxygen, it does not cool the burning substances significantly and when the carbon dioxide disperses they are free to catch fire upon exposure to atmospheric oxygen. Carbon dioxide has also been widely used as an extinguishing agent in fixed fire protection systems for local application of specific hazards and total flooding of a protected space. International Maritime Organization standards also recognize carbon dioxide systems for fire protection of ship holds and engine rooms. Carbon dioxide based fire protection systems have been linked to several deaths, because it can cause suffocation in sufficiently high concentrations. A review of CO₂ systems identified 51 incidents between 1975 and the date of the report, causing 72 deaths and 145 injuries.

Super critical CO₂ as solvent
Liquid carbon dioxide is a good solvent for many lipophilic organic compounds and is used to remove caffeine from coffee. Carbon dioxide has attracted attention in the pharmaceutical and other chemical processing industries as a less toxic alternative to more traditional solvents such as organochlorides. It is used by some dry cleaners for this reason (see green chemistry).

**Agricultural and biological applications**

Plants require carbon dioxide to conduct photosynthesis. Greenhouses may (if of large size, must) enrich their atmospheres with additional CO₂ to sustain and increase plant growth. A photosynthesis-related drop (by a factor less than two) in carbon dioxide concentration in a greenhouse compartment would kill green plants, or, at least, completely stop their growth. At very high concentrations (100 times atmospheric concentration, or greater), carbon dioxide can be toxic to animal life, so raising the concentration to 10,000 ppm (1%) or higher for several hours will eliminate pests such as whiteflies and spider mites in a greenhouse. Carbon dioxide is used in greenhouses as the main carbon source for Spirulina algae.

In medicine, up to 5% carbon dioxide (130 times atmospheric concentration) is added to oxygen for stimulation of breathing after apnea and to stabilize the O₂/CO₂ balance in blood.

It has been proposed that carbon dioxide from power generation be bubbled into ponds to grow algae that could then be converted into biodiesel fuel.

**Oil recovery**

Carbon dioxide is used in enhanced oil recovery (EOR) where it is injected into or adjacent to producing oil wells, usually under supercritical conditions. This kind of production may increase original oil recovery by 7 per cent to 23 per cent further from primary extraction. It acts as both a pressurizing agent and, when dissolved into the underground crude oil, significantly reduces its viscosity, enabling the oil to flow more rapidly through the earth to the removal well. In mature oil fields, extensive pipe networks are used to carry the carbon dioxide to the injection points.

**Refrigerant**

Liquid and solid carbon dioxide are important refrigerants, especially in the food industry, where they are employed during the transportation and storage of ice cream and other frozen foods. Solid carbon dioxide is always below −78.5 °C at regular atmospheric pressure, regardless of the air temperature.

Liquid carbon dioxide (industry nomenclature R744 or R-744) was used as a refrigerant prior to the discovery of R-12 and may enjoy a renaissance due to the fact that r134a contributes to climate change. Its physical properties are highly favorable for cooling, refrigeration, and heating purposes, having a high volumetric cooling capacity. Due to its operation at pressures of up to 130 bar (1880 psi), CO₂ systems require highly resistant components that have already been
developed for mass production in many sectors. In automobile air conditioning, in more than 90% of all driving conditions for latitudes higher than 50°, R744 operates more efficiently than systems using R-134a. Its environmental advantages (GWP of 1, non-ozone depleting, non-toxic, non-flammable) could make it the future working fluid to replace current HFCs in cars, supermarkets, hot water heat pumps, among others. Coca-Cola has fielded CO2-based beverage coolers and the U.S. Army is interested in CO2 refrigeration and heating technology.\[27\][28]

The global automobile industry is expected to decide on the next-generation refrigerant in car air conditioning. CO2 is one discussed option.(see Sustainable automotive air conditioning)

**Coal bed methane recovery**

In enhanced coal bed methane recovery, carbon dioxide is pumped into the coal seam to displace methane.\[29\]

**Niche uses**

![A carbon dioxide laser.](image)

Carbon dioxide is so inexpensive and so innocuous, that it finds many small uses that represent what might be called niche uses. For example it is used in the carbon dioxide laser, which is one of the earliest type of lasers.

Carbon dioxide can be used as a means of controlling the pH of swimming pools, by continuously adding gas to the water, thus keeping the pH level from rising. Among the advantages of this is the avoidance of handling (more hazardous) acids. Similarly, it is also used in the maintaining reef aquaria, where it is commonly used in calcium reactors to temporarily lower the pH of water being passed over calcium carbonate in order to allow the calcium carbonate to dissolve into the water more freely where it is used by some corals to build their skeleton.

Dry ice, is the solid form of carbon dioxide. It is used primarily as a cooling agent. Its advantages include lower temperature than that of water ice and not leaving any residue (other than incidental frost from moisture in the atmosphere). It is useful for preserving frozen foods, ice cream, etc., where mechanical cooling is unavailable.
Dry ice sublimates at −78.5 °C (−109.3 °F) at atmospheric pressure. This extreme cold makes the solid dangerous to handle without protection due to burns caused by freezing (frostbite). While generally not very toxic, the outgassing from it can cause hypercapnia due to buildup in confined locations.

**Properties**

For supplementary chemical data, see [Carbon dioxide (data page)](https://en.wikipedia.org/wiki/Carbon_dioxide#Properties). Dry ice is the solid form of carbon dioxide (chemical formula CO₂), comprising two oxygen atoms bonded to a single carbon atom. It is colorless, with a sour zesty odor, non-flammable, and slightly acidic.[1]

![](image)

**Phase diagram** of carbon dioxide

At temperatures below −56.4 °C (−69.5 °F) and pressures below 5.13 atm (the triple point), CO₂ changes from a solid to a gas with no intervening liquid form, through a process called sublimation. The opposite process is called deposition, where CO₂ changes from the gas to solid phase (dry ice). At atmospheric pressure, sublimation/deposition occurs at −78.5 °C (−109.3 °F).

The density of dry ice varies, but usually ranges between about 1.4 and 1.6 g/cm³ (87–100 lb/ft³).[2] The low temperature and direct sublimation to a gas makes dry ice an effective coolant, since it is colder than water ice and leaves no residue as it changes state.[3] Its enthalpy of sublimation is 571 kJ/kg (25.2 kJ/mol).

Dry ice is non-polar, with a dipole moment of zero, so attractive intermolecular van der Waals forces operate.[4] The composition results in low thermal and electrical conductivity.[5]

**Applications**

The most common use of dry ice is to preserve food,[1] using non-cyclic refrigeration.
It is frequently used to package items that need to remain cold or frozen, such as ice cream or biological samples, without the use of mechanical cooling.

Dry ice can be used to flash freeze food,[16] laboratory biological samples,[17] carbonate beverages,[16] and make ice cream.[18]

Dry ice can be used to arrest and prevent insect activity in closed containers of grains and grain products, as it displaces oxygen, but does not alter the taste or quality of such foods. For the same reason, it can prevent or retard food oils and fats from becoming rancid.

When dry ice is placed in water sublimation is accelerated, and low-sinking, dense clouds of smoke-like fog are created. This is used in fog machines, at theaters, discothèques, haunted house attractions, and nightclubs for dramatic effects. Unlike most artificial fog machines, in which fog rises like smoke, fog from dry ice hovers above the ground.[15] Dry ice is useful in theater productions that require dense fog effects.[19]

Plumbers use equipment that forces pressurised liquid CO₂ into a jacket around a pipe; the dry ice formed causes the water to freeze, forming an ice plug, allowing them to perform repairs without turning off the water mains. This technique can be used on pipes up to 4 inches (100 mm) in diameter.[22]

**Industrial**

Dry ice blasting used for cleaning a rubber mold

Dry ice can be used for loosening asphalt floor tiles or car sound deadening making it easy to pry off,[24] as well as freezing water in valveless pipes to enable repair.[25]

One of the largest mechanical uses of dry ice is blast cleaning. Dry ice pellets are shot out of a nozzle with compressed air, combining the power of the speed of the pellets with the action of the sublimation. This can remove residues from industrial equipment. Examples of materials being removed include ink, glue, oil, paint, mold and rubber. Dry ice blasting can replace sandblasting, steam blasting, water blasting or solvent blasting. The primary environmental residue of dry ice blasting is the sublimed CO₂, thus making it a useful technique where residues
from other blasting techniques are undesirable. Recently, blast cleaning has been introduced into the industry of removing smoke damage from structures after fires.

Dry ice is also useful for the de-gassing of flammable vapours from storage tanks — the sublimation of dry ice pellets inside an emptied and vented tank causes an outrush of CO₂ that carries with it the flammable vapours.

The removal and fitting of cylinder liners in large marine engines requires the use of dry ice to chill and thus shrink the liner so that it freely slides within the block. When warmed in place the resulting interference fit prevents motion. Similar procedures may be used in fabricating mechanical assemblies with a high resultant strength, replacing the need for pins, keys or welds.