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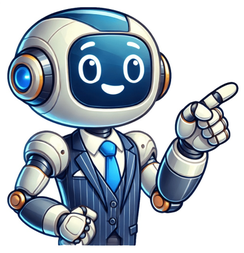

Chemical compound with formula CO2 "CO2" and "CO_2" redirect here. For other uses, see CO2 (disambiguation). Carbon dioxide Structural formula of carbon dioxide with bond length Ball-and-stick model of carbon dioxide Space-filling model of carbon dioxide Names IUPAC name Carbon dioxide Other names Carbonic acid gasCarbonic anhydrideCarbonic dioxideCarbonic oxideCarbon(IV) oxideMethanedioneR-744 (refrigerant)R744 (refrigerant alternative spelling)Dry ice (solid phase) Identifiers CAS Number 124-38-9 Y 3D model (JSmol) Interactive imageInteractive image Beilstein Reference 1900390 ChEBI CHEBI:16526 Y ChEMBL ChEMBL1231871 N ChemSpider 274 Y ECHA InfoCard 100.004.271 EC Number 204-696-9 E number E290 (preservatives) Gmelin Reference 989 KEGG D00004 Y MeSH Carbon+dioxide PubChem CID 280 RTECS number FF6400000 UNII 142M471B3J Y UN number 1013 (gas), 1845 (solid) CompTox Dashboard (EPA) DTXSID4027028 InChI InChI=1S/CO2/c2-1-3 YKey: CURLTUGMZLYLDI-UHFFFAOYSA-N YInChI=1/CO2/c2-1-3Key: CURLTUGMZLYLDI-UHFFFAOYAO SMILES O=C=OC(=O)=O Properties Chemical formula CO2 Molar mass 44.009 g·mol−1 Appearance Colorless gas Odor Low concentrations: noneHigh concentrations: sharp; acidic[1] Density 1562 kg/m3 (solid at 1 atm (100 kPa) and −78.5 °C (−109.3 °F)) 1101 kg/m3 (liquid at saturation −37 °C (−35 °F)) 1.977 kg/m3 (gas at 1 atm (100 kPa) and 0 °C (32 °F)) Critical point (T, P) 304.128(15) K[2] (30.978(15) °C), 7.3773(30) MPa[2] (72.808(30) atm) Sublimationconditions 194.6855(30) K (−78.4645(30) °C) at 1 atm (0.101325 MPa) Solubility in water 1.45 g/L at 25 °C (77 °F), 100 kPa (0.99 atm) Vapor pressure 5.7292(30) MPa, 56.54(30) atm (20 °C (293.15 K)) Acidity (pKa) Carbonic acid:pKa1 = 3.6pKa1(apparent) = 6.35pKa2 = 10.33 Magnetic susceptibility (χ) −20.5·10−6 cm3/mol Thermal conductivity 0.01662 W·m−1·K−1 (300 K (27 °C; 80 °F))[3] Refractive index (nD) 1.00045 Viscosity 14.90 μPa·s at 25 °C (298 K)[4] 70 μPa·s at −78.5 °C (194.7 K) Dipole moment 0 D Structure Crystal structure Trigonal Point group D∞h Molecular shape Linear Thermochemistry Heat capacity (C) 37.135 J/(K·mol) Std molarentropy (S298) 214 J·mol−1·K−1 Std enthalpy offormation (ΔfH298) −393.5 kJ·mol−1 Pharmacology ATC code V03AN02 (WHO) Hazards NFPA 704 (fire diamond) [7][8] 2 0 0SA Lethal dose or concentration (LD, LC): LCLo (lowest published) 90,000 ppm (162,000 mg/m3) (human, 5 min)[6] NIOSH (US health exposure limits): PEL (Permissible) TWA 5000 ppm (9000 mg/m3)[5] REL (Recommended) TWA 5000 ppm (9000 mg/m3), ST 30,000 ppm (54,000 mg/m3)[5] IDLH (Immediate danger) 40,000 ppm (72,000 mg/m3)[5] Safety data sheet (SDS) Sigma-Aldrich Related compounds Other anions Carbon disulfideCarbon diselenideCarbon ditelluride Other cations Silicon dioxideGermanium dioxideTin dioxideLead dioxideTitanium dioxideZirconium dioxideHafnium dioxideCerium dioxideThorium dioxide Related carbon oxides See Oxocarbon Related compounds Carbonic acidCarbonyl sulfideCarbonyl selenide Supplementary data page Carbon dioxide (data page) Except where otherwise noted, data are given for materials in their standard state (at 25 °C [77 °F], 100 kPa). N verify (what is YN ?) Infobox references Chemical compound Carbon dioxide is a chemical compound with the chemical formula CO2. It is made up of molecules that each have one carbon atom covalently double bonded to two oxygen atoms. It is found in a gas state at room temperature and at normally-encountered concentrations it is odorless. As the source of carbon in the carbon cycle, atmospheric CO2 is the primary carbon source for life on Earth. In the air, carbon dioxide is transparent to visible light but absorbs infrared radiation, acting as a greenhouse gas. Carbon dioxide is soluble in water and is found in groundwater, lakes, ice caps, and seawater. It is a trace gas in Earth's atmosphere at 421 parts per million (ppm),[a] or about 0.042% (as of May 2022) having risen from pre-industrial levels of 280 ppm or about 0.028%.[10][11] Burning fossil fuels is the main cause of these increased CO2 concentrations, which are the primary cause of climate change.[12] Its concentration in Earth's pre-industrial atmosphere since late in the Precambrian was regulated by organisms and geological features. Plants, algae and cyanobacteria use energy from sunlight to synthesize carbohydrates from carbon dioxide and water in a process called photosynthesis, which produces oxygen as a waste product.[13] In turn, oxygen is consumed and CO2 is released as waste by all aerobic organisms when they metabolize organic compounds to produce energy by respiration.[14] CO2 is released from organic materials when they decay or combust, such as in forest fires. When carbon dioxide dissolves in water, it forms carbonate and mainly bicarbonate (HCO−3), which causes ocean acidification as atmospheric CO2 levels increase.[15] Carbon dioxide is 53% more dense than dry air, but is long lived and thoroughly mixes in the atmosphere. About half of excess CO2 emissions to the atmosphere are absorbed by land and ocean carbon sinks.[16] These sinks can become saturated and are volatile, as decay and wildfires result in the CO2 being released back into the atmosphere.[17] CO2, or the carbon it holds, is eventually sequestered (stored for the long term) in rocks and organic deposits like coal, petroleum and natural gas. Nearly all CO2 produced by humans goes into the atmosphere. Less than 1% of CO2 produced annually is put to commercial use, mostly in the fertilizer industry and in the oil and gas industry for enhanced oil recovery. Other commercial applications include food and beverage production, metal fabrication, cooling, fire suppression and stimulating plant growth in greenhouses.[18]:3 See also: Molecular orbital diagram § Carbon dioxide The symmetry of a carbon dioxide molecule is linear and centrosymmetric at its equilibrium geometry. The length of the carbon–oxygen bond in carbon dioxide is 116.3 pm, noticeably shorter than the roughly 140 pm length of a typical single C–O bond, and shorter than most other C–O multiply bonded functional groups such as carbonyls.[19] Since it is centrosymmetric, the molecule has no electric dipole moment. Stretching and bending oscillations of the CO2 molecule. Upper left: symmetric stretching. Upper right: antisymmetric stretching. Lower line: degenerate pair of bending modes. As a linear triatomic molecule, CO2 has four vibrational modes as shown in the diagram. In the symmetric and the antisymmetric stretching modes, the atoms move along the axis of the molecule. There are two bending modes, which are degenerate, meaning that they have the same frequency and same energy, because of the symmetry of the molecule. When a molecule touches a surface or touches another molecule, the two bending modes can differ in frequency because the interaction is different for the two modes. Some of the vibrational modes are observed in the infrared (IR) spectrum: the antisymmetric stretching mode at wavenumber 2349 cm−1 (wavelength 4.25 μm) and the degenerate pair of bending modes at 667 cm−1 (wavelength 15.0 μm). The symmetric stretching mode does not create an electric dipole so is not observed in IR spectroscopy, but it is detected in Raman spectroscopy at 1388 cm−1 (wavelength 7.20 μm), with a Fermi resonance doublet at 1285 cm−1.[20] In the gas phase, carbon dioxide molecules undergo significant vibrational motions and do not keep a fixed structure. However, in a Coulomb explosion imaging experiment, an instantaneous image of the molecular structure can be deduced. Such an experiment[21] has been performed for carbon dioxide. The result of this experiment, and the conclusion of theoretical calculations[22] based on an ab initio potential energy surface of the molecule, is that none of the molecules in the gas phase are ever exactly linear. This counter-intuitive result is trivially due to the fact that the nuclear motion volume element vanishes for linear geometries.[22] This is so for all molecules except diatomic molecules. See also: Carbonic acid Carbon dioxide is soluble in water, in which it reversibly forms H2CO3 (carbonic acid), which is a weak acid, because its ionization in water is incomplete. CO2 + H2O ⇌ H2CO3 The hydration equilibrium constant of carbonic acid is, at 25 °C: K h = [H 2 CO 3] [CO 2 (aq)] = 1.70 × 10 − 3 {\displaystyle K_{\mathrm {h} }={\frac {{\ce {[H2CO3]}}}{{\ce {[CO2_{(aq)}]}}}}=1.70\times 10^{-3}} Hence, the majority of the carbon dioxide is not converted into carbonic acid, but remains as CO2 molecules, not affecting the pH. The relative concentrations of CO2, H2CO3, and the deprotonated forms HCO−3 (bicarbonate) and CO2−3(carbonate) depend on the pH. As shown in a Bjerrum plot, 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): H2CO3 ⇌ HCO−3 + H+ Ka1 = 2.5 × 10−4 mol/L; pKa1 = 3.6 at 25 °C.[19] This is the true first acid dissociation constant, defined as K a 1 = [HCO 3 −] [H +] [H 2 CO 3] {\displaystyle K_{\mathrm {a1} }={\frac {{\ce {[HCO3-][H+]}}}{{\ce {[H2CO3]}}}}} where the denominator includes only covalently bound H2CO3 and does not include hydrated CO2(aq). The much smaller and often-quoted value near 4.16 × 10−7 (or pKa1 = 6.38) is an apparent value calculated on the (incorrect) assumption that all dissolved CO2 is present as carbonic acid, so that K a 1 (a p p a r e n t) = [HCO 3 −] [H +] [H 2 CO 3] + [CO 2 (aq)] {\displaystyle K_{\mathrm {a1} }={\rm {(apparent)}}={\frac {{\ce {[HCO3-][H+]}}}{{\ce {[H2CO3] + [CO2_{(aq)}]}}}}} Since most of the dissolved CO2 remains as CO2 molecules, Ka1(apparent) has a much larger denominator and a much smaller value than the true Ka1.[23] The bicarbonate ion is an amphoteric species that can act as an acid or as a base, depending on pH of the solution. At high pH, it dissociates significantly into the carbonate ion (CO2−3): HCO−3 ⇌ CO2−3 + H+ Ka2 = 4.69 × 10−11 mol/L; pKa2 = 10.329 In organisms, carbonic acid production is catalysed by the enzyme known as carbonic anhydrase. In addition to altering its acidity, the presence of carbon dioxide in water also affects its electrical properties. Electrical conductivity of carbondioxide saturated desalinated water when heated from 20 to 98 °C. The shadowed regions indicate the error bars associated with the measurements. A comparison with the temperature dependence of vented desalinated water can be found here . When carbon dioxide dissolves in desalinated water, the electrical conductivity increases significantly from below 1 μS/cm to nearly 30 μS/cm. When heated, the water begins to gradually lose the conductivity induced by the presence of C O 2 {\displaystyle \mathrm {CO_{2}} } , especially noticeable as temperatures exceed 30 °C. The temperature dependence of the electrical conductivity of fully deionized water without CO2 saturation is comparably low in relation to these data. CO2 is a potent electrophile having an electrophilic reactivity that is comparable to benzaldehyde or strongly electrophilic α,β-unsaturated carbonyl compounds. However, unlike electrophiles of similar reactivity, the reactions of nucleophiles with CO2 are thermodynamically less favored and are often found to be highly reversible.[24] The reversible reaction of carbon dioxide with amines to make carbamates is used in CO2 scrubbers and has been suggested as a possible starting point for carbon capture and storage by amine gas treating. Only very strong nucleophiles, like the carbanions provided by Grignard reagents and organolithium compounds react with CO2 to give carboxylates: MR + CO2 → RCO2M where M = Li or MgBr and R = alkyl or aryl. In metal carbon dioxide complexes, CO2 serves as a ligand, which can facilitate the conversion of CO2 to other chemicals.[25] The reduction of CO2 to CO is ordinarily a difficult and slow reaction: CO2 + 2 e− + 2 H+ → CO + H2O The redox potential for this reaction near pH 7 is about −0.53 V versus the standard hydrogen electrode. The nickel-containing enzyme carbon monoxide dehydrogenase catalyses this process.[26] Photoautotrophs (i.e. plants and cyanobacteria) use the energy contained in sunlight to photosynthesize simple sugars from CO2 absorbed from the air and water: n CO2 + n H2O → (CH2O)n + n O2 Further information: Carbon dioxide data Pellets of "dry ice", a common form of solid carbon dioxide Carbon dioxide is colorless. At low concentrations, the gas is odorless; however, at sufficiently high concentrations, it has a sharp, acidic odor.[1] At standard temperature and pressure, the density of carbon dioxide is around 1.98 kg/m3, about 1.53 times that of air.[27] Carbon dioxide has no liquid state at pressures below 0.51795(10) MPa[2] (5.11177(99) atm). At a pressure of 1 atm (0.101325 MPa), the gas deposits directly to a solid at temperatures below 194.6855(30) K[2] (−78.4645(30) °C) and the solid sublimes directly to a gas above this temperature. In its solid state, carbon dioxide is commonly called dry ice. Pressure–temperature phase diagram of carbon dioxide. Note that it is a log-lin chart. Liquid carbon dioxide forms only at pressures above 0.51795(10) MPa[2] (5.11177(99) atm); the triple point of carbon dioxide is 216.592(3) K[2] (−56.558(3) °C) at 0.51795(10) MPa[2] (5.11177(99) atm) (see phase diagram). The critical point is 304.128(15) K[2] (30.978(15) °C) at 7.3773(30) MPa[2] (72.808(30) atm). Another form of solid carbon dioxide observed at high pressure is an amorphous glass-like solid.[28] This form of glass, called carbonia, is produced by supercooling heated CO2 at extreme pressures (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 dioxide (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. At temperatures and pressures above the critical point, carbon dioxide behaves as a supercritical fluid known as supercritical carbon dioxide. Table of thermal and physical properties of saturated liquid carbon dioxide:[29][30] Temperature(°C) Density(kg/m3) Specific heat(kJ/(kg·K)) Kinematic viscosity(m2/s) Thermal conductivity(W/(m·K)) Thermal diffusivity(m2/s) Prandtl Number −50 1156.34 1.84 1.19 × 10−7 0.0855 4.02 × 10−8 2.96 −40 1117.77 1.88 1.18 × 10−7 0.1011 4.81 × 10−8 2.46 −30 1076.76 1.97 1.17 × 10−7 0.1116 5.27 × 10−8 2.22 −20 1032.39 2.05 1.15 × 10−7 0.1151 5.45 × 10−8 2.12 −10 983.38 2.18 1.13 × 10−7 0.1099 5.13 × 10−8 2.2 0 926.99 2.47 1.08 × 10−7 0.1045 4.58 × 10−8 2.38 10 860.03 3.14 1.01 × 10−7 0.0971 3.61 × 10−8 2.8 20 772.57 5 9.10 × 10−8 0.0872 2.22 × 10−8 4.1 30 597.81 36.4 8.00 × 10−8 0.0703 0.279 × 10−8 28.7 Table of thermal and physical properties of carbon dioxide (CO2) at atmospheric pressure:[29][30] Temperature(K) Density(kg/m3) Specific heat(kJ/(kg·°C)) Dynamic viscosity(kg/(m·s)) Kinematic viscosity(m2/s) Thermal conductivity(W/(m·°C)) Thermal diffusivity(m2/s) Prandtl Number 220 2.4733 0.783 1.11 × 10−5 4.49 × 10−6 0.010805 5.92 × 10−6 0.818 250 2.1657 0.804 1.26 × 10−5 5.81 × 10−6 0.012884 7.40 × 10−6 0.793 300 1.7973 0.871 1.50 × 10−5 8.32 × 10−6 0.016572 1.06 × 10−5 0.77 350 1.5362 0.9 1.72 × 10−5 1.12 × 10−5 0.02047 1.48 × 10−5 0.755 400 1.3424 0.942 1.93 × 10−5 1.44 × 10−5 0.02461 1.95 × 10−5 0.738 450 1.1918 0.98 2.13 × 10−5 1.79 × 10−5 0.02897 2.48 × 10−5 0.721 500 1.0732 1.013 2.33 × 10−5 2.17 × 10−5 0.03352 3.08 × 10−5 0.702 550 0.9739 1.047 2.51 × 10−5 2.57 × 10−5 0.03821 3.75 × 10−5 0.685 600 0.8938 1.076 2.68 × 10−5 3.00 × 10−5 0.04311 4.48 × 10−5 0.668 650 0.8143 1.1 2.88 × 10−5 3.54 × 10−5 0.0445 4.97 × 10−5 0.712 700 0.7564 1.13 3.05 × 10−5 4.03 × 10−5 0.0481 5.63 × 10−5 0.717 750 0.7057 1.15 3.21 × 10−5 4.55 × 10−5 0.0517 6.37 × 10−5 0.714 800 0.6614 1.17 3.37 × 10−5 5.10 × 10−5 0.0551 7.12 × 10−5 0.716 Carbon dioxide is an end product of cellular respiration in organisms that obtain energy by breaking down sugars, fats and amino acids with oxygen as part of their metabolism. This includes all plants, algae and animals and aerobic fungi and bacteria. In vertebrates, the carbon dioxide travels in the blood from the body's tissues to the skin (e.g., amphibians) or the gills (e.g., fish), from where it dissolves in the water, or to the lungs from where it is exhaled. During active photosynthesis, plants can absorb more carbon dioxide from the atmosphere than they release in respiration. Overview of the Calvin cycle and carbon fixation Carbon fixation is a biochemical process by which atmospheric carbon dioxide is incorporated by plants, algae and cyanobacteria into energy-rich organic molecules such as glucose, thus creating their own food by photosynthesis. Photosynthesis uses carbon dioxide and water to produce sugars from which other organic compounds can be constructed, and oxygen is produced as a by-product. Ribulose-1,5-bisphosphate carboxylase oxygenase, commonly abbreviated to RuBisCO, is the enzyme involved in the first major step of carbon fixation, the production of two molecules of 3-phosphoglycerate from CO2 and ribulose bisphosphate, as shown in the diagram at left. RuBisCO is thought to be the single most abundant protein on Earth.[31] Phototrophs use the products of their photosynthesis as internal food sources and as raw material for the biosynthesis of more complex organic molecules, such as polysaccharides, nucleic acids, and proteins. These are used for their own growth, and also as the basis of the food chains and webs that feed other organisms, including animals such as ourselves. Some important phototrophs, the coccolithophores synthesise hard calcium carbonate scales.[32] A globally significant species of coccolithophore is Emiliania huxleyi whose calcite scales have formed the basis of many sedimentary rocks such as limestone, where what was previously atmospheric carbon can remain fixed for geological timescales.Overview of photosynthesis and respiration. Carbon dioxide (at right), together with water, form oxygen and organic compounds (at left) by photosynthesis (green), which can be respired (red) to water and CO2. Plants can grow as much as 50% faster in concentrations of 1,000 ppm CO2 when compared with ambient conditions, though this assumes no change in climate and no limitation on other nutrients.[33] Elevated CO2 levels cause increased growth reflected in the harvestable yield of crops, with wheat, rice and soybean all showing increases in yield of 12–14% under elevated CO2 in FACE experiments.[34][35] Increased atmospheric CO2 concentrations result in fewer stomata developing on plants[36] which leads to reduced water usage and increased water-use efficiency.[37] Studies using FACE have shown that CO2 enrichment leads to decreased concentrations of micronutrients in crop plants.[38] This may have knock-on effects on other parts of ecosystems as herbivores will need to eat more food to gain the same amount of protein.[39] The concentration of secondary metabolites such as phenylpropanoids and flavonoids can also be altered in plants exposed to high concentrations of CO2.[40][41] Plants also emit CO2 during respiration, and so the majority of plants and algae, which use C3 photosynthesis, are only net absorbers during the day. Though a growing forest will absorb many tons of CO2 each year, a mature forest will produce as much CO2 from respiration and decomposition of dead specimens (e.g., fallen branches) as is used in photosynthesis in growing plants.[42] Contrary to the long-standing view that they are carbon neutral, mature forests can continue to accumulate carbon[43] and remain valuable carbon sinks, helping to maintain the carbon balance of Earth's atmosphere. Additionally, and crucially to life on earth, photosynthesis by phytoplankton consumes dissolved CO2 in the upper ocean and thereby promotes the absorption of CO2 from the atmosphere.[44] See also: Carbon dioxide poisoning Symptoms of carbon dioxide toxicity, by increasing volume percent in air[45] Carbon dioxide content in fresh air (averaged between sea-level and 10 kPa level, i.e., about 30 km (19 mi) altitude) varies between 0.036% (360 ppm) and 0.041% (412 ppm), depending on the location.[46] In humans, exposure to CO2 at concentrations greater than 5% causes the development of hypercapnia and respiratory acidosis.[47] Concentrations of 7% to 10% (70,000 to 100,000 ppm) may cause suffocation, even in the presence of sufficient oxygen, manifesting as dizziness, headache, visual and hearing dysfunction, and unconsciousness within a few minutes to an hour.[48] Concentrations of more than 10% may cause convulsions, coma, and death. CO2 levels of more than 30% act rapidly leading to loss of consciousness in seconds.[47] Because it is heavier than air, in locations where the gas seeps from the ground (due to sub-surface volcanic or geothermal activity) in relatively high concentrations, without the dispersing effects of wind, it can collect in sheltered/pocketed locations below average ground level, causing animals located therein to be suffocated. Carrion feeders attracted to the carcasses are then also killed. Children have been killed in the same way near the city of Goma by CO2 emissions from the nearby volcano Mount Nyiragongo.[49] The Swahili term for this phenomenon is mazuku. Rising levels of CO2 threatened the Apollo 13 astronauts, who had to adapt cartridges from the command module to supply the carbon dioxide scrubber in the Apollo Lunar Module, which they used as a lifeboat. Adaptation to increased concentrations of CO2 occurs in humans, including modified breathing and kidney bicarbonate production, in order to balance the effects of blood acidification (acidosis). Several studies suggested that 2.0 percent inspired concentrations could be used for closed air spaces (e.g. a submarine) since the adaptation is physiological and reversible, as deterioration in performance or in normal physical activity does not happen at this level of exposure for five days.[50][51] Yet, other studies show a decrease in cognitive function even at much lower levels.[52][53] Also, with ongoing respiratory acidosis, adaptation or compensatory mechanisms will be unable to reverse the condition. There are few studies of the health effects of long-term continuous CO2 exposure on humans and animals at levels below 1%. Occupational CO2 exposure limits have been set in the United States at 0.5% (5000 ppm) for an eight-hour period.[54] At this CO2 concentration, International Space Station crew experienced headaches, lethargy, mental slowness, emotional irritation, and sleep disruption.[55] Studies in animals at 0.5% CO2 have demonstrated kidney calcification and bone loss after eight weeks of exposure.[56] A study of humans exposed in 2.5 hour sessions demonstrated significant negative effects on cognitive abilities at concentrations as low as 0.1% (1000 ppm) CO2 likely due to CO2 induced increases in cerebral blood flow.[52] Another study observed a decline in basic activity level and information usage at 1000 ppm, when compared to 500 ppm.[53] However a review of the literature found that a reliable subset of studies on the phenomenon of carbon dioxide induced cognitive impairment to only show a small effect on high-level decision making (for concentrations below 5000 ppm). Most of the studies were confounded by inadequate study designs, environmental comfort, uncertainties in exposure doses and differing cognitive assessments used.[57] Similarly a study on the effects of the concentration of CO2 in motorcycle helmets has been criticized for having dubious methodology in not noting the self-reports of motorcycle riders and taking measurements using mannequins. Further when normal motorcycle conditions were achieved (such as highway or city speeds) or the visor was raised the concentration of CO2 declined to safe levels (0.2%).[58][59] Typical CO2 concentration effects Concentration Note 280 ppm Pre-industrial levels 421 ppm Current (May 2022) levels ~1121 ppm ASHRAE recommendation for indoor air[60] 5,000 ppm USA 8h exposure limit[54] 10,000 ppm Cognitive impairment, Canada's long term exposure limit[45] 10,000-20,000 ppm Drowsiness[48] 20,000-50,000 ppm Headaches, sleepiness; poor concentration, loss of attention, slight nausea also possible[54] A carbon dioxide sensor that measures CO2 concentration using a nondispersive infrared sensor Poor ventilation is one of the main causes of excessive CO2 concentrations in closed spaces, leading to poor indoor air quality. Carbon dioxide differential above outdoor concentrations at steady state conditions (when the occupancy and ventilation system operation are sufficiently long that CO2 concentration has stabilized) are sometimes used to estimate ventilation rates per person.[61] Higher CO2 concentrations are associated with occupant health, comfort and performance degradation.[62][63] ASHRAE Standard 62.1–2007 ventilation rates may result in indoor concentrations up to 2,100 ppm above ambient outdoor conditions. Thus if the outdoor concentration is 400 ppm, indoor concentrations may reach 2,500 ppm with ventilation rates that meet this industry consensus standard. Concentrations in poorly ventilated spaces can be found even higher than this (range of 3,000 or 4,000 ppm). Miners, who are particularly vulnerable to gas exposure due to insufficient ventilation, referred to mixtures of carbon dioxide and nitrogen as "blackdamp", "choke damp" or "stythe". Before more effective technologies were developed, miners would frequently monitor for dangerous levels of blackdamp and other gases in mine shafts by bringing a caged canary with them as they worked. The canary is more sensitive to asphyxiant gases than humans, and as it became unconscious would stop singing and fall off its perch. The Davy lamp could also detect high levels of blackdamp (which sinks, and collects near the floor) by burning less brightly, while methane, another suffocating gas and explosion risk, would make the lamp burn more brightly. In February 2020, three people died from suffocation at a party in Moscow when dry ice (frozen CO2) was added to a swimming pool to cool it down.[64] A similar accident occurred in 2018 when a woman died from CO2 fumes emanating from the large amount of dry ice she was transporting in her car.[65] Humans spend more and more time in a confined atmosphere (around 80-90% of the time in a building or vehicle). According to the French Agency for Food, Environmental and Occupational Health & Safety (ANSES) and various actors in France, the CO2 rate in the indoor air of buildings (linked to human or animal occupancy and the presence of combustion installations), weighted by air renewal, is "usually between about 350 and 2,500 ppm".[66] In homes, schools, nurseries and offices, there are no systematic relationships between the levels of CO2 and other pollutants, and indoor CO2 is statistically not a good predictor of pollutants linked to outdoor road (or air, etc.) traffic.[67] CO2 is the parameter that changes the fastest (with hygrometry and oxygen levels when humans or animals are gathered in a closed or poorly ventilated room). In poor countries, many open hearths are sources of CO2 and CO emitted directly into the living environment.[68] Local concentrations of carbon dioxide can reach high values near strong sources, especially those that are isolated by surrounding terrain. At the Bossoleto hot spring near Rapolano Terme in Tuscany, Italy, situated in a bowl-shaped depression about 100 m (330 ft) in diameter, concentrations of CO2 rise to above 75% overnight, sufficient to kill insects and small animals. After sunrise the gas is dispersed by convection.[69] High concentrations of CO2 produced by disturbance of deep lake water saturated with CO2 are thought to have caused 37 fatalities at Lake Monoun, Cameroon in 1984 and 1700 casualties at Lake Nyos, Cameroon in 1986.[70] Reference ranges or averages for partial pressures of carbon dioxide (abbreviated pCO2) Blood compartment (kPa) (mm Hg) Venous blood carbon dioxide 5.5–6.8 41–51[71] Alveolar pulmonarygas pressures 4.8 36 Arterial blood carbon dioxide 4.7–6.0 35–45[71] The body produces approximately 2.3 pounds (1.0 kg) of carbon dioxide per day per person,[72] containing 0.63 pounds (290 g) of carbon. In humans, this carbon dioxide is carried through the venous system and is breathed out through the lungs, resulting in lower concentrations in the arteries. The carbon dioxide content of the blood is often given as the partial pressure, which is the pressure which carbon dioxide would have had if it alone occupied the volume.[73] In humans, the blood carbon dioxide contents are shown in the adjacent table. CO2 is carried in blood in three different ways. Exact percentages vary between arterial and venous blood. Majority (about 70% to 80%) is converted to bicarbonate ions HCO−3 by the enzyme carbonic anhydrase in the red blood cells,[74] by the reaction: CO2 + H2O → H2CO3 → H+ + HCO−3 5–10% is dissolved in blood plasma[74] 5–10% is bound to hemoglobin as carbamino compounds[74] Hemoglobin, the main oxygen-carrying molecule in red blood cells, carries both oxygen and carbon dioxide. However, the CO2 bound to hemoglobin does not bind to the same site as oxygen. Instead, it combines with the N-terminal groups on the four globin chains. However, because of allosteric effects on the hemoglobin molecule, the binding of CO2 decreases the amount of oxygen that is bound for a given partial pressure of oxygen. This is known as the Haldane Effect, and is important in the transport of carbon dioxide from the tissues to the lungs. Conversely, a rise in the partial pressure of CO2 or a lower pH will cause offloading of oxygen from hemoglobin, which is known as the Bohr effect. Carbon dioxide is one of the mediators of local autoregulation of blood supply. If its concentration is high, the capillaries expand to allow a greater blood flow to that tissue.[75] Bicarbonate ions are crucial for regulating blood pH. A person's breathing rate influences the level of CO2 in their blood. Breathing that is too slow or shallow causes respiratory acidosis, while breathing that is too rapid leads to hyperventilation, which can cause respiratory alkalosis.[76] Although the body requires oxygen for metabolism, low oxygen levels normally do not stimulate breathing. Rather, breathing is stimulated by higher carbon dioxide levels. As a result, breathing low-pressure air or a gas mixture with no oxygen at all (such as pure nitrogen) can lead to loss of consciousness without ever experiencing air hunger. This is especially perilous for high-altitude fighter pilots. It is also why flight attendants instruct passengers, in case of loss of cabin pressure, to apply the oxygen mask to themselves first before helping others; otherwise, one risks losing consciousness.[74] The respiratory centers try to maintain an arterial CO2 pressure of 40 mmHg. With intentional hyperventilation, the CO2 content of arterial blood may be lowered to 10–20 mmHg (the oxygen content of the blood is little affected), and the respiratory drive is diminished. This is why one can hold one's breath longer after hyperventilating than without hyperventilating. This carries the risk that unconsciousness may result before the need to breathe becomes overwhelming, which is why hyperventilation is particularly dangerous before free diving.[77] Further information: Carbon cycle This section is an excerpt from Carbon dioxide in Earth's atmosphere.[edit] Atmospheric CO2 concentration measured at Mauna Loa Observatory in Hawaii from 1958 to 2023 (also called the Keeling Curve). The rise in CO2 over that time period is clearly visible. The concentration is expressed as μmole per mole, or ppm. In Earth's atmosphere, carbon dioxide is a trace gas that plays an integral part in the greenhouse effect, carbon cycle, photosynthesis and oceanic carbon cycle. It is one of three main greenhouse gases in the atmosphere of Earth. The concentration of carbon dioxide (CO2) in the atmosphere reached 427 ppm (0.0427%) on a molar basis in 2024, representing 3341 gigatonnes of CO2.[78] This is an increase of 50% since the start of the Industrial Revolution, up from 280 ppm during the 10,000 years prior to the mid-18th century.[79][80][81] The increase is due to human activity.[82] The current increase in CO2 concentrations is primarily driven by the burning of fossil fuels.[83] Other significant human activities that emit CO2 include cement production, deforestation, and biomass burning. The increase in atmospheric concentrations of CO2 and other long-lived greenhouse gases such as methane increase the absorption and emission of infrared radiation by the atmosphere. This has led to a rise in average global temperature and ocean acidification. Another direct effect is the CO2 fertilization effect. The increase in atmospheric concentrations of CO2 causes a range of further effects of climate change on the environment and human living conditions. Carbon dioxide is a greenhouse gas. It absorbs and emits infrared radiation at its two infrared-active vibrational frequencies. The two wavelengths are 4.26 μm (2,347 cm−1) (asymmetric stretching vibrational mode) and 14.99 μm (667 cm−1) (bending vibrational mode). CO2 plays a significant role in influencing Earth's surface temperature through the greenhouse effect.[84] Light emission from the Earth's surface is most intense in the infrared region between 200 and 2500 cm−1,[85] as opposed to light emission from the much hotter Sun which is most intense in the visible region. Absorption of infrared light at the vibrational frequencies of atmospheric CO2 traps energy near the surface, warming the surface of Earth and its lower atmosphere. Less energy reaches the upper atmosphere, which is therefore cooler because of this absorption.[86] The present atmospheric concentration of CO2 is the highest for 14 million years.[87] Concentrations of CO2 in the atmosphere were as high as 4,000 ppm during the Cambrian period about 500 million years ago, and as low as 180 ppm during the Quaternary glaciation of the last two million years.[79] Reconstructed temperature records for the last 420 million years indicate that atmospheric CO2 concentrations peaked at approximately 2,000 ppm. This peak happened during the Devonian period (400 million years ago). Another peak occurred in the Triassic period (220–200 million years ago).[88] Annual CO2 flows from anthropogenic sources (left) into Earth's atmosphere, land, and ocean sinks (right) since the 1960s. Units in equivalent gigatonnes carbon per year.[89] Main articles: Carbon cycle and Ocean acidification Carbon dioxide dissolves in the ocean to form carbonic acid (H2CO3), bicarbonate (HCO−3), and carbonate (CO2−3). There is about fifty times as much carbon dioxide dissolved in the oceans as exists in the atmosphere. The oceans act as an enormous carbon sink, and have taken up about a third of CO2 emitted by human activity.[90] This section is an excerpt from Ocean acidification.[edit] Ocean acidification is the ongoing decrease in the pH of the Earth's ocean. Between 1950 and 2020, the average pH of the ocean surface fell from approximately 8.15 to 8.05.[91] Carbon dioxide emissions from human activities are the primary cause of ocean acidification, with atmospheric carbon dioxide (CO2) levels exceeding 422 ppm (as of 2024[update]).[92] CO2 from the atmosphere is absorbed by the oceans. This chemical reaction produces carbonic acid (H2CO3) which dissociates into a bicarbonate ion (HCO−3) and a hydrogen ion (H+). The presence of free hydrogen ions (H+) lowers the pH of the ocean, increasing acidity (this does not mean that seawater is acidic yet; it is still alkaline, with a pH higher than 8). Marine calcifying organisms, such as mollusks and corals, are especially vulnerable because they rely on calcium carbonate to build shells and skeletons.[93] A change in pH by 0.1 represents a 26% increase in hydrogen ion concentration in the world's oceans (the pH scale is logarithmic, so a change of one in pH units is equivalent to a tenfold change in hydrogen ion concentration). Sea-surface pH and carbonate saturation states vary depending on ocean depth and location. Colder and higher latitude waters are capable of absorbing more CO2. This can cause acidity to rise, lowering the pH and carbonate saturation levels in these areas. There are several other factors that influence the atmosphere-ocean CO2 exchange, and thus local ocean acidification. These include ocean currents and upwelling zones, proximity to large continental rivers, sea ice coverage, and atmospheric exchange with nitrogen and sulfur from fossil fuel burning and agriculture.[94][95][96] Pterapod shell dissolved in seawater adjusted to an ocean chemistry projected for the year 2100 This section is an excerpt from Ocean acidification § Decreased calcification in marine organisms.[edit] Changes in ocean chemistry can have extensive direct and indirect effects on organisms and their habitats. One of the most important repercussions of increasing ocean acidity relates to the production of shells out of calcium carbonate (CaCO3).[93] This process is called calcification and is important to the biology and survival of a wide range of marine organisms. Calcification involves the precipitation of dissolved ions into solid CaCO3 structures, structures for many marine organisms, such as coccolithophores, foraminifera, crustaceans, mollusks, etc. After they are formed, these CaCO3 structures are vulnerable to dissolution unless the surrounding seawater contains saturating concentrations of carbonate ions (CO2−3). Very little of the extra carbon dioxide that is added into the ocean remains as dissolved carbon dioxide. The majority dissociates into additional bicarbonate and free hydrogen ions. The increase in hydrogen is larger than the increase in bicarbonate,[97] creating an imbalance in the reaction: HCO−3 ⇌ CO2−3 + H+ To maintain chemical equilibrium, some of the carbonate ions already in the ocean combine with some of the hydrogen ions to make further bicarbonate. Thus the ocean's concentration of carbonate ions is reduced, removing an essential building block for marine organisms to build shells, or calcify: Ca2+ + CO2−3 ⇌ CaCO3 Carbon dioxide is also introduced into the oceans through hydrothermal vents. The Champagne hydrothermal vent, found at the Northwest Eifuku volcano in the Mariana Trench, produces almost pure liquid carbon dioxide, one of only two known sites in the world as of 2004, the other being in the Okinawa Trough.[98] The finding of a submarine lake of liquid carbon dioxide in the Okinawa Trough was reported in 2006.[99] The burning of fossil fuels for energy produces 36.8 billion tonnes of CO2 per year as of 2023.[100] Nearly all of this goes into the atmosphere, where approximately half is subsequently absorbed into natural carbon sinks.[101] Less than 1% of CO2 produced annually is put to commercial use.[18]:3 Carbon dioxide is a by-product of the fermentation of sugar in the brewing of beer, whisky and other alcoholic beverages and in the production of bioethanol. Yeast metabolizes sugar to produce CO2 and ethan

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