[Template:About](/wiki/Template:About" \o "Template:About) [Template:Pp-move-indef](/wiki/Template:Pp-move-indef) [Template:Use dmy dates](/wiki/Template:Use_dmy_dates) [Template:Infobox sulfur](/wiki/Template:Infobox_sulfur) **Sulfur** or **sulphur** (see [spelling differences](/wiki/Sulfur#Spelling_and_etymology)) is a [chemical element](/wiki/Chemical_element) with symbol **S** and [atomic number](/wiki/Atomic_number) 16. It is an [abundant](/wiki/Abundance_of_the_chemical_elements), [multivalent](/wiki/Valence_(chemistry)) [non-metal](/wiki/Non-metal). Under [normal conditions](/wiki/Standard_conditions_for_temperature_and_pressure), sulfur atoms form cyclic octatomic molecules with chemical formula S8. Elemental sulfur is a bright yellow [crystalline](/wiki/Crystal) solid at room temperature. Chemically, sulfur reacts with all elements except for gold, platinum, iridium, nitrogen, tellurium, iodine and the noble gases.

Elemental sulfur occurs [naturally](/wiki/Nature) as the [element](/wiki/Chemical_element) ([native](/wiki/Native_element_minerals) sulfur), but most commonly occurs in combined forms as [sulfide](/wiki/Sulfide_minerals) and [sulfate minerals](/wiki/Sulfate_minerals). Being abundant in native form, sulfur was known in ancient times, being mentioned for its uses in [ancient India](/wiki/Ancient_India), [ancient Greece](/wiki/Ancient_Greece), [China](/wiki/History_of_China#Ancient_China), and [Egypt](/wiki/Ancient_Egypt). In the [Bible](/wiki/Bible), sulfur is called *brimstone*.<ref name=Greenwd/> Today, almost all elemental sulfur is produced as a byproduct of removing sulfur-containing contaminants from [natural gas](/wiki/Natural_gas) and [petroleum](/wiki/Petroleum). The greatest commercial use of the element is the production of [sulfuric acid](/wiki/Sulfuric_acid) for sulfate and phosphate [fertilizers](/wiki/Fertilizer), and other chemical processes. The element sulfur is used in [matches](/wiki/Match), [insecticides](/wiki/Insecticide), and [fungicides](/wiki/Fungicide). Many sulfur compounds are odoriferous, and the smells of odorized natural gas, skunk scent, grapefruit, and garlic are due to [organosulfur](/wiki/Organosulfur) compounds. [Hydrogen sulfide](/wiki/Hydrogen_sulfide) gives the characteristic odor to rotting eggs and other biological processes.

Sulfur is an [essential element](/wiki/Essential_element) for all life, but almost always in the form of [organosulfur](/wiki/Organosulfur_compounds) compounds or metal sulfides. Three [amino acids](/wiki/Amino_acid) ([cysteine](/wiki/Cysteine), [cystine](/wiki/Cystine), and [methionine](/wiki/Methionine)) and two vitamins ([biotin](/wiki/Biotin) and [thiamine](/wiki/Thiamine)) are organosulfur compounds. Many [cofactors](/wiki/Cofactor_(biochemistry)) also contain sulfur including [glutathione](/wiki/Glutathione) and [thioredoxin](/wiki/Thioredoxin) and [iron–sulfur proteins](/wiki/Iron–sulfur_protein). [Disulfides](/wiki/Disulfide), S–S bonds, confer mechanical strength and insolubility of the protein [keratin](/wiki/Keratin), found in outer skin, hair, and feathers. Elemental sulfur is not common in higher forms of life, but is both a product and an [oxidant](/wiki/Oxidant) for various bacteria.

## Contents

* 1 Spelling and etymology[[edit](/index.php?title=(none)&action=edit&section=1)]
* 2 Characteristics[[edit](/index.php?title=(none)&action=edit&section=2)]
  + 2.1 Physical properties[[edit](/index.php?title=(none)&action=edit&section=3)]
  + 2.2 Chemical properties[[edit](/index.php?title=(none)&action=edit&section=4)]
  + 2.3 Allotropes[[edit](/index.php?title=(none)&action=edit&section=5)]
  + 2.4 Isotopes[[edit](/index.php?title=(none)&action=edit&section=6)]
  + 2.5 Natural occurrence[[edit](/index.php?title=(none)&action=edit&section=7)]
* 3 Production[[edit](/index.php?title=(none)&action=edit&section=8)]
* 4 Compounds[[edit](/index.php?title=(none)&action=edit&section=9)]
  + 4.1 Sulfur polycations[[edit](/index.php?title=(none)&action=edit&section=10)]
  + 4.2 Sulfides[[edit](/index.php?title=(none)&action=edit&section=11)]
  + 4.3 Oxides, oxoacids and oxoanions[[edit](/index.php?title=(none)&action=edit&section=12)]
  + 4.4 Halides and oxyhalides[[edit](/index.php?title=(none)&action=edit&section=13)]
  + 4.5 Pnictides[[edit](/index.php?title=(none)&action=edit&section=14)]
  + 4.6 Metal sulfides[[edit](/index.php?title=(none)&action=edit&section=15)]
  + 4.7 Organic compounds[[edit](/index.php?title=(none)&action=edit&section=16)]
* 5 History[[edit](/index.php?title=(none)&action=edit&section=17)]
  + 5.1 Antiquity[[edit](/index.php?title=(none)&action=edit&section=18)]
  + 5.2 Modern times[[edit](/index.php?title=(none)&action=edit&section=19)]
* 6 Applications[[edit](/index.php?title=(none)&action=edit&section=20)]
  + 6.1 Sulfuric acid[[edit](/index.php?title=(none)&action=edit&section=21)]
  + 6.2 Other important sulfur chemistry[[edit](/index.php?title=(none)&action=edit&section=22)]
  + 6.3 Fertilizer[[edit](/index.php?title=(none)&action=edit&section=23)]
  + 6.4 Fine chemicals[[edit](/index.php?title=(none)&action=edit&section=24)]
  + 6.5 Fungicide and pesticide[[edit](/index.php?title=(none)&action=edit&section=25)]
  + 6.6 Bactericide in winemaking and food preservation[[edit](/index.php?title=(none)&action=edit&section=26)]
  + 6.7 Pharmaceuticals[[edit](/index.php?title=(none)&action=edit&section=27)]
    - 6.7.1 Mechanism of action[[edit](/index.php?title=(none)&action=edit&section=28)]
* 7 Biological role[[edit](/index.php?title=(none)&action=edit&section=29)]
  + 7.1 Protein and organic cofactors[[edit](/index.php?title=(none)&action=edit&section=30)]
  + 7.2 Metalloproteins and inorganic cofactors[[edit](/index.php?title=(none)&action=edit&section=31)]
  + 7.3 Sulfur metabolism and the sulfur cycle[[edit](/index.php?title=(none)&action=edit&section=32)]
* 8 Precautions[[edit](/index.php?title=(none)&action=edit&section=33)]
* 9 See also[[edit](/index.php?title=(none)&action=edit&section=34)]
* 10 References[[edit](/index.php?title=(none)&action=edit&section=35)]
* 11 External links[[edit](/index.php?title=(none)&action=edit&section=36)]

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

*Sulfur* is derived from the Latin word *sulpur*, which was [Hellenized](/wiki/Hellenized) to *sulphur*. The spelling *sulfur* appears toward the end of the Classical period. (The true Greek word for sulfur, *θεῖον*, is the source of the international chemical prefix [*thio-*](/wiki/Thio-).) In 12th-century [Anglo-French](/wiki/Anglo-Norman_language), it was *sulfre*; in the 14th century the Latin *ph* was restored, for *sulphre*; and by the 15th century the full Latin spelling was restored, for *sulfur, sulphur*. The parallel *f~ph* spellings continued in Britain until the 19th century, when the word was standardized as *sulphur*.<ref name=OED>[Template:OED](/wiki/Template:OED)</ref> *Sulfur* was the form chosen in the United States, whereas Canada uses both. The [IUPAC](/wiki/International_Union_of_Pure_and_Applied_Chemistry) adopted the spelling *sulfur* in 1990, as did the Nomenclature Committee of the [Royal Society of Chemistry](/wiki/Royal_Society_of_Chemistry) in 1992, restoring the spelling *sulfur* to Britain.[[1]](#cite_note-1) The Oxford Dictionaries note that "in chemistry ... the -f- spelling is now the standard form in all related words in the field in both British and US contexts."[[2]](#cite_note-2) The late Latin form continues in the Romance languages: French *soufre*, Italian *zolfo* (from *solfo*), Spanish *azufre* (from *açufre*, from earlier *çufre*), Portuguese *enxofre* (from *xofre*). The Spanish and Portuguese words are prefixed with the [Arabic article](/wiki/Arabic_article), despite not being Arabic words.[[3]](#cite_note-3) The root has been traced back to reconstructed [proto-Indo-European](/wiki/Proto-Indo-European) [Template:PIE](/wiki/Template:PIE) (genitive [Template:PIE](/wiki/Template:PIE)), a nominal derivative of [Template:PIE](/wiki/Template:PIE) 'to burn', a lineage also preserved in the Germanic languages, where it is found as the modern German *Schwefel*, Dutch *zwavel*, and Swedish *svavel*, and as [Old English](/wiki/Old_English) *swefl*.[[4]](#cite_note-4)

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

[thumb|left|When burned, sulfur melts to a blood-red liquid and emits a blue flame that is best observed in the dark.](/wiki/File:Burning-sulfur.png)

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

Sulfur forms polyatomic molecules with different chemical formulas, the best-known allotrope being [octasulfur](/wiki/Octasulfur), cyclo-S8. The point group of cyclo-S8 is D4d and its dipole moment is 0 D.[[5]](#cite_note-5) Octasulfur is a soft, bright-yellow solid with only a faint odor, similar to that of [matches](/wiki/Match).[[6]](#cite_note-6) It melts at [Template:Convert](/wiki/Template:Convert), boils at [Template:Convert](/wiki/Template:Convert) and sublimes easily.<ref name=Greenwd/> At [Template:Convert](/wiki/Template:Convert), below its melting temperature, cyclo-octasulfur changes from α-octasulfur to the β-[polymorph](/wiki/Polymorphism_(materials_science)).[[7]](#cite_note-7) The structure of the S8 ring is virtually unchanged by this phase change, which affects the intermolecular interactions. Between its melting and boiling temperatures, octasulfur changes its allotrope again, turning from β-octasulfur to γ-sulfur, again accompanied by a lower density but increased [viscosity](/wiki/Viscosity) due to the formation of [polymers](/wiki/Polymer).[[7]](#cite_note-7) At higher temperatures, the viscosity decreases as depolymerization occurs. Molten sulfur assumes a dark red color above [Template:Convert](/wiki/Template:Convert). The density of sulfur is about 2 g·cm−3, depending on the allotrope; all of the stable allotropes are excellent electrical insulators.

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

Sulfur burns with a blue flame with formation of [sulfur dioxide](/wiki/Sulfur_dioxide), which has a suffocating and corrosive odor. Sulfur is insoluble in water but soluble in [carbon disulfide](/wiki/Carbon_disulfide) and, to a lesser extent, in other nonpolar organic solvents, such as [benzene](/wiki/Benzene) and [toluene](/wiki/Toluene). The first and second ionization energies of sulfur are 999.6 and 2252 kJ·mol−1, respectively. Despite such figures, the +2 oxidation state is rare, with +4 and +6 being more common. The fourth and sixth ionization energies are 4556 and 8495.8 kJ·mol−1, the magnitude of the figures caused by electron transfer between orbitals; these states are only stable with strong oxidants such as [fluorine](/wiki/Fluorine), [oxygen](/wiki/Oxygen), and [chlorine](/wiki/Chlorine). [Template:Citation needed](/wiki/Template:Citation_needed) Sulfur reacts with nearly all other elements with the exception of gold, platinum, iridium, nitrogen, tellurium, iodine and the noble gases. Some of those reactions need elevated temperatures.[[8]](#cite_note-8)

### Allotropes[[edit](/index.php?title=(none)&action=edit&section=5)]

[thumb|left|The structure of the cyclooctasulfur molecule, S8.](/wiki/File:Cyclooctasulfur-above-3D-balls.png) [Template:Main article](/wiki/Template:Main_article) Sulfur forms over 30 solid [allotropes](/wiki/Allotropy), more than any other element.[[9]](#cite_note-9) Besides S8, several other rings are known.[[10]](#cite_note-10) Removing one atom from the crown gives S7, which is more deeply yellow than S8. [HPLC](/wiki/High-performance_liquid_chromatography) analysis of "elemental sulfur" reveals an equilibrium mixture of mainly S8, but with S7 and small amounts of S6.[[11]](#cite_note-11) Larger rings have been prepared, including S12 and S18.[[12]](#cite_note-12)[[13]](#cite_note-13) [Amorphous](/wiki/Amorphous) or "plastic" sulfur is produced by rapid cooling of molten sulfur—for example, by pouring it into cold water. [X-ray crystallography](/wiki/X-ray_crystallography) studies show that the amorphous form may have a [helical](/wiki/Helix) structure with eight atoms per turn. The long coiled polymeric molecules make the brownish substance [elastic](/wiki/Elasticity_(physics)), and in bulk this form has the feel of crude rubber. This form is [metastable](/wiki/Metastability_in_molecules) at room temperature and gradually reverts to crystalline molecular allotrope, which is no longer elastic. This process happens within a matter of hours to days, but can be rapidly catalyzed. [Template:Clear left](/wiki/Template:Clear_left)

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

[Template:Main article](/wiki/Template:Main_article) Sulfur has 25 known [isotopes](/wiki/Isotope), four of which are stable: 32S (95.02%), 33S (0.75%), 34S (4.21%), and 36S (0.02%). Other than 35S, with a [half-life](/wiki/Half-life) of 87 days and formed in [cosmic ray spallation](/wiki/Cosmic_ray_spallation) of 40[Ar](/wiki/Argon), the [radioactive](/wiki/Radioactivity) isotopes of sulfur have half-lives less than 3 hours.

When [sulfide minerals](/wiki/Sulfide_mineral) are precipitated, isotopic equilibration among solids and liquid may cause small differences in the δS-34 values of co-genetic minerals. The differences between minerals can be used to estimate the temperature of equilibration. The δ[C](/wiki/Carbon)-13 and δS-34 of coexisting [carbonate minerals](/wiki/Carbonate_minerals) and sulfides can be used to determine the [pH](/wiki/PH) and oxygen [fugacity](/wiki/Fugacity) of the ore-bearing fluid during ore formation.

In most [forest](/wiki/Forest) ecosystems, sulfate is derived mostly from the atmosphere; weathering of ore minerals and evaporites contribute some sulfur. Sulfur with a distinctive isotopic composition has been used to identify pollution sources, and enriched sulfur has been added as a tracer in [hydrologic](/wiki/Hydrology) studies. Differences in the [natural abundances](/wiki/Natural_abundance) can be used in systems where there is sufficient variation in the 34S of ecosystem components. [Rocky Mountain](/wiki/Rocky_Mountain) lakes thought to be dominated by atmospheric sources of sulfate have been found to have different [δ34S](/wiki/Δ34S) values from lakes believed to be dominated by watershed sources of sulfate.

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

[thumb|Sulfur vat from which railroad cars are loaded, Freeport Sulphur Co., Hoskins Mound, Texas (1943).](/wiki/File:Nearly_exhausted_sulphur_vat_from_which_railroad_cars_are_loaded,_Freeport_Sulphur_Co.,_Hoskins_Mound,_Texas,_1a35438v.jpg) [thumb|Most of the yellow and orange hues of](/wiki/File:Io_highest_resolution_true_color.jpg) [Io](/wiki/Io_(moon)) are due to elemental sulfur and sulfur compounds deposited by active [volcanoes](/wiki/Volcano). [thumb|A man carrying sulfur blocks from](/wiki/File:Kawah_Ijen_-East_Java_-Indonesia_-sulphur-31July2009.jpg) [Kawah Ijen](/wiki/Kawah_Ijen), a volcano in East Java, Indonesia, 2009 32S is created inside massive stars, at a depth where the temperature exceeds 2.5×109 K, by the [fusion](/wiki/Silicon_burning) of one nucleus of silicon plus one nucleus of helium.[[14]](#cite_note-14) As this is part of the [alpha process](/wiki/Alpha_process) that produces elements in abundance, sulfur is the 10th most common element in the universe.

Sulfur, usually as sulfide, is present in many types of [meteorites](/wiki/Meteorite). Ordinary chondrites contain on average 2.1% sulfur, and carbonaceous chondrites may contain as much as 6.6%. It is normally present as [troilite](/wiki/Troilite) (FeS), but there are exceptions, with carbonaceous chondrites containing free sulfur, sulfates and other sulfur compounds.[[15]](#cite_note-15) The distinctive colors of [Jupiter's](/wiki/Jupiter) [volcanic](/wiki/Volcano) moon [Io](/wiki/Io_(moon)) are attributed to various forms of molten, solid and gaseous sulfur.[[16]](#cite_note-16) [thumb|left|Sulfur occurs in](/wiki/File:Fumarola_Vulcano.jpg) [fumaroles](/wiki/Fumaroles) such as this one in [Vulcano](/wiki/Vulcano), Italy

On Earth, elemental sulfur can be found near [hot springs](/wiki/Hot_spring) and [volcanic](/wiki/Volcanic) regions in many parts of the world, especially along the [Pacific Ring of Fire](/wiki/Pacific_Ring_of_Fire); such volcanic deposits are currently mined in Indonesia, Chile, and Japan. Such deposits are polycrystalline, with the largest documented single crystal measuring 22×16×11 cm.[[17]](#cite_note-17) Historically, [Sicily](/wiki/Sicily) was a large source of sulfur in the [Industrial Revolution](/wiki/Industrial_Revolution).[[18]](#cite_note-18) Native sulfur is synthesised by [anaerobic bacteria](/wiki/Anaerobic_bacteria) acting on [sulfate minerals](/wiki/Sulfate_minerals) such as [gypsum](/wiki/Gypsum) in [salt domes](/wiki/Salt_domes).[[19]](#cite_note-19)[[20]](#cite_note-20) Significant deposits in salt domes occur along the coast of the [Gulf of Mexico](/wiki/Gulf_of_Mexico), and in [evaporites](/wiki/Evaporite) in eastern Europe and western Asia. Native sulfur may be produced by geological processes alone. Fossil-based sulfur deposits from salt domes were until recently the basis for commercial production in the United States, Russia, Turkmenistan, and Ukraine.<ref name=Nehb/> Currently, commercial production is still carried out in the Osiek mine in Poland. Such sources are now of secondary commercial importance, and most are no longer worked.

Common naturally occurring sulfur compounds include the [sulfide minerals](/wiki/Mineral#Sulfide_class), such as [pyrite](/wiki/Pyrite) (iron sulfide), [cinnabar](/wiki/Cinnabar) (mercury sulfide), [galena](/wiki/Galena) (lead sulfide), [sphalerite](/wiki/Sphalerite) (zinc sulfide) and [stibnite](/wiki/Stibnite) (antimony sulfide); and the sulfates, such as [gypsum](/wiki/Gypsum) (calcium sulfate), [alunite](/wiki/Alunite) (potassium aluminium sulfate), and [barite](/wiki/Barite) (barium sulfate). On Earth, just as upon Jupiter's moon Io, elemental sulfur occurs naturally in volcanic emissions, including emissions from [hydrothermal vents](/wiki/Hydrothermal_vent).

## Production[[edit](/index.php?title=(none)&action=edit&section=8)]

Sulfur may be found by itself and historically was usually obtained in this form; pyrite has also been a source of sulfur.[[21]](#cite_note-21) In volcanic regions in [Sicily](/wiki/Sicily), in ancient times, it was found on the surface of the Earth, and the *"Sicilian process"* was used: sulfur deposits were piled and stacked in brick kilns built on sloping hillsides, with airspaces between them. Then, some sulfur was pulverized, spread over the stacked ore and ignited, causing the free sulfur to melt down the hills. Eventually the surface-borne deposits played out, and miners excavated veins that ultimately dotted the Sicilian landscape with labyrinthine mines. Mining was unmechanized and labor-intensive, with pickmen freeing the ore from the rock, and mine-boys or [*carusi*](/wiki/Carusu) carrying baskets of ore to the surface, often through a mile or more of tunnels. Once the ore was at the surface, it was reduced and extracted in smelting ovens. The conditions in Sicilian sulfur mines were horrific, prompting [Booker T. Washington](/wiki/Booker_T._Washington) to write "I am not prepared just now to say to what extent I believe in a physical hell in the next world, but a sulphur mine in Sicily is about the nearest thing to hell that I expect to see in this life."[[22]](#cite_note-22) Elemental sulfur was once extracted from [salt domes](/wiki/Salt_dome) where it sometimes occurs in nearly pure form, but this method has been obsolete since the late 20th century. Today's sulfur production is as a side product of other industrial processes such as oil refining; in these processes, sulfur often occurs as undesired or detrimental compounds that are extracted and converted to elemental sulfur. As a mineral, native sulfur under salt domes is thought to be a fossil mineral resource, produced by the action of ancient bacteria on sulfate deposits. It was removed from such salt-dome mines mainly by the [Frasch process](/wiki/Frasch_process).<ref name=Nehb/> In this method, superheated water was pumped into a native sulfur deposit to melt the sulfur, and then compressed air returned the 99.5% pure melted product to the surface. Throughout the 20th century this procedure produced elemental sulfur that required no further purification. Due to a limited number of such sulfur deposits and the high cost of working them, this process for mining sulfur has not been employed in a major way anywhere in the world since 2002.[[23]](#cite_note-23)[[24]](#cite_note-24) [thumb|Sulfur recovered from hydrocarbons in](/wiki/File:AlbertaSulfurAtVancouverBC.jpg) [Alberta](/wiki/Alberta), stockpiled for shipment in North Vancouver, British Columbia Today, sulfur is produced from petroleum, [natural gas](/wiki/Natural_gas), and related fossil resources, from which it is obtained mainly as [hydrogen sulfide](/wiki/Hydrogen_sulfide). [Organosulfur compounds](/wiki/Organosulfur_compound), undesirable impurities in petroleum, may be upgraded by subjecting them to [hydrodesulfurization](/wiki/Hydrodesulfurization), which cleaves the C–S bonds:[[23]](#cite_note-23)[[24]](#cite_note-24):R-S-R + 2 H2 → 2 RH + H2S The resulting hydrogen sulfide from this process, and also as it occurs in natural gas, is converted into elemental sulfur by the [Claus process](/wiki/Claus_process). This process entails oxidation of some hydrogen sulfide to sulfur dioxide and then the [comproportionation](/wiki/Comproportionation) of the two:[[23]](#cite_note-23)[[24]](#cite_note-24):3 O2 + 2 H2S → 2 SO2 + 2 H2O

SO2 + 2 H2S → 3 S + 2 H2O

[thumb|Production and price (US market) of elemental sulfur](/wiki/File:SulfurPrice.png) Owing to the high sulfur content of the [Athabasca Oil Sands](/wiki/Athabasca_Oil_Sands), stockpiles of elemental sulfur from this process now exist throughout [Alberta](/wiki/Alberta), Canada.[[25]](#cite_note-25) Another way of storing sulfur is as a [binder](/wiki/Binder_(material)) for concrete, the resulting product having many desirable properties (see [sulfur concrete](/wiki/Sulfur_concrete)).[[26]](#cite_note-26) Sulfur is still mined from surface deposits in poorer nations with volcanoes, such as Indonesia, and worker conditions have not improved much since Booker T. Washington's days.[[27]](#cite_note-27) The world production of sulfur in 2011 amounted to 69 million tonnes (Mt), with more than 15 countries contributing more than 1 Mt each. Countries producing more than 5 Mt are China (9.6), US (8.8), Canada (7.1) and Russia (7.1).[[28]](#cite_note-28) Production has been slowly increasing from 1900 to 2010; the price was unstable in the 1980s and around 2010.<ref name=USGS/>

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

[Template:Category see also](/wiki/Template:Category_see_also)

Common [oxidation states](/wiki/Oxidation_state) of sulfur range from −2 to +6. Sulfur forms stable compounds with all elements except the [noble gases](/wiki/Noble_gas).

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

Sulfur [polycations](/wiki/Polycation), S82+, S42+ and S162+ are produced when sulfur is reacted with mild oxidising agents in a strongly acidic solution.[[29]](#cite_note-29) The colored solutions produced by dissolving sulfur in [oleum](/wiki/Oleum) were first reported as early as 1804 by C.F Bucholz, but the cause of the color and the structure of the polycations involved was only determined in the late 1960s. S82+ is deep blue, S42+ is yellow and S162+ is red.[[7]](#cite_note-7)

### Sulfides[[edit](/index.php?title=(none)&action=edit&section=11)]

Treatment of sulfur with hydrogen gives [hydrogen sulfide](/wiki/Hydrogen_sulfide). When dissolved in water, hydrogen sulfide is mildly acidic:<ref name=Greenwd>Greenwood, N. N.; & Earnshaw, A. (1997). Chemistry of the Elements (2nd ed.), Oxford:Butterworth-Heinemann. ISBN 0-7506-3365-4.</ref>

H2S [Template:Eqm](/wiki/Template:Eqm) HS− + H+

Hydrogen sulfide gas and the hydrosulfide anion are extremely toxic to mammals, due to their inhibition of the oxygen-carrying capacity of hemoglobin and certain [cytochromes](/wiki/Cytochrome) in a manner analogous to [cyanide](/wiki/Cyanide) and [azide](/wiki/Azide) (see below, under *precautions*).

Reduction of elemental sulfur gives [polysulfides](/wiki/Polysulfide), which consist of chains of sulfur atoms terminated with S− centers:

2 Na + S8 → Na2S8

This reaction highlights a distinctive property of sulfur: its ability to [catenate](/wiki/Catenation) (bind to itself by formation of chains). [Protonation](/wiki/Protonation) of these polysulfide anions produces the [polysulfanes](/wiki/Polysulfane), H2Sx where x = 2, 3, and 4.[[30]](#cite_note-30) Ultimately, reduction of sulfur produces sulfide salts:

16 Na + S8 → 8 Na2S

The interconversion of these species is exploited in the [sodium-sulfur battery](/wiki/Sodium-sulfur_battery).

The [radical anion](/wiki/Trisulfur) S3− gives the blue color of the mineral [lapis lazuli](/wiki/Lapis_lazuli). [thumb|upright|](/wiki/File:Lapis_lazuli_block.jpg)[Lapis lazuli](/wiki/Lapis_lazuli) owes its blue color to a [trisulfur](/wiki/Trisulfur) radical anion ([Template:Chem](/wiki/Template:Chem)) [thumb|Two parallel sulfur chains grown inside a single-wall](/wiki/File:S@CNT.jpg) [carbon nanotube](/wiki/Carbon_nanotube) (CNT, a). Zig-zag (b) and straight (c) S chains inside double-wall CNTs.[[31]](#cite_note-31)

### Oxides, oxoacids and oxoanions[[edit](/index.php?title=(none)&action=edit&section=12)]

The principal sulfur oxides are obtained by burning sulfur:

S + O2 → SO2

2 SO2 + O2 → 2 SO3

Multiple sulfur oxides are known; the [sulfur-rich oxides](/wiki/Lower_sulfur_oxides) include sulfur monoxide, disulfur monoxide, disulfur dioxides, and [higher oxides](/wiki/Higher_sulfur_oxides) containing peroxo groups.

Sulfur forms [sulfur oxoacids](/wiki/Oxoacids), some of which cannot be isolated and are only known through the salts. Sulfur dioxide and [sulfites](/wiki/Sulfite) ([Template:Chem](/wiki/Template:Chem)) are related to the unstable sulfurous acid (H2SO3). [Sulfur trioxide](/wiki/Sulfur_trioxide) and [sulfates](/wiki/Sulfate) ([Template:Chem](/wiki/Template:Chem)) are related to [sulfuric acid](/wiki/Sulfuric_acid). Sulfuric acid and SO3 combine to give oleum, a solution of [pyrosulfuric acid](/wiki/Pyrosulfuric_acid) (H2S2O7) in sulfuric acid.

[Thiosulfate](/wiki/Thiosulfate) salts ([Template:Chem](/wiki/Template:Chem)), sometimes referred as "hyposulfites", used in [photographic fixing](/wiki/Photographic_fixer) (hypo) and as reducing agents, feature sulfur in two oxidation states. [Sodium dithionite](/wiki/Sodium_dithionite) ([Template:Chem](/wiki/Template:Chem)), contains the more highly reducing [dithionite](/wiki/Dithionite) anion ([Template:Chem](/wiki/Template:Chem)).

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

Several sulfur halides are important to modern industry. S[ulfur hexafluoride](/wiki/Sulfur_hexafluoride) is a dense gas used as an [insulator gas](/wiki/Dielectric_gas) in high voltage [transformers](/wiki/Transformers); it is also a nonreactive and nontoxic propellant for pressurized containers. [Sulfur tetrafluoride](/wiki/Sulfur_tetrafluoride) is rarely used organic reagent that and is highly toxic.[[32]](#cite_note-32) [Sulfur dichloride](/wiki/Sulfur_dichloride) and [disulfur dichloride](/wiki/Disulfur_dichloride) are important industrial chemicals. [Sulfuryl chloride](/wiki/Sulfuryl_chloride) and [chlorosulfuric acid](/wiki/Chlorosulfuric_acid) are derivatives of sulfuric acid; [thionyl chloride](/wiki/Thionyl_chloride) (SOCl2) is a common reagent in [organic synthesis](/wiki/Organic_synthesis).[[33]](#cite_note-33)

### Pnictides[[edit](/index.php?title=(none)&action=edit&section=14)]

An important S–N compound is the cage [tetrasulfur tetranitride](/wiki/Tetrasulfur_tetranitride) (S4N4). Heating this compound gives [polymeric sulfur nitride](/wiki/Polythiazyl) ((SN)x), which has metallic properties even though it does not contain any [metal](/wiki/Metal) atoms. [Thiocyanates](/wiki/Thiocyanate) contain the SCN− group. Oxidation of thiocyanate gives [thiocyanogen](/wiki/Thiocyanogen), (SCN)2 with the connectivity NCS-SCN. [Phosphorus sulfides](/wiki/Phosphorus_sulfide) are numerous, the most important commercially being the cages P4S10 and P4S3.[[34]](#cite_note-34)<ref name=Chivers>[Template:Cite book](/wiki/Template:Cite_book)</ref>

### Metal sulfides[[edit](/index.php?title=(none)&action=edit&section=15)]

[Template:Main article](/wiki/Template:Main_article) The principal ores of copper, zinc, nickel, cobalt, molybdenum, and other metals are sulfides. These materials tend to be dark-colored [semiconductors](/wiki/Semiconductor) that are not readily attacked by water or even many acids. They are formed, both [geochemically](/wiki/Geochemical_cycle) and in the laboratory, by the reaction of hydrogen sulfide with metal salts. The mineral [galena](/wiki/Galena) (PbS) was the first demonstrated semiconductor and was used as a signal [rectifier](/wiki/Rectifier) in the [cat's whiskers](/wiki/Cat's-whisker_detector) of early [crystal radios](/wiki/Crystal_radio). The iron sulfide called [pyrite](/wiki/Pyrite), the so-called "fool's gold," has the formula FeS2.[[35]](#cite_note-35) Processing these ores, usually by [roasting](/wiki/Smelting), is costly and environmentally hazardous. Sulfur corrodes many metals through [tarnishing](/wiki/Tarnishing).

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

[Template:Main article](/wiki/Template:Main_article) <gallery caption="Illustrative organosulfur compounds"> File:R-allicin-2D-skeletal.png|[Allicin](/wiki/Allicin), the active ingredient in garlic File:Cysteine.svg| (*R*)-[cysteine](/wiki/Cysteine), an [amino acid](/wiki/Amino_acid) containing a thiol group File:Methionin - Methionine.svg|[Methionine](/wiki/Methionine), an [amino acid](/wiki/Amino_acid) containing a thioether File:Diphenyl disulfide.png|[Diphenyl disulfide](/wiki/Diphenyl_disulfide), a representative disulfide File:Perfluorooctanesulfonic acid.png|[Perfluorooctanesulfonic acid](/wiki/Perfluorooctanesulfonic_acid), a controversial surfactant File:Dibenzothiophen - Dibenzothiophene.svg|[Dibenzothiophene](/wiki/Dibenzothiophene), a component of crude oil File:Penicillin core.svg|[Penicillin](/wiki/Penicillin) an antibiotic where "R" is the variable group </gallery>

Some of the main classes of sulfur-containing organic compounds include the following:<ref name=Cremlyn>Cremlyn R. J.; "An Introduction to Organosulfur Chemistry" John Wiley and Sons: Chichester (1996). ISBN 0-471-95512-4.</ref>

* [Thiols](/wiki/Thiol) or mercaptans (so called because they capture mercury as [chelators](/wiki/Chelation)) are the sulfur analogs of [alcohols](/wiki/Alcohol); treatment of thiols with base gives [thiolate](/wiki/Thiolate) ions.
* [Thioethers](/wiki/Thioether) are the sulfur analogs of [ethers](/wiki/Ether).
* [Sulfonium](/wiki/Sulfonium) ions have three groups attached to a cationic sulfur center. [Dimethylsulfoniopropionate](/wiki/Dimethylsulfoniopropionate) (DMSP) is one such compound, important in the marine organic [sulfur cycle](/wiki/Sulfur_cycle).
* [Sulfoxides](/wiki/Sulfoxide) and [sulfones](/wiki/Sulfone) are thioethers with one and two oxygen atoms attached to the sulfur atom, respectively. The simplest sulfoxide, [dimethyl sulfoxide](/wiki/Dimethyl_sulfoxide), is a common solvent; a common sulfone is [sulfolane](/wiki/Sulfolane).
* [Sulfonic acids](/wiki/Sulfonic_acid) are used in many detergents.

Compounds with carbon-sulfur multiple bonds are uncommon, an exception being [carbon disulfide](/wiki/Carbon_disulfide), a volatile colorless liquid that is structurally similar to carbon dioxide. It is used as a reagent to make the polymer [rayon](/wiki/Rayon) and many organosulfur compounds. Unlike [carbon monoxide](/wiki/Carbon_monoxide), [carbon monosulfide](/wiki/Carbon_monosulfide) is stable only as an extremely dilute gas, found between solar systems.[[36]](#cite_note-36) Organosulfur compounds are responsible for some of the unpleasant odors of decaying organic matter. They are widely known as the [odorant](/wiki/Odorizer) in domestic natural gas, garlic odor, and skunk spray. Not all organic sulfur compounds smell unpleasant at all concentrations: the sulfur-containing [monoterpenoid](/wiki/Terpene) ([grapefruit mercaptan](/wiki/Grapefruit_mercaptan)) in small concentrations is the characteristic scent of grapefruit, but has a generic thiol odor at larger concentrations. [Sulfur mustard](/wiki/Sulfur_mustard), a potent [vesicant](/wiki/Blister_agent), was [used in World War I](/wiki/Chemical_weapons_in_World_War_I) as a disabling agent.[[37]](#cite_note-37) Sulfur-sulfur bonds are a structural component used to stiffen rubber, similar to the disulfide bridges that rigidify proteins (see biological below). In the most common type of industrial "curing" or hardening and strengthening of natural [rubber](/wiki/Rubber), elemental sulfur is heated with the rubber to the point that chemical reactions form [disulfide](/wiki/Disulfide) bridges between [isoprene](/wiki/Isoprene) units of the polymer. This process, patented in 1843, made rubber a major industrial product, especially in automobile tires. Because of the heat and sulfur, the process was named [vulcanization](/wiki/Vulcanization), after the Roman god of the forge and [volcanism](/wiki/Volcanism).

## History[[edit](/index.php?title=(none)&action=edit&section=17)]

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

[thumb|Pharmaceutical container for sulfur from the first half of the 20th century. From the](/wiki/File:MODOAzufre.jpg) [Museo del Objeto del Objeto](/wiki/Museo_del_Objeto_del_Objeto) collection

Being abundantly available in native form, sulfur was known in ancient times and is referred to in the [Torah](/wiki/Torah) ([Genesis](/wiki/Book_of_Genesis)). [English translations of the Bible](/wiki/English_translations_of_the_Bible) commonly referred to burning sulfur as "brimstone", giving rise to the term "[fire-and-brimstone](/wiki/Fire_and_brimstone)" [sermons](/wiki/Sermon), in which listeners are reminded of the fate of [eternal damnation](/wiki/Damnation) that await the unbelieving and unrepentant. It is from this part of the Bible that [Hell](/wiki/Hell) is implied to "smell of sulfur" (likely due to its association with volcanic activity). According to the [Ebers Papyrus](/wiki/Ebers_Papyrus), a sulfur ointment was used in ancient [Egypt](/wiki/Egypt) to treat granular eyelids. Sulfur was used for fumigation in preclassical [Greece](/wiki/Greece);[[38]](#cite_note-38) this is mentioned in the [*Odyssey*](/wiki/Odyssey).[[39]](#cite_note-39) [Pliny the Elder](/wiki/Pliny_the_Elder) discusses sulfur in book 35 of his [*Natural History*](/wiki/Natural_History_(Pliny)), saying that its best-known source is the island of [Melos](/wiki/Melos). He mentions its use for fumigation, medicine, and bleaching cloth.[[40]](#cite_note-40) A natural form of sulfur known as *shiliuhuang* (石硫黄) was known in China since the 6th century BC and found in [Hanzhong](/wiki/Hanzhong).[[41]](#cite_note-41) By the 3rd century, the Chinese discovered that sulfur could be extracted from [pyrite](/wiki/Pyrite).[[41]](#cite_note-41) Chinese [Daoists](/wiki/Daoists) were interested in sulfur's flammability and its reactivity with certain metals, yet its earliest practical uses were found in [traditional Chinese medicine](/wiki/Traditional_Chinese_medicine).[[41]](#cite_note-41) A [Song dynasty](/wiki/Song_dynasty) military treatise of 1044 AD described different formulas for Chinese [black powder](/wiki/Black_powder), which is a mixture of [potassium nitrate](/wiki/Potassium_nitrate) ([Template:Chem](/wiki/Template:Chem)), [charcoal](/wiki/Charcoal), and sulfur. It remains an ingredient of [black gunpowder](/wiki/Gunpowder).

Indian alchemists, practitioners of "the science of mercury" ([sanskrit](/wiki/Sanskrit) rasaśāstra, रसशास्त्र), wrote extensively about the use of sulfur in alchemical operations with mercury, from the eighth century AD onwards.<ref name=white-alchemical>[Template:Cite book](/wiki/Template:Cite_book)</ref> In the [rasaśāstra](/wiki/Rasa_shastra) tradition, sulfur is called "the smelly" (sanskrit gandhaka, गन्धक).

Early [European](/wiki/Europe) [alchemists](/wiki/Alchemy) gave sulfur a unique [alchemical symbol](/wiki/Alchemical_symbol), a triangle at the top of a cross ([20px](/wiki/File:Sulphur.svg), but also [20px](/wiki/File:Sulfur_symbol_1_2.svg) in use.). In traditional skin treatment, elemental sulfur was used (mainly in creams) to alleviate such conditions as [scabies](/wiki/Scabies), [ringworm](/wiki/Ringworm), [psoriasis](/wiki/Psoriasis), [eczema](/wiki/Eczema), and [acne](/wiki/Acne). The mechanism of action is unknown—though elemental sulfur does oxidize slowly to sulfurous acid, which is (through the action of [sulfite](/wiki/Sulfite)) a mild reducing and antibacterial agent.[[42]](#cite_note-42)[[43]](#cite_note-43)[[44]](#cite_note-44)

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

[thumb|Sicilian kiln used to obtain sulfur from volcanic rock.](/wiki/File:Soufre_extraction_1.jpg) In 1777, [Antoine Lavoisier](/wiki/Antoine_Lavoisier) helped convince the scientific community that sulfur was an element, not a compound.

Sulfur deposits in [Sicily](/wiki/Sicily) were the dominant source for more than a century. By the late 18th century, about 2,000 tons per year of sulfur were imported into [Marseilles](/wiki/Marseilles), France for the production of [sulfuric acid](/wiki/Sulfuric_acid) by the [Leblanc process](/wiki/Leblanc_process). In [industrializing](/wiki/Industrial_Revolution) Britain, with the repeal of [tariffs](/wiki/Tariff) on salt in 1824, demand for sulfur from Sicily surged upward. The increasing British control and exploitation of the mining, refining, and transportation of the sulfur, coupled with the failure of this lucrative export to transform Sicily's backward and impoverished economy, led to the 'Sulfur Crisis' of 1840, when [King Ferdinand II](/wiki/Ferdinand_II_of_the_Two_Sicilies) gave a monopoly of the sulfur industry to a French firm, violating an earlier 1816 trade agreement with Britain. A peaceful solution was eventually negotiated by France.[[45]](#cite_note-45)[[46]](#cite_note-46) In 1867, sulfur was discovered in underground deposits in [Louisiana](/wiki/Louisiana) and [Texas](/wiki/Texas). The highly successful [Frasch process](/wiki/Frasch_process) was developed to extract this resource.[[47]](#cite_note-47) In the late 18th century, [furniture](/wiki/Furniture) makers used molten sulfur to produce decorative [inlays](/wiki/Inlay) in their craft. Because of the [sulfur dioxide](/wiki/Sulfur_dioxide) produced during the process of melting sulfur, the craft of sulfur inlays was soon abandoned. Molten sulfur is sometimes still used for setting steel bolts into drilled concrete holes where high shock resistance is desired for floor-mounted equipment attachment points. Pure powdered sulfur was used as a medicinal tonic and laxative.<ref name=Nehb/> With the advent of the [contact process](/wiki/Contact_process), the majority of sulfur today is used to make [sulfuric acid](/wiki/Sulfuric_acid) for a wide range of uses, particularly fertilizer.[[48]](#cite_note-48)

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

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

Elemental sulfur is used mainly as a precursor to other chemicals. Approximately 85% (1989) is converted to [sulfuric acid](/wiki/Sulfuric_acid) ([H](/wiki/Hydrogen)2SO4):

2 S + 3 O2 + 2 H2O → 2 H2SO4[thumb|Sulfuric acid production in 2000](/wiki/File:2000sulphuric_acid.PNG)

Because of its importance, sulfuric acid was considered an excellent indicator of a country's industrial well-being.[[49]](#cite_note-49) For example, with 32.5 million tonnes in 2010, the United States produces more sulfuric acid every year than any other inorganic industrial chemical.<ref name=USGS>[Template:Cite web](/wiki/Template:Cite_web)</ref> The principal use for the acid is the extraction of phosphate ores for the production of fertilizer manufacturing. Other applications of sulfuric acid include oil refining, wastewater processing, and mineral extraction.<ref name=Nehb/>

### Other important sulfur chemistry[[edit](/index.php?title=(none)&action=edit&section=22)]

Sulfur reacts directly with methane to give [carbon disulfide](/wiki/Carbon_disulfide), used to manufacture [cellophane](/wiki/Cellophane) and [rayon](/wiki/Rayon).<ref name=Nehb>[Template:Cite book](/wiki/Template:Cite_book)</ref> One of the direct uses of sulfur is in [vulcanization](/wiki/Vulcanization) of rubber, where [polysulfide](/wiki/Polysulfide) chains crosslink organic polymers. Large quantities of [sulfites](/wiki/Sulfite) are used to [bleach](/wiki/Bleach_(chemical)) [paper](/wiki/Paper) and to preserve dried [fruit](/wiki/Fruit). Many [surfactants](/wiki/Surfactant) and [detergents](/wiki/Detergents) (e.g. [sodium lauryl sulfate](/wiki/Sodium_lauryl_sulfate)) are sulfate derivatives. [Calcium sulfate](/wiki/Calcium_sulfate), gypsum, (CaSO4·2H2O) is mined on the scale of 100 million tons each year for use in [Portland cement](/wiki/Portland_cement) and fertilizers.

When silver-based [photography](/wiki/Photography) was widespread, sodium and ammonium [thiosulfate](/wiki/Sodium_thiosulfate) were widely used as "fixing agents." Sulfur is a component of [gunpowder](/wiki/Gunpowder) ("black powder").

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

Sulfur is increasingly used as a component of [fertilizers](/wiki/Fertilizer). The most important form of sulfur for fertilizer is the mineral [calcium sulfate](/wiki/Calcium_sulfate). Elemental sulfur is [hydrophobic](/wiki/Hydrophobic) (not soluble in water) and cannot be used directly by plants. Over time, soil bacteria can convert it to soluble derivatives, which can then be used by plants. Sulfur improves the efficiency of other essential plant nutrients, particularly nitrogen and phosphorus.[[50]](#cite_note-50) Biologically produced sulfur particles are naturally hydrophilic due to a biopolymer coating and are easier to disperse over the land in a spray of diluted slurry, resulting in a faster update.

The botanical requirement for sulfur equals or exceeds the requirement for phosphorus. It is an essential nutrient for plant growth, root nodule formation of legumes, and immunity and defense systems. Sulfur deficiency has become widespread in many countries in Europe.[[51]](#cite_note-51)[[52]](#cite_note-52)[[53]](#cite_note-53) Because atmospheric inputs of sulfur continue to decrease, the deficit in the sulfur input/output is likely to increase unless sulfur fertilizers are used.

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

[thumb|left|A molecular model of the pesticide](/wiki/File:Malathion-3D-vdW.png) [malathion](/wiki/Malathion). Organosulfur compounds are used in [pharmaceuticals](/wiki/Pharmaceutical), [dyestuffs](/wiki/Dyestuff), and agrochemicals. Many drugs contain sulfur, early examples being antibacterial [sulfonamides](/wiki/Sulfonamide_(medicine)), known as *sulfa drugs*. Sulfur is a part of many bacterial defense molecules. Most [β-lactam](/wiki/Β-lactam) antibiotics, including the [penicillins](/wiki/Penicillin), [cephalosporins](/wiki/Cephalosporins) and [monolactams](/wiki/Monolactam) contain sulfur.<ref name=Cremlyn/>

[Magnesium sulfate](/wiki/Magnesium_sulfate), known as Epsom salts when in hydrated crystal form, can be used as a [laxative](/wiki/Laxative), a bath additive, an [exfoliant](/wiki/Exfoliant), [magnesium](/wiki/Magnesium) supplement for plants, or (when in dehydrated form) as a [desiccant](/wiki/Desiccant).

### Fungicide and pesticide[[edit](/index.php?title=(none)&action=edit&section=25)]

[thumb|upright|Sulfur candle originally sold for home fumigation](/wiki/File:Sulphur_Candle.jpg) Elemental sulfur is one of the oldest fungicides and pesticides. "Dusting sulfur," elemental sulfur in powdered form, is a common fungicide for grapes, strawberry, many vegetables and several other crops. It has a good efficacy against a wide range of powdery mildew diseases as well as black spot. In organic production, sulfur is the most important fungicide. It is the only fungicide used in [organically](/wiki/Organic_agriculture) farmed apple production against the main disease [apple scab](/wiki/Apple_scab) under colder conditions. Biosulfur (biologically produced elemental sulfur with hydrophilic characteristics) can also be used for these applications.

Standard-formulation dusting sulfur is applied to crops with a sulfur duster or from a dusting plane. Wettable sulfur is the commercial name for dusting sulfur formulated with additional ingredients to make it water [miscible](/wiki/Miscibility).[[54]](#cite_note-54)[[55]](#cite_note-55) It has similar applications and is used as a [fungicide](/wiki/Fungicide) against [mildew](/wiki/Mildew) and other mold-related problems with plants and soil.

Elemental sulfur powder is used as an "[organic](/wiki/Organic_farming)" (i.e. "green") [insecticide](/wiki/Insecticide) (actually an [acaricide](/wiki/Acaricide)) against [ticks](/wiki/Tick) and [mites](/wiki/Mites). A common method of application is dusting the clothing or limbs with sulfur powder.

A diluted solution of [lime sulfur](/wiki/Lime_sulfur) (made by combining [calcium hydroxide](/wiki/Calcium_hydroxide) with elemental sulfur in water) is used as a dip for pets to destroy [ringworm (fungus)](/wiki/Ringworm), [mange](/wiki/Mange), and other [dermatoses](/wiki/Cutaneous_conditions) and [parasites](/wiki/Parasitism).

Sulfur candles of almost pure sulfur are burned to [fumigate](/wiki/Fumigant) structures and wine barrels, but are now considered too toxic for residences.

### Bactericide in winemaking and food preservation[[edit](/index.php?title=(none)&action=edit&section=26)]

Small amounts of [sulfur dioxide](/wiki/Sulfur_dioxide) gas addition (or equivalent [potassium metabisulfite](/wiki/Potassium_metabisulfite) addition) to fermented wine to produce traces of [sulfurous acid](/wiki/Sulfurous_acid) (produced when SO2 reacts with water) and its [sulfite](/wiki/Sulfite) salts in the mixture, has been called "the most powerful tool in winemaking."[[56]](#cite_note-56) After the yeast-fermentation stage in [winemaking](/wiki/Winemaking), sulfites absorb oxygen and inhibit [aerobic](/wiki/Aerobic_organism) bacterial growth that otherwise would turn ethanol into acetic acid, souring the wine. Without this preservative step, indefinite refrigeration of the product before consumption is usually required. Similar methods go back into antiquity but modern historical mentions of the practice go to the fifteenth century. The practice is used by large industrial wine producers and small organic wine producers alike.

Sulfur dioxide and various sulfites have been used for their antioxidant antibacterial preservative properties in many other parts of the food industry. The practice has declined since reports of an allergy-like reaction of some persons to sulfites in foods.

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

[Template:Infobox drug](/wiki/Template:Infobox_drug) Sulfur (specifically [octasulfur](/wiki/Octasulfur), S8) is used in pharmaceutical skin preparations for the treatment of [acne](/wiki/Acne) and other conditions. It acts as a [keratolytic](/wiki/Keratolytic) agent and also kills bacteria, fungi, [scabies](/wiki/Scabies) mites and other parasites.[[57]](#cite_note-57) Precipitated sulfur and colloidal sulfur are used, in form of [lotions](/wiki/Lotion), creams, powders, soaps, and bath additives, for the treatment of [acne vulgaris](/wiki/Acne_vulgaris), [acne rosacea](/wiki/Acne_rosacea), and [seborrhoeic dermatitis](/wiki/Seborrhoeic_dermatitis).[[58]](#cite_note-58) Common adverse effects include irritation of the skin at the application site, such as dryness, stinging, itching and peeling.[[59]](#cite_note-59)

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

[Template:Expand section](/wiki/Template:Expand_section) Sulfur is converted to hydrogen sulfide (H2S) through [reduction](/wiki/Redox), partly by bacteria. H2S kills bacteria (possibly including [*Propionibacterium acnes*](/wiki/Propionibacterium_acnes) which plays a role in acne,[[60]](#cite_note-60)) fungi, and parasites such as scabies mites.[[57]](#cite_note-57)

## Biological role[[edit](/index.php?title=(none)&action=edit&section=29)]

### Protein and organic cofactors[[edit](/index.php?title=(none)&action=edit&section=30)]

Sulfur is an essential component of all living [cells](/wiki/Cell_(biology)). It is the seventh or eighth most abundant element in the human body by weight, about equal in abundance to [potassium](/wiki/Potassium), and slightly greater than sodium and chlorine. A [Template:Convert](/wiki/Template:Convert) human body contains about 140 grams of sulfur.

In [plants](/wiki/Plant) and [animals](/wiki/Animal), the [amino acids](/wiki/Amino_acid) [cysteine](/wiki/Cysteine) and [methionine](/wiki/Methionine) contain most of the sulfur, and the element is present in all [polypeptides](/wiki/Polypeptide), [proteins](/wiki/Protein), and [enzymes](/wiki/Enzyme) that contain these amino acids. In humans, methionine is an essential amino acid that must be ingested. However, save for the vitamins [biotin](/wiki/Biotin) and [thiamine](/wiki/Thiamine), cysteine and all sulfur-containing compounds in the human body can be synthesized from methionine. The enzyme [sulfite oxidase](/wiki/Sulfite_oxidase) is needed for the metabolism of methionine and cysteine in humans and animals.

[Disulfide bonds](/wiki/Disulfide_bond) (S-S bonds) between cysteine residues in peptide chains are very important in protein assembly and structure. These covalent bonds between peptide chains confer extra toughness and rigidity.<ref name=Lehn/> For example, the high strength of feathers and hair is due in part to the high content of S-S bonds with cysteine and sulfur. Eggs are high in sulfur to nourish feather formation in chicks, and the characteristic odor of rotting eggs is due to [hydrogen sulfide](/wiki/Hydrogen_sulfide). The high disulfide bond content of hair and feathers contributes to their indigestibility and to their characteristic disagreeable odor when burned.

[Homocysteine](/wiki/Homocysteine) and [taurine](/wiki/Taurine) are other sulfur-containing acids that are similar in structure, but not coded by [DNA](/wiki/DNA), and are not part of the [primary structure](/wiki/Primary_structure) of proteins. Many important cellular enzymes use prosthetic groups ending with -SH moieties to handle reactions involving acyl-containing biochemicals: two common examples from basic metabolism are [coenzyme A](/wiki/Coenzyme_A) and [alpha-lipoic acid](/wiki/Alpha-lipoic_acid).<ref name=Lehn>[Template:Cite book](/wiki/Template:Cite_book)</ref> Two of the 13 classical vitamins, [biotin](/wiki/Biotin) and [thiamine](/wiki/Thiamine), contain sulfur, with the latter being named for its sulfur content.

In intracellular chemistry, sulfur operates as a carrier of reducing hydrogen and its electrons for cellular repair of oxidation. Reduced [glutathione](/wiki/Glutathione), a sulfur-containing tripeptide, is a reducing agent through its sulfhydryl (-SH) moiety derived from [cysteine](/wiki/Cysteine). The [thioredoxins](/wiki/Thioredoxin), a class of small proteins essential to all known life, use neighboring pairs of reduced cysteines to work as general protein reducing agents, with similar effect.

[Methanogenesis](/wiki/Methanogenesis), the route to most of the world's methane, is a multistep biochemical transformation of [carbon dioxide](/wiki/Carbon_dioxide). This conversion requires several organosulfur cofactors. These include [coenzyme M](/wiki/Coenzyme_M), CH3SCH2CH2SO3−, the immediate precursor to [methane](/wiki/Methane).[[61]](#cite_note-61)

### Metalloproteins and inorganic cofactors[[edit](/index.php?title=(none)&action=edit&section=31)]

Inorganic sulfur forms a part of [iron-sulfur clusters](/wiki/Iron-sulfur_cluster) as well as many copper, nickel, and iron proteins. Most pervasive are the ferrodoxins, which serve as electron shuttles in cells. In bacteria, the important [nitrogenase](/wiki/Nitrogenase) enzymes contains an Fe-Mo-S cluster, is a [catalyst](/wiki/Catalyst) that performs the important function of [nitrogen fixation](/wiki/Nitrogen_fixation), converting atmospheric nitrogen to ammonia that can be used by microorganisms and plants to make proteins, DNA, RNA, alkaloids, and the other organic nitrogen compounds necessary for life.[[62]](#cite_note-62):[center|500px](/wiki/File:FdRedox.png)

### Sulfur metabolism and the sulfur cycle[[edit](/index.php?title=(none)&action=edit&section=32)]

[Template:Main article](/wiki/Template:Main_article) The sulfur cycle was the first of the [biogeochemical cycles](/wiki/Biogeochemical_cycle) to be discovered. In the 1880s, while studying [Beggiatoa](/wiki/Beggiatoa) (a bacterium living in a sulfur rich environment), [Sergei Winogradsky](/wiki/Sergei_Winogradsky) found that it oxidized [hydrogen sulfide](/wiki/Hydrogen_sulfide) (H2S) as an energy source, forming intracellular sulfur droplets. Winogradsky referred to this form of metabolism as inorgoxidation (oxidation of inorganic compounds). He continued to study it together with [Selman Waksman](/wiki/Selman_Waksman) until the 1950s.

Sulfur oxidizers can use as energy sources reduced sulfur compounds, including hydrogen sulfide, elemental sulfur, [sulfite](/wiki/Sulfite), [thiosulfate](/wiki/Thiosulfate), and various polythionates (e.g., [tetrathionate](/wiki/Tetrathionate)).[[63]](#cite_note-63) They depend on enzymes such as [sulfur oxygenase](/wiki/Sulfur_dioxygenase) and [sulfite oxidase](/wiki/Sulfite_oxidase) to oxidize sulfur to sulfate. Some [lithotrophs](/wiki/Lithotroph) can even use the energy contained in sulfur compounds to produce sugars, a process known as [chemosynthesis](/wiki/Chemosynthesis). Some [bacteria](/wiki/Bacteria) and [archaea](/wiki/Archaea) use hydrogen sulfide in place of water as the [electron donor](/wiki/Electron_donor) in chemosynthesis, a process similar to [photosynthesis](/wiki/Photosynthesis) that produces sugars and utilizes oxygen as the [electron acceptor](/wiki/Electron_acceptor). The [photosynthetic](/wiki/Photosynthesis) [green sulfur bacteria](/wiki/Green_sulfur_bacteria) and [purple sulfur bacteria](/wiki/Purple_sulfur_bacteria) and some [lithotrophs](/wiki/Lithotroph) use elemental oxygen to carry out such oxidization of hydrogen sulfide to produce elemental sulfur (S0), oxidation state = 0. Primitive bacteria that live around deep ocean [volcanic vents](/wiki/Hydrothermal_vent) oxidize hydrogen sulfide in this way with oxygen; the [giant tube worm](/wiki/Giant_tube_worm) is an example of a large organism that uses hydrogen sulfide (via bacteria) as food to be oxidized.

The so-called [sulfate-reducing bacteria](/wiki/Sulfate-reducing_bacteria), by contrast, "breathe sulfate" instead of oxygen. They use organic compounds or molecular hydrogen as the energy source. They use sulfur as the electron acceptor, and reduce various oxidized sulfur compounds back into sulfide, often into hydrogen sulfide. They can grow on other partially oxidized sulfur compounds (e.g. thiosulfates, thionates, polysulfides, sulfites). The hydrogen sulfide produced by these bacteria is responsible for some of the smell of intestinal gases ([flatus](/wiki/Flatus)) and decomposition products.

Sulfur is absorbed by [plants](/wiki/Plant) [roots](/wiki/Root) from soil as [sulfate](/wiki/Sulfate) and transported as a phosphate ester. Sulfate is reduced to sulfide via sulfite before it is incorporated into [cysteine](/wiki/Cysteine) and other organosulfur compounds.[[64]](#cite_note-64):SO42− → SO32− → H2S → cysteine → methionine

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

[Template:Refimprove section](/wiki/Template:Refimprove_section) [Effect of acid rain on a forest, Jizera Mountains, Czech Republic|thumb](/wiki/File:Acid_rain_woods1.JPG) Elemental sulfur is non-toxic, as are most of the soluble [sulfate](/wiki/Sulfate) salts, such as [Epsom salts](/wiki/Epsom_salt). Soluble sulfate salts are poorly absorbed and laxative. When injected parenterally, they are freely filtered by the kidneys and eliminated with very little toxicity in multi-gram amounts.

When sulfur burns in air, it produces [sulfur dioxide](/wiki/Sulfur_dioxide). In water, this gas produces sulfurous acid and sulfites; sulfites are antioxidants that inhibit growth of aerobic bacteria and a useful [food additive](/wiki/Food_additive) in small amounts. At high concentrations these acids harm the [lungs](/wiki/Human_lungs), [eyes](/wiki/Human_eyes) or other [tissues](/wiki/Biological_tissue). In organisms without lungs such as insects or plants, sulfite in high concentration prevents [respiration](/wiki/Respiration_(physiology)).

[Sulfur trioxide](/wiki/Sulfur_trioxide) (made by catalysis from sulfur dioxide) and [sulfuric acid](/wiki/Sulfuric_acid) are similarly highly acidic and corrosive in the presence of water. Sulfuric acid is a strong dehydrating agent that can strip available water molecules and water components from sugar and organic tissue.[[65]](#cite_note-65) The burning of [coal](/wiki/Coal) and/or [petroleum](/wiki/Petroleum) by industry and [power plants](/wiki/Power_plants) generates sulfur dioxide (SO2) that reacts with atmospheric water and oxygen to produce sulfuric acid (H2SO4) and [sulfurous acid](/wiki/Sulfurous_acid) (H2SO3). These acids are components of [acid rain](/wiki/Acid_rain), lowering the [pH](/wiki/PH) of [soil](/wiki/Soil) and freshwater bodies, sometimes resulting in substantial damage to the [environment](/wiki/Environment_(biophysical)) and [chemical weathering](/wiki/Chemical_weathering) of statues and structures. Fuel standards increasingly require that fuel producers extract sulfur from [fossil fuels](/wiki/Fossil_fuel) to prevent acid rain formation. This extracted and refined sulfur represents a large portion of sulfur production. In coal-fired power plants, [flue gases](/wiki/Flue_gases) are sometimes purified. More modern power plants that use [synthesis gas](/wiki/Synthesis_gas) extract the sulfur before they burn the gas.

[Hydrogen sulfide](/wiki/Hydrogen_sulfide) is as [toxic](/wiki/Toxic) as [hydrogen cyanide](/wiki/Hydrogen_cyanide), and kills by the same mechanism (inhibition of the respiratory enzyme [cytochrome oxidase](/wiki/Cytochrome_oxidase)),[[66]](#cite_note-66) though hydrogen sulfide is less likely to cause surprise poisonings from small inhaled amounts because of its disagreeable odor. Hydrogen sulfide quickly deadens the sense of smell and a victim may breathe increasing quantities without noticing the increase until severe symptoms cause death. Dissolved [sulfide](/wiki/Sulfide) and [hydrosulfide](/wiki/Hydrosulfide) salts are toxic by the same mechanism.

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

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

* [Stratospheric sulfur aerosols](/wiki/Stratospheric_sulfur_aerosols)
* [Sulfur assimilation](/wiki/Sulfur_assimilation)
* [Ultra-low sulfur diesel](/wiki/Ultra-low_sulfur_diesel)

[Template:Colend](/wiki/Template:Colend) [Template:Subject bar](/wiki/Template:Subject_bar)

## References[[edit](/index.php?title=(none)&action=edit&section=35)]

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

## External links[[edit](/index.php?title=(none)&action=edit&section=36)]

* [Sulfur](http://www.periodicvideos.com/videos/016.htm) at [*The Periodic Table of Videos*](/wiki/The_Periodic_Table_of_Videos) (University of Nottingham)
* [Atomic Data for Sulfur](http://physics.nist.gov/PhysRefData/Handbook/Tables/sulfurtable1.htm), [NIST](/wiki/NIST) Physical Measurement Laboratory
* [Sulfur phase diagram](http://library.tedankara.k12.tr/chemistry/vol2/allotropy/z129.htm), Introduction to Chemistry For Ages 13–17
* [Crystalline, liquid and polymerization of sulfur on Vulcano Island, Italy](http://www.stromboli.net/perm/vulcano/sulphur-vulcano-en.html)
* [Sulfur and its use as a pesticide](http://extoxnet.orst.edu/pips/sulfur.htm)
* [The Sulphur Institute](http://www.sulphurinstitute.org/)
* [Nutrient Stewardship and The Sulphur Institute](http://www.nutrientstewardship.com/partners/products-and-services/sulfur-institute)

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

[Template:Sulfur compounds](/wiki/Template:Sulfur_compounds) [Template:Compact periodic table](/wiki/Template:Compact_periodic_table)

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

[Category:Sulfur](/wiki/Category:Sulfur) [Category:Chemical elements](/wiki/Category:Chemical_elements) [Category:Chalcogens](/wiki/Category:Chalcogens) [Category:Polyatomic nonmetals](/wiki/Category:Polyatomic_nonmetals) [Category:Native element minerals](/wiki/Category:Native_element_minerals) [Category:Dietary minerals](/wiki/Category:Dietary_minerals) [Category:Inorganic polymers](/wiki/Category:Inorganic_polymers) [Category:Pyrotechnic fuels](/wiki/Category:Pyrotechnic_fuels) [Category:Agricultural chemicals](/wiki/Category:Agricultural_chemicals) [Category:Biology and pharmacology of chemical elements](/wiki/Category:Biology_and_pharmacology_of_chemical_elements) [Category:Anti-acne preparations](/wiki/Category:Anti-acne_preparations) [Category:Orthorhombic minerals](/wiki/Category:Orthorhombic_minerals)