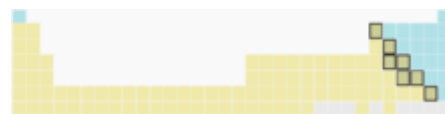


Properties of metals, metalloids and nonmetals

The chemical elements can be broadly divided into metals, metalloids and nonmetals according to their shared physical and chemical properties. All metals have a shiny appearance (at least when freshly polished); are good conductors of heat and electricity; form alloys with other metals; and have at least one basic oxide. Metalloids are metallic-looking brittle solids that are either semiconductors or exist in semiconducting forms, and have amphoteric or weakly acidic oxides. Typical nonmetals have a dull, coloured or colourless appearance; are brittle when solid; are poor conductors of heat and electricity; and have acidic oxides. Most or some elements in each category share a range of other properties; a few elements have properties that are either anomalous given their category or otherwise extraordinary



The periodic table showing:

metals in most of the left and centre;
metalloids in a narrow diagonal band
nonmetals in the right, and hydrogen

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Properties

Metals

Metals appear lustrous (beneath any patina); form mixtures (alloys) when combined with other metals; tend to lose or share electrons when they react with other substances; and each forms at least one predominantly basic oxide.

Most metals are silvery looking, high density, relatively soft and easily deformed solids with good electrical and thermal conductivity, closely packed structures low ionisation energies and electronegativities and are found naturally in combined states.

Some metals appear coloured (Cu, Cs, Au), have low densities (e.g. Be, Al) or very high melting points, are liquids at or near room temperature, are brittle (e.g. Os, Bi), not easily machined (e.g. Ti, Re), or are noble (hard to oxidise) or have nonmetallic structures (Mn and Ga are structurally analogous to, respectively white P and I).

Metals comprise the large majority of the elements, and can be subdivided into several different categories. From left to right in the periodic table, these categories include the highly reactive alkali metals; the less reactive alkaline earth metals, lanthanides and radioactive actinides; the archetypal transition metals, and the physically and chemically weak post-transition metals. Specialized subcategories such as the refractory metals and the noble metals also exist.



Pure (99.97%+) iron chips, electrolytically refined accompanied by a high purity (99.9999% = 6N) 1 cm³ cube

Metalloids



Tellurium, described by Dmitri Mendeleev as forming a transition between metals and nonmetals^[1]

Metalloids are metallic looking brittle solids; tend to share electrons when they react with other substances; have weakly acidic or amphoteric oxides; and are usually found naturally in combined states.

Most are semiconductors, and moderate thermal conductors, and have structures that are more open than those of most metals.

Some metalloids (As, Sb) conduct electricity like metals.

The metalloids, as the smallest major category of elements, are not subdivided further.

Nonmetals

Nonmetals have open structures (unless solidified from gaseous or liquid forms); tend to gain or share electrons when they react with other substances; and do not form distinctly basic oxides.

Most are gases at room temperature; have relatively low densities; are poor electrical and thermal conductors; have relatively high ionisation energies and electronegativities; form acidic oxides; and are found naturally in uncombined states in large amounts.

Some nonmetals (C, black P, S and Se) are brittle solids at room temperature (although each of these also have malleable, pliable or ductile allotropes).

From left to right in the periodic table, the nonmetals can be subdivided into the polyatomic nonmetals which, being nearest to the metalloids, show some incipient metallic character; the diatomic nonmetals, which are essentially nonmetallic; and the monatomic noble gases, which are almost completely inert.



25 ml of bromine, a dark red-brown liquid at room temperature

Comparison of properties

Overview

Number of metalloid properties that resemble metals or nonmetals (or that are reasonably distinct)				
Properties compared:	(36)	Resemble metals 7 (19%)	Relatively distinctive 25 (68%)	Resemble nonmetals 5 (13%)
Physical	(21)	5 (24%)	14 (67%)	2 (10%)

• Presentation & structure (10)	2	6	2
• Electron-related (6)	1	5	
• Thermodynamics (5)	2	3	
Chemical (16)	2 (13%)	11 (69%)	3 (19%)
• Elemental chemistry (6)		3	3
• Combined form chemistry (6)	2	4	
• Environmental chemistry (4)		4	

The characteristic properties of metals and nonmetals are quite distinct, as shown in the table below. Metalloids, straddling the metal-nonmetal border, are mostly distinct from either, but in a few properties resemble one or the other, as shown in the shading of the metalloid column below and summarized in the small table at the top of this section.

Authors differ in where they divide metals from nonmetals and in whether they recognize an intermediate metalloid category. Some authors count metalloids as nonmetals with weakly nonmetallic properties.^[n 1] Others count some of the metalloids as post-transition metals.^[n 2]

Detailed

Physical and chemical properties ^[n 3]			
	Metals ^[8]	Metalloids	Nonmetals ^[8]
Presentation and structure			
<u>Colour</u>	- nearly all are shiny and grey-white - Cu, Cs, Au: shiny and golden^[9]	shiny and grey-white^[10]	- most are colourless or dull red, yellow, green, or intermediate shades^[11] - C, P, Se, I: shiny and grey-white
<u>Reflectivity</u>	intermediate to typically high^{[12][13]}	intermediate^{[14][15]}	zero or low (mostly)^[16] to intermediate^[17]
<u>Form</u>	- almost all solid - Rb, Cs, Fr, Ga, Hg: liquid at/near <u>stp</u>^{[18][19][n 4]}	all solid^[10]	- most are gases^[21] - C, P, S, Se, I: solid; Br: liquid
<u>Density</u>	generally high, with some exceptions such as the <u>alkali metals</u>^[22]	lower than nearby <u>metals</u> but higher than nearby <u>nonmetals</u>^[23]	often low
<u>Deformability (as a solid)</u>	- most are <u>ductile</u> and malleable - some are brittle (Cr, Mn, Ga, Ru, W, Os, Bi)^{[24][n 5]}	<u>brittle</u>^[27]	- brittle, when solid - some (C, P, S, Se) have non-brittle forms^[n 6]
<u>Poisson's ratio</u> ^[n 7]	low to high^[n 8]	low to intermediate^[n 9]	low to intermediate^[n 10]
<u>Crystalline structure at freezing point</u> ^[47]	- most are <u>hexagonal</u> or <u>cubic</u> - Ga, U, Np: orthorhombic; In, Sn, Pa: tetragonal; Sm, Hg, Bi: rhombohedral; Pu: monoclinic	- B, As, Sb: rhombohedral - Si, Ge: cubic - Te: hexagonal	- H, He, C, N, Se: hexagonal - O, F, Ne, P, Ar, Kr, Xe, Rn: cubic - S, Cl, Br, I: orthorhombic
<u>Packing & coordination number</u>	- close-packed crystal structures^[48] - high coordination numbers	- relatively open crystal structures^[49] - medium coordination numbers^[50]	- open structures^[51] - low coordination numbers

Atomic radius (calculated) ^[52]	- intermediate to very large 112–298 pm, average 187	- small to intermediate: <u>B</u>, <u>Si</u>, <u>Ge</u>, <u>As</u>, <u>Sb</u>, <u>Te</u> 87–123 pm, average 115.5 pm	- very small to intermediate 31–120 pm, average 76.4 pm
Allotropes ^{[53][n 11]}	- around half form allotropes - one (<u>Sn</u>) has a metalloid-like allotrope (grey <u>Sn</u>, which forms below 13.2 °C^[54])	- all or nearly all form allotropes - some (e.g. red <u>B</u>, yellow <u>As</u>) are more nonmetallic in nature	- some form allotropes - some (e.g. graphitic <u>C</u>, black <u>P</u>, grey <u>Se</u>) are more metalloidal or metallic in nature

Electron-related

Periodic table block	s, p, d, f^[55]	p^[56]	s, p^[56]
Outer s and p electrons	- few in number (1–3) - except 0 (<u>Pd</u>); 4 (<u>Sn</u>, <u>Pb</u>, <u>Fl</u>); 5 (<u>Bi</u>); 6 (<u>Po</u>)	medium number (3–7)	- high number (4–8) - except 1 (<u>H</u>); 2 (<u>He</u>)
Electron bands (valence, conduction)	- nearly all have substantial band overlap <u>Bi</u>: has slight band overlap (semimetal)	- most have narrow band gap (semiconductors) <u>As</u>, <u>Sb</u> are semimetals	- most have wide band gap (insulators) <u>C</u> (graphite): a semimetal <u>P</u> (black), <u>Se</u>, <u>I</u>: semiconductors
Electron behaviour	"free" electrons (facilitating electrical and thermal conductivity)	- valence electrons less freely delocalized; considerable covalent bonding present^[57] - have Goldhammer-Herzfeld criterion^[n 12] ratios straddling unity^{[61][62]}	no, few, or directionally confined "free" electrons (generally hampering electrical and thermal conductivity)
Electrical conductivity	good to high^[n 13]	intermediate^[64] to good^[n 14]	poor to good^[n 15]
... as a liquid ^[70]	falls gradually as temperature rises^[n 16]	most behave like metals^{[61][72]}	increases as temperature rises

Thermodynamics

Thermal conductivity	medium to high^[73]	mostly intermediate,^{[27][74]} <u>Si</u> is high	almost negligible^[75] to very high^[76]
Temperature coefficient of resistance ^[n 17]	nearly all positive (<u>Pu</u> is negative)^[77]	negative (<u>B</u>, <u>Si</u>, <u>Ge</u>, <u>Te</u>)^[78] or positive (<u>As</u>, <u>Sb</u>)^[79]	nearly all negative (<u>C</u>, as graphite, is positive in the direction of its planes)^{[80][81]}
Melting point	very high and solid at room temperature (except mercury)	very high and solid at room temperature	mostly low and gas at room temperature
Melting behaviour	volume generally expands^[82]	some contract, unlike (most)^[83] metals^[84]	volume generally expands^[82]
Enthalpy of fusion	low to high	intermediate to very high	very low to low (except <u>C</u>: very high)

Elemental chemistry

Overall behaviour			
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<u>Ion formation</u>	- metallic - tend to form <u>cations</u>	- nonmetallic^[85] - some tendency to form <u>anions</u> in water^[6] - solution chemistry dominated by formation and reactions of <u>oxyanions</u>^{[86][87]}	- nonmetallic - tend to form <u>anions</u>
<u>Bonds</u>	seldom form covalent compounds	form <u>salts</u> as well as <u>covalent</u> compounds^[88]	form many covalent compounds
<u>Oxidation number</u>	nearly always positive	positive or negative^[89]	positive or negative
<u>Ionization energy</u>	relatively low	intermediate^{[90][91]}	high
<u>Electronegativity</u>	usually low	close to 2,^[92] i.e., 1.9–2.2^{[93][n 18]}	high

Combined form chemistry

With metals	form <u>alloys</u>	can form <u>alloys</u>^{[88][96][97]}	form ionic or <u>interstitial</u> compounds
With carbon	<u>carbides</u> and <u>organometallic</u> compounds	same as metals	carbon-nonmetal (e.g. <u>CO₂</u>, <u>CS₂</u>)^[n 19] or <u>organic</u> (e.g. <u>CH₄</u>, <u>C₆H₁₂O₆</u>) compounds
With hydrogen (<u>hydrides</u>)	- ionic, with <u>alkali</u>, <u>alkaline earth</u> metals - metallic, with <u>transition</u> metals - covalent, with <u>post-transition</u> metals	covalent, volatile <u>hydrides</u>^[98]	covalent, gaseous or liquid hydrides
With oxygen (<u>oxides</u>)	- nearly all solid (<u>Mn₂O₇</u> is a liquid) - very few glass formers^[99] - lower oxides: <u>ionic</u> and <u>basic</u> - higher oxides: more covalent, <u>acidic</u>	- solid - glass formers (B, Si, Ge, As, Sb, Te)^[100] - polymeric in structure,^[101] tend to be <u>amphoteric</u> or weakly <u>acidic</u>^{[10][102]}	- solid, liquid or gaseous - few glass formers (<u>P</u>, <u>S</u>, <u>Se</u>)^[103] - covalent, <u>acidic</u>
With sulfur (<u>sulfates</u>)	do form^{[n 20][n 21]}	most form^[n 22]	some form^[n 23]
With halogens (<u>halides</u> , esp. <u>chlorides</u>) (see also ^[124])	- typically ionic, <u>involatile</u> - generally insoluble in organic solvents - mostly water-soluble (not <u>hydrolysed</u>) - more covalent, <u>volatile</u>, and susceptible to <u>hydrolysis</u>^[n 24] and organic solvents with higher halogens and weaker metals^{[125][126]}	- covalent, <u>volatile</u>^[127] - usually dissolve in organic solvents^[128] - partly or completely <u>hydrolysed</u>^[129] - some reversibly <u>hydrolysed</u>^[129]	- covalent, <u>volatile</u> - usually dissolve in organic solvents - generally completely or extensively <u>hydrolyzed</u> - not always susceptible to <u>hydrolysis</u> if parent nonmetal at maximum <u>covalency</u> for period e.g. <u>CF₄</u>, <u>SF₆</u> (then nil reaction)^[130]

Environmental chemistry

<u>Molar composition of Earth's <u>ecosphere</u></u> ^[n 25]	about 14%, mostly Al, Na, Ng, Ca, Fe, K	about 17%, mostly Si	about 69%, mostly O, H
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Primary form on Earth	- most occur in combined states, as carbonates, silicates, phosphates, oxides, sulfides, or halides - some (e.g. Au, Cu, Ag, Pt) occur in free or uncombined states^[134]	all occur in combined states, as borates, silicates, sulfides, or tellurides	- elemental C, N, O, S, noble gases are plentiful - H, ^[n 26]F^[n 27], Se occur primarily in compounds - P, Cl, Br, I occur only in compounds, as phosphates, oxides, selenides or halides
Required by mammals	- large amounts needed: Na, Mg, K, Ca - trace amounts needed of some others	trace amounts needed: B, Si, As	- large amounts needed: H, C, N, O, P, S, Cl - trace amounts needed: Se, Br, I, possibly F - only noble gases not needed
Composition of the human body, by weight	- about 1.5% Ca - traces of most others through ⁹²U	trace amounts of B, Si, Ge, As, Sb, Te	- about 97% O, C, H, N, P - others detectable except noble gases

Anomalous properties

Within each category, elements can be found with one or two properties very different from the expected norm, or that are otherwise notable.

Metals

Sodium, potassium, rubidium, caesium, barium, platinum, gold

- The common notions that "alkali metal ions (group 1A) always have a +1 charge"^[136] and that "transition elements do not form anions"^[137] are textbook errors. The synthesis of a crystalline salt of the sodium anion Na⁻ was reported in 1974. Since then further compounds ("alkalides") containing anions of all other alkali metals except Li and Fr, as well as that of Ba, have been prepared. In 1943, Sommer reported the preparation of the yellow transparent compound CsAu. This was subsequently shown to consist of caesium cations (Cs⁺) and auride anions (Au⁻) although it was some years before this conclusion was accepted. Several other aurides (KAu, RbAu) have since been synthesized, as well as the red transparent compound CsPt which was found to contain Cs⁺ and Pt²⁻ ions.^[138]

“ There were exceptions...in the periodic table, anomalies too—some of them profound. Why, for example, was manganese such a bad conductor of electricity, when the elements on either side of it were reasonably good conductors? Why was strong magnetism confined to the iron metals? And yet these exceptions, I was somehow convinced, reflected special additional mechanisms at work... ”

Oliver Sacks

Uncle Tungsten (2001, p. 204)

Manganese

- Well-behaved metals have crystal structures featuring unit cells with up to four atoms. Manganese has a complex crystal structure with a 58-atom unit cell, effectively four different atomic radii, and four different coordination numbers (10, 11, 12 and 16). It has been described as resembling "a quaternary intermetallic compound with four Mn atom types bonding as if they were different elements."^[139] The half-filled 3d shell of manganese appears to be the cause of the complexity. This confers a large magnetic moment on each atom. Below 727 °C, a unit cell of 58 spatially diverse atoms represents the energetically lowest way of achieving a zero net magnetic moment.^[140] The crystal structure of manganese makes it a hard and brittle metal, with low electrical and thermal conductivity. At higher temperatures "greater lattice vibrations nullify magnetic effects"^[139] and manganese adopts less complex structures.^[141]

Iron, cobalt, nickel, gadolinium, terbium, dysprosium, holmium, erbium, thulium

- The only elements strongly attracted to magnets are iron, cobalt, and nickel at room temperature, gadolinium just below, and terbium, dysprosium, holmium, erbium, and thulium at ultra cold temperatures (below $-54\text{ }^{\circ}\text{C}$, $-185\text{ }^{\circ}\text{C}$, $-254\text{ }^{\circ}\text{C}$, $-254\text{ }^{\circ}\text{C}$, and $-241\text{ }^{\circ}\text{C}$ respectively).^[142]

Iridium

- The only element encountered with an oxidation state of +9 is iridium, in the $[\text{IrO}]^+$ cation. Other than this, the highest known oxidation state is +8, in Ru, Xe, Os, Ir, and Hs.^[143]

Gold

- The malleability of gold is extraordinary: a fist sized lump can be hammered and separated into one million paper back sized sheets, each 10nm thick, 1600 times thinner than regular kitchen aluminium foil (0.016 mm thick).

Mercury

1. Bricks and bowling balls will float on the surface of mercury thanks to it having a density 13.5 times that of water. Equally, a solid mercury bowling ball would weigh around 50 pounds and, if it could be kept cold enough, would float on the surface of liquidgold.
2. The only metal having an ionisation energy higher than some nonmetals (sulfur and selenium) is mercury.
3. Mercury and its compounds have a reputation for toxicity but on a scale of 1 to 10 dimethylmercury ($(\text{CH}_3)_2\text{Hg}$) (abbr. DMM), a volatile colourless liquid, has been described as a 15. It is so dangerous that scientists have been encouraged to use less toxic mercury compounds wherever possible. In 1997, Karen Wetterhahn, a professor of chemistry specialising in toxic metal exposure, died of mercury poisoning ten months after a few drops of DMM landed on her "protective" latex gloves. Although Wetterhahn had been following the then published procedures for handling this compound, it passed through her gloves and skin within seconds. It is now known that DMM is exceptionally permeable to (ordinary) gloves, skin and tissues. And its toxicity is such that less than one-tenth of a n applied to the skin will be seriously toxic.^[144]

Lead

- The expression, to 'go down like a lead balloon' is anchored in the common view of lead as a dense, heavy metal—being nearly as dense as mercury. However, it is possible to construct a balloon made of lead foil, filled with a helium and air mixture, which will float and be buoyant enough to carry a small load.

Bismuth

- Bismuth has the longest half life of any naturally occurring element; its only primordial isotope, bismuth-209, was found in 2003 to be slightlyradioactive, decaying via alpha decay with a half life more than a billion times the estimated age of the universe. Prior to this discovery bismuth-209 was thought to be the heaviest naturally occurring stable isotope;^[145] this distinction now belongs to lead-208.

Uranium

- The only element with a naturally occurring isotope capable of undergoing nuclear fission is uranium.^[146] The capacity of uranium-235 to undergo fission was first suggested (and ignored) in 1934, and subsequently discovered in 1938.^[n 28]

Plutonium

- It is a commonly held belief that metals reduce their electrical conductivity when heated. Plutonium increases its electrical conductivity when heated in the temperature range of around -175 to $+125\text{ }^{\circ}\text{C}$.

Metalloids

Boron

- Boron is the only element with a partially disordered structure in its most thermodynamically stable crystalline form.^[149]

Boron, antimony

- These elements are record holders within the field of superacid chemistry. For seven decades, fluorosulfonic acid HSO_3F and trifluoromethanesulfonic acid $\text{CF}_3\text{SO}_3\text{H}$ were the strongest known acids that could be isolated as single compounds. Both are about a thousand times more acidic than pure sulfuric acid. In 2004, a boron compound broke this record by a thousand fold with the synthesis of carborane acid $\text{H}(\text{CHB}_{10}\text{Cl}_{11})$. Another metalloid, antimony features in the strongest known acid, a mixture 10 billion times stronger than carborane acid. This is fluoroantimonic acid $\text{H}_2\text{F}[\text{SbF}_6]$, a mixture of antimony pentafluoride SbF_5 and hydrofluoric acid HF .

Silicon

- The thermal conductivity of silicon is better than that of most metals.
- A sponge-like porous form of silicon (p-Si) is typically prepared by the electrochemical etching of silicon wafers in a hydrofluoric acid solution.^[150] Flakes of p-Si sometimes appear red,^[151] it has a band gap of 1.97–2.1 eV.^[152] The many tiny pores in porous silicon give it an enormous internal surface area, up to $1,000 \text{ m}^2/\text{cm}^3$.^[153] When exposed to an oxidant,^[154] especially a liquid oxidant,^[153] the high surface-area to volume ratio of p-Si creates a very efficient burn, accompanied by nano-explosions,^[150] and sometimes by ball-lightning-like plasmoids with, for example, a diameter of 0.1–0.8 m, a velocity of up to 0.5 m/s and a lifetime of up to 1 s.^[155] The first ever spectrographic analysis of a ball lightning event (in 2012) revealed the presence of silicon, iron and calcium, these elements also being present in the soil.^[156]

Arsenic

- Metals are said to be fusible, resulting in some confusion in old chemistry as to whether arsenic was a true metal, or a nonmetal, or something in between. It sublimes rather than melts at standard atmospheric pressure, like the nonmetals carbon and red phosphorus.

Antimony

- A high-energy explosive form of antimony was first obtained in 1858. It is prepared by the electrolysis of any of the heavier antimony trihalides (SbCl_3 , SbBr_3 , SbI_3) in a hydrochloric acid solution at low temperature. It comprises amorphous antimony with some occluded antimony trihalide (7–20% in the case of the trichloride). When scratched, struck, powdered or heated quickly to 200 °C, it "flares up, emits sparks and is converted explosively into the lower-energy crystalline grey antimony."^[157]

Nonmetals

Hydrogen

- Water (H_2O), a well known oxide of hydrogen, is a spectacular anomaly.^[158] Extrapolating from the heavier hydrogen chalcogenides namely hydrogen sulfide H_2S , hydrogen selenide H_2Se , and hydrogen telluride H_2Te , water should be "a foul-smelling, poisonous, inflammable gas...condensing to a nasty liquid [at] around -100°C ". Instead, due to hydrogen bonding water is "stable, potable, odorless, benign, and...indispensable to life".^[159]
- Less well known of the oxides of hydrogen is the trioxide, H_2O_3 . Berthelot proposed the existence of this oxide in 1880 but his suggestion was soon forgotten as there was no way of testing it using the technology of the time.^[160] Hydrogen trioxide was prepared in 1994 by replacing the oxygen used in the industrial process for making hydrogen peroxide, with ozone. The yield is about 40 per cent, at -78°C ; above around -40°C it decomposes into water and oxygen.^[161] Derivatives of hydrogen trioxide, such as $\text{F}_3\text{C}-\text{O}-\text{O}-\text{O}-\text{CF}_3$ ("bis(trifluoromethyl) trioxide") are known; these are metastable at room temperature.^[162] Mendeleev went a step further, in 1895, and proposed the existence of hydrogen tetroxide $\text{HO}-\text{O}-\text{O}-\text{OH}$ as a transient intermediate in the decomposition of hydrogen peroxide,^[160] this was prepared and characterised in 1974, using a matrix isolation technique. Alkali metal ozonide salts of the unknown hydrogen ozonide (HO_3) are also known; these have the formula MO_3 .^[162]

Helium

- At temperatures below 0.3 and 0.8 K respectively, helium-3 and helium-4 each have a negative enthalpy of fusion. This means that, at the appropriate constant pressures, these substances freeze with the addition of heat.
- Until 1999 helium was thought to be too small to form a cage clathrate—a compound in which a guest atom or molecule is encapsulated in a cage formed by a host molecule—at atmospheric pressure. In that year the synthesis of microgram quantities of $\text{He}@\text{C}_{20}\text{H}_{20}$ represented the first such helium clathrate and (what was described as) the world's smallest helium balloon.^[163]

Carbon

1. Graphite is the most electrically conductive nonmetal, better than some metals.
2. Diamond is the best natural conductor of heat; it even feels cold to the touch. Its thermal conductivity (2,200 W/m•K) is five times greater than the most conductive metal (Ag at 429); 300 times higher than the least conductive metal (Pu at 6.74); and nearly 4,000 times that of water (0.58) and 100,000 times that of air (0.0224). This high thermal conductivity is used by jewelers and gemologists to separate diamonds from imitations.
3. Graphene aerogel, produced in 2012 by freeze-drying a solution of carbon nanotubes and graphite oxide sheets and chemically removing oxygen, is seven times lighter than air and ten per cent lighter than helium. It is the lightest solid known (0.16 mg/cm³), conductive and elastic.^[164]

Phosphorus

- The least stable and most reactive form of phosphorus is the white allotrope. It is a hazardous, highly flammable and toxic substance, spontaneously igniting in air and producing phosphoric acid residue. It is therefore normally stored under water. White phosphorus is also the most common, industrially important, and easily reproducible allotrope, and for these reasons is regarded as the standard state of phosphorus. The most stable form is the black allotrope, which is a metallic looking, brittle and relatively non-reactive semiconductor (unlike the white allotrope, which has a white or yellowish appearance, is pliable, highly reactive and a semiconductor). When assessing periodicity in the physical properties of the elements it needs to be borne in mind that the quoted properties of phosphorus tend to be those of its least stable form rather than, as is the case with all other elements, the most stable form.

Iodine

- The mildest of the halogens, iodine is the active ingredient in tincture of iodine, a disinfectant. This can be found in household medicine cabinets or emergency survival kits. Tincture of iodine will rapidly dissolve gold,^[165] a task ordinarily requiring the use of aqua regia (a highly corrosive mixture of nitric and hydrochloric acids).

Notes

1. For example:
 - Brinkley^[2] writes that boron has weakly nonmetallic properties.
 - Glinka^[3] describes silicon as a weak nonmetal.
 - Eby et al.^[4] discuss the weak chemical behaviour of the elements close to the metal-nonmetal borderline.
 - Booth and Bloom^[5] say "A period represents a stepwise change from elements strongly metallic to weakly metallic to weakly nonmetallic to strongly nonmetallic, and then, at the end, to an abrupt cessation of almost all chemical properties ...".
 - Cox^[6] notes "nonmetallic elements close to the metallic borderline (Si, Ge, As, Sb, Se, Te) show less tendency to anionic behaviour and are sometimes called metalloids."
2. See, for example, Huheey Keiter & Keiter^[7] who classify Ge and Sb as post-transition metals.
3. At standard pressure and temperature, for the elements in their most thermodynamically stable forms, unless otherwise noted
4. Copernicium is reported to be the only metal known to be a gas at room temperature.^[20]
5. Whether polonium is ductile or brittle is unclear. It is predicted to be ductile based on its calculated elastic constants.^[25] It has a simple cubic crystalline structure. Such a structure has few slip systems and "leads to very low ductility and hence low fracture resistance".^[26]
6. Carbon as exfoliated (expanded) graphite^[28] and as metre-long carbon nanotube wire,^[29] phosphorus as white phosphorus (soft as wax, pliable and can be cut with a knife, at room temperature),^[30] sulfur as plastic sulfur,^[31] and selenium as selenium wires.^[32]
7. For polycrystalline forms of the elements unless otherwise noted. Determining Poisson's ratio accurately is a difficult proposition and there could be considerable uncertainty in some reported values.^[33]
8. Beryllium has the lowest known value (0.0476) amongst elemental metals; indium and thallium each have the highest known value (0.46). Around one third show a value ≥ 0.35 .^[34]

9. Boron 0.13;^[35] silicon 0.22;^[36] germanium 0.278;^[37] amorphous arsenic 0.27;^[38] antimony 0.25;^[39] tellurium ~0.2.^[40]
10. Graphitic carbon 0.25;^[41] [diamond 0.0718];^[42] black phosphorus 0.30;^[43] sulfur 0.287;^[44] amorphous selenium 0.32;^[45] amorphous iodine ~0!^[46]
11. At atmospheric pressure for elements with known structures
12. The Goldhammer-Herzfeld criterion is a ratio that compares the force holding an individual atom's valence electrons in place with the forces, acting on the same electrons, arising from interactions between the atoms in the solid or liquid element. When the interatomic forces are greater than or equal to the atomic force, valence electron itinerancy is indicated. Metallic behaviour is then predicted.^[58] Otherwise nonmetallic behaviour is anticipated. The Goldhammer-Herzfeld criterion is based on classical arguments.^[59] It nevertheless offers a relatively simple first order rationalization for the occurrence of metallic character amongst the elements.^[60]
13. Metals have electrical conductivity values of from $6.9 \times 10^5 \text{ S}\cdot\text{cm}^{-1}$ for manganese to 6.3×10^5 for silver.^[63]
14. Metalloids have electrical conductivity values of from $1.5 \times 10^6 \text{ S}\cdot\text{cm}^{-1}$ for boron to 3.9×10^4 for arsenic.^[65] If selenium is included as a metalloid the applicable conductivity range would start from $\sim 10^9$ to $10^{-12} \text{ S}\cdot\text{cm}^{-1}$.^{[66][67][68]}
15. Nonmetals have electrical conductivity values of from $\sim 10^{18} \text{ S}\cdot\text{cm}^{-1}$ for the elemental gases to 3×10^4 in graphite.^[69]
16. Mott and Davis^[71] note however that 'liquid europium has a negative temperature coefficient of resistance' i.e. that conductivity increases with rising temperature
17. At or near room temperature
18. Chedd^[94] defines metalloids as having electronegativity values of 1.8 to 2.2 (Allred-Rochow scale). He included boron, silicon, germanium, arsenic, antimony, tellurium, polonium and astatine in this category. In reviewing Chedd's work, Adler^[95] described this choice as arbitrary given other elements have electronegativities in this range, including copper, silver, phosphorus, mercury and bismuth. He went on to suggest defining a metalloid simply as, 'a semiconductor or semimetal' and 'to have included the interesting materials bismuth and selenium in the book'.
19. Phosphorus is known to form a carbide in thin films.
20. See, for example, the sulfates of the transition metals^[104] the lanthanides^[105] and the actinides.^[106]
21. Sulfates of osmium have not been characterized with any great degree of certainty.^[107]
22. *Common metalloids*: Boron is reported to be capable of forming an oxysulfate $(\text{BO})_2\text{SO}_4$,^[108] a bisulfate $\text{B}(\text{HSO}_4)_3$ ^[109] and a sulfate $\text{B}_2(\text{SO}_4)_3$.^[110] The existence of a sulfate has been disputed.^[111] In light of the existence of silicon phosphate, a silicon sulfate might also exist.^[112] Germanium forms an unstable sulfate $\text{Ge}(\text{SO}_4)_2$ (d 200 °C).^[113] Arsenic forms oxide sulfates $\text{As}_2\text{O}(\text{SO}_4)_2$ (= $\text{As}_2\text{O}_3 \cdot 2\text{SO}_3$)^[114] and $\text{As}_2(\text{SO}_4)_3$ (= $\text{As}_2\text{O}_3 \cdot 3\text{SO}_3$).^[115] Antimony forms a sulfate $\text{Sb}_2(\text{SO}_4)_3$ and an oxysulfate $(\text{SbO})_2\text{SO}_4$.^[116] Tellurium forms an oxide sulfate $\text{Te}_2\text{O}_3(\text{SO}_4)_4$.^[117] *Less common*: Polonium forms a sulfate $\text{Po}(\text{SO}_4)_2$.^[118] It has been suggested that the astatine cation forms a weak complex with sulfate ions in acidic solutions.^[119]
23. Hydrogen forms hydrogen sulfate H_2SO_4 . Carbon forms (a blue) graphite hydrogen sulfate $\text{C}_{24}^+\text{HSO}_4^- \cdot 2.4\text{H}_2\text{SO}_4$.^[120] Nitrogen forms nitrosyl hydrogen sulfate $(\text{NO})\text{HSO}_4$ and nitronium (or nitryl) hydrogen sulfate $(\text{NO}_2)\text{HSO}_4$.^[121] There are indications of a basic sulfate of selenium SeO_2SO_3 or $\text{SeO}(\text{SO}_4)$.^[122] Iodine forms a polymeric yellow sulfate $(\text{IO}_2)_2\text{SO}_4$.^[123]
24. layer-lattice types often reversibly so
25. Based on a table of the elemental composition of the biosphere, and lithosphere (crust, atmosphere, and seawater) in Georgievskii,^[131] and the masses of the crust and hydrosphere give in Lide and Frederikse.^[132] The mass of the biosphere is negligible, having a mass of about one billionth that of the lithosphere. The oceans constitute about 98 percent of the hydrosphere, and thus the average composition of the hydrosphere is, for all practical purposes, that of seawater."^[133]
26. Hydrogen gas is produced by some bacteria and algae and is a natural component of flatus. It can be found in the Earth's atmosphere at a concentration of 1 part per million by volume.
27. Fluorine can be found in its elemental form, as an occlusion in the mineral antozonite.^[135]

28. In 1934, a team led by [Enrico Fermi](#) postulated that [transuranic elements](#) may have been produced as a result of bombarding uranium with neutrons, a finding which was widely accepted for a few years. In the same year [Ida Noddack](#), a German scientist and subsequently a three-time [Nobel prize](#) nominee, criticised this assumption, writing "It is conceivable that the nucleus *breaks up into several large fragments* which would of course be isotopes of known elements but would not be neighbors of the irradiated element."^[147] [emphasis added] In this, Noddack defied the understanding of the time without offering experimental proof or theoretical basis, but nevertheless presaged what would be known a few years later as nuclear fission. Her paper was generally ignored as, in 1925, she and two colleagues claimed to have discovered element 43, then proposed to be called masurium (later discovered in 1936 by Perrier and Segrè, and named [technetium](#)). Had Ida Noddack's paper been accepted it is likely that Germany would have had an [atomic bomb](#) and, 'the history of the world would have been [very] different.'^[148]

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