Continue

A nonmetal is simply an element that does not display the properties of a metal. It is not defined by what it is, but by what it is not. It doesn't look metallic, can't be made into a wire, pounded into shape or bent, doesn't conduct heat or electricity well, and doesn't have a high melting or boiling point. The nonmetals are in the minority on the periodic table, mostly located on the right-hand side of the periodic table. The exception is hydrogen, which behaves as a nonmetal at room temperature and pressure and is found on the upper left corner of the periodic table. Under conditions of high pressure, hydrogen is predicted to behave as an alkali metal. The nonmetals are a small group of elements on the periodic table.These elements are located on the righthand side of the table, with the exception of hydrogen.The nonmetals include the group called the nonmetals, as well as the halogens and the noble gases.Nonmetals typically don't look metallic. Often, they are colorful.Most nonmetals take many forms called allotropes. For example, diamond and graphite are both pure carbon.Nonmetals are typically poor conductors of heat and electricity, with low melting and boiling points. They tend not to be malleable or ductile, so they form brittle solids.Nonmetals include solids, liquids, and gases at room temperature and pressure. The nonmetals are located on the upper right side of the periodic table. Nonmetals are separated from metals by a line that cuts diagonally through the region of the periodic table containing elements with partially filled p orbitals. The halogens and noble gases are nonmetals, but the nonmetal element group usually consists of the following elements: hydrogencarbonnitrogenoxygenphosphorussulfurselenium The halogen elements are: fluorinechlorinebromineiodineastatinetennessine (possibly, although most scientists think this element will behave as a metalloid) The noble gas elements are: heliumneonargonkryptonxenonradonoganesson - This element is predicted to be a liquid noble "gas", but is still a nonmetal. Nonmetals have high ionization energies and electronegativities. They are generally poor conductors of heat and electricity. Solid nonmetals are generally brittle, with little or no metallic luster. Most nonmetals have the ability to gain electrons easily. Nonmetals display a wide range of chemical properties and reactivities. Here is a summary of the properties of the nonmetals. High ionization energies High electronegativities Poor thermal conductors Poor electrical conductors Brittle solids—not malleable or ductile Little or no metallic luster Gain electrons easily Dull, not metallic-shiny, although they may be colorful Lower melting points and boiling point than the metals The chart below displays a comparison of the physical and chemical properties of the metals and nonmetals. These properties apply to the metals in general (alkali metals, alkaline earth, transition metals, basic metals, lanthanides, actinides) and nonmetals in general (nonmetals, halogens, noble gases). Metals Nonmetals chemical properties easily lose valence electrons easily share or gain valence electrons 1-3 electrons (usually) in the outer shell 4-8 electrons in the outer shell (7 for halogens and 8 for noble gases) form basic oxides form acidic oxides good reducing agents good oxidizing agents have low electronegativity have higher electronegativity physical properties solid at room temperature (except mercury) may be liquid, solid, or gas (noble gases are gases) have metallic luster do not have metallic luster good conductor of heat and electricity poor conductor of heat and electricity typically malleable and ductile usually brittle opaque in a thin sheet transparent in a thin sheet Atkins, P. A. (2001). The Periodic Kingdom: A Journey Into the Land of the Chemical Elements. London: Phoenix. ISBN 978-1-85799-449-0.Brady, J. E.; Senese, F. (2009). Chemistry: The Study of Matter and its Changes (5th ed.). New York: John Wiley & Sons. ISBN 978-0-470-57642-7.Challoner, J. (2014). The Elements: The New Guide to the Building Blocks of our Universe. Carlton Publishing Group. ISBN 978-0-233-00436-5.Oxtoby, D. W.; Gillis, H. P.; Butler, L. J. (2015). Principles of Modern Chemistry (8th ed.). Boston: Cengage Learning. ISBN 978-1-305-07911-3.Steudel, R. (1977). Chemistry of the Non-metals: With an Introduction to Atomic Structure and Chemical Bonding. Berlin: Walter de Gruyter. ISBN 978-3-11-004882-7. Science, Tech, Math All Science, Tech, Math Humanities All Humanities Languages All Languages Resources All Resources In the periodic table, elements are generally classified as metals or non-metals based on their physical and chemical properties. Understanding the physical properties of metals and non-metals helps us explain why we use these materials in certain ways, such as why metals are used for building structures and non-metals are used for insulation. For Year 8 science, we will focus on learning about the differences in physical properties between metals and non-metals. Metals have certain characteristics that make them useful in many applications: Shiny Appearance: Metals have a shiny or lustrous surface when polished. Good Conductors of Heat and Electricity: Metals allow heat and electricity to pass through them easily, making them ideal for cooking pots and electrical wiring. High Melting and Boiling Points: Metals generally have high melting and boiling points, making them solid at room temperature (except for mercury). Malleable and Ductile: Metals can be hammered into thin sheets (malleable) or drawn into wires (ductile) without breaking. High Density: Metals usually have a high density, meaning they feel heavy for their size. Non-metals have different physical properties that make them suitable for other purposes: Dull Appearance: Most non-metals do not have a shiny appearance. Poor Conductors of Heat and Electricity: Non-metals are generally insulators, meaning they do not conduct heat or electricity well. Low Melting and Boiling Points: Many non-metals have low melting and boiling points and can be gases or brittle solids at room temperature. Brittle: Non-metals are not malleable or ductile; they break easily when struck or bent. Low Density: Non-metals generally have a lower density than metals. Here is a set of questions to test your understanding of the physical properties of metals and non-metals, with 20 questions each at easy, medium, and hard levels. Are metals typically shiny or dull? What is the term for metals that can be hammered into shapes without breaking? Is copper a good conductor of electricity? Are non-metals generally good or poor conductors of heat? What is the physical state of mercury at room temperature? What term describes metals that can be drawn into wires? Do non-metals have high or low density? Are most metals solid, liquid, or gas at room temperature? Is oxygen a metal or a non-metal? Name one use of a metal in everyday life. Which group generally has higher melting points: metals or non-metals? Is graphite a conductor or an insulator of electricity? What property makes metals suitable for electrical wires? Do metals or non-metals tend to be brittle? Are metals generally malleable or brittle? Which property makes metals suitable for making jewellery? Are non-metals usually hard or soft? Is aluminium a metal or a non-metal? What is the appearance of most non-metals? Is gold a good conductor of heat? Explain why metals are used for cooking utensils. Why are non-metals poor conductors of electricity? Describe what happens when you try to hammer a piece of coal. Why are metals often used in buildings and construction? Explain why non-metals like plastic are used as insulators in electrical cables. Compare the melting points of metals and non-metals. What makes metals malleable? Is diamond, a form of carbon, a good or poor conductor of electricity? Why is aluminium used for making cans? Explain why graphite, a non-metal, conducts electricity. What is ductility, and which type of element is usually ductile? What happens to most non-metals when they are struck? Describe the density of metals compared to non-metals. Why is copper commonly used in household wiring? Explain why metals are shiny. Why is iron used in construction despite rusting? Why can metals conduct electricity so well? How does the brittleness of non-metals affect their uses? Why are metals generally denser than non-metals? Why is silver used for high-quality jewellery and mirrors? Explain the atomic structure that makes metals good conductors. Discuss the reasons for the malleability of metals. Why are some metals magnetic and others not? Describe how metallic bonding contributes to metal properties. Explain why non-metals are typically poor conductors of heat. Why does mercury, a metal, exist as a liquid at room temperature? Explain how alloys are made and why they are useful. Compare the atomic arrangement in metals and non-metals. Why is tungsten used in light bulb filaments? Describe the difference in electron movement between metals and non-metals. Why are transition metals harder than alkali metals? Explain why aluminium does not rust like iron. What is metallic bonding, and how does it affect conductivity? Why is stainless steel used for cutlery instead of pure iron? Discuss how density affects the use of metals and non-metals. Why is lead used in shielding for radiation? Explain why metals have high melting points. What causes metals to be shiny? Why do alkali metals react more vigorously than other metals? How does the structure of graphite allow it to be used as a lubricant? Shiny – Metals are typically shiny when polished. Malleable – Metals can be hammered into shapes without breaking. Yes – Copper is an excellent conductor of electricity. Poor conductors – Non-metals generally do not conduct heat well. Liquid – Mercury is a liquid at room temperature. Ductile – Metals can be drawn into wires. Low density – Non-metals generally have a lower density than metals. Solid – Most metals are solid at room temperature. Non-metal – Oxygen is a non-metal. Cooking utensils, jewellery, etc. – Metals have many everyday uses. Metals – Metals generally have higher melting points than non-metals. Conductor – Graphite, an allotrope of carbon, conducts electricity. Conductivity – Metals are good conductors of electricity. Non-metals – Non-metals are more likely to be brittle. Malleable – Metals are generally malleable. Shininess and malleability – These properties make metals suitable for jewellery. Soft – Non-metals are generally softer than metals. Metal – Aluminium is a metal. Dull – Most non-metals appear dull. Yes – Gold is a good conductor of heat. Metals conduct heat well, making them ideal for cooking utensils. Non-metals lack free electrons to carry an electric current. Coal (carbon) would break if hammered because it is brittle. Metals are strong and durable, ideal for building materials. Plastic insulates electricity, preventing accidental electric shocks. Metals have higher melting points than non-metals. The layers in metals can slide, making them malleable. Diamond is a poor conductor of electricity (it has a rigid structure with no free electrons). Aluminium is lightweight and resistant to corrosion. Graphite has free-moving electrons between layers, allowing conductivity. Ductility is the ability to be drawn into wires, a property of metals. Non-metals are brittle and may shatter if struck. Metals are denser than non-metals due to tightly packed atoms. Copper conducts electricity very well. Metals are shiny because they reflect light effectively. Iron is strong and widely available, even though it rusts. Free-moving electrons make metals good conductors. Brittleness limits non-metals to certain applications like insulation. **High density in metals is due to closely packed atoms.** Silver is shiny, reflective, and valuable, ideal for jewellery. Metals have free electrons in a 'sea', allowing them to conduct electricity. The atomic layers in metals can slide, making them malleable. Metals like iron are magnetic due to electron alignment; others lack this property. Metallic bonding involves a 'sea of electrons,' giving metals their properties. Non-metals lack free-moving electrons to conduct heat effectively. Mercury has a weak bond structure, making it liquid at room temperature. Alloys combine metals for specific properties, like increased strength. Metals have a regular atomic arrangement; non-metals have varied structures. Tungsten has a very high melting point, ideal for filament use. Electrons in metals move freely; in non-metals, they are tightly held. Transition metals have stronger bonds, making them harder. Aluminium forms a protective oxide layer, preventing rust. Metallic bonding allows free electron movement, aiding conductivity. Stainless steel resists rust and is durable, unlike pure iron. High density in metals suits building; low density in non-metals suits insulation. Lead's high density and atomic structure block radiation. Strong bonds in metals result in high melting points. The 'sea of electrons' reflects light, making metals shiny. Alkali metals react vigorously due to their single, easily lost outer electron. Graphite has layers that slide easily, making it a good lubricant. These questions and answers offer a comprehensive exploration of the physical properties of metals and non-metals, helping Year 8 students prepare effectively for their Key Stage 3 exams. Quantitative observation is the type of observation that deals in quantifiable variables, things that you can use numbers to express. In contrast, qualitative observation focuses…Read more Push and pull factors of migration are driven by the push of conflict, extreme hardship, war, lack of economic opportunities, etc. combined with the pull…Read more One of the main factors to take into account when looking at an IQ score is the age of the person that has taken the…Read more An experimental control is used in scientific experiments to minimize the effect of variables which are not the interest of the study. The control can…Read more The highest IQ possible in the world is theoretically 200, although some people have been known to have an IQ of above 200. Let's discuss how…Read more The 3 types of volcanoes are stratovolcano (also known as a composite volcano), cinder cone volcano, and shield volcano. Each one is different in its…Read more Broadly speaking, the general public doesn't read scientific journals. Most people subscribe to magazines like Time or Reader's Digest, not academic publications like Nature or Science. Yet this doesn't mean that scientific…Read more A great debate of United States politics in the 20th century rages on. The moment Donald Trump took to the White House as the unlikeliest…Read more Imagine getting on a plane in London, taking a three-hour nap, and then waking up in New York City. For the start-up company Boom Supersonic,…Read more Planes don't just disappear. On March 8th, 2014, people all around the world said some version of that sentence to themselves as global media outlets…Read more When the editors of the popular United Kingdom-based publication The Guardian decided to publish an article with the title, "Want to fight climate change? Have…Read more The melting point of an element is when it converts from solid form to a liquid. Metals, which are physically flexible elements that can conduct heat and electricity, tend to be solid at room temperature due to their relatively high melting points. Nonmetals, which are physically weak and poor conductors of heat and electricity, can be solid, liquid or gaseous, depending on the element. Melting points of both metals and nonmetals vary widely, but metals tend to melt at higher temperatures. Once you include the melting points of all the elements on the periodic table, a pattern emerges. As you move from left to right on a period — a horizontal row –, the melting point of the elements start to increase, then they peak at Group 14 — the vertical column with carbon at the top — and finally they decrease as you approach the right-hand side. As you move from top to bottom on the table, the rise and fall pattern gets smaller, meaning that elements on lower periods have more similar melting points. There are two types of bonding that lead to higher melting points: covalent and metallic. Covalent bonds are when electron pairs are shared equally between atoms, and they pull atoms even closer together if multiple pairs of electrons are involved. Metallic bonds involve electrons that are delocalized: they float between many atoms, not just two, and positively charged nuclei are firmly bound to the surrounding "sea" of electrons. As strong bonds between atoms give elements higher melting points, it is also true that lower melting points are a result of weaker bonds or a lack of bonds between atoms. Mercury, the metal with the lowest melting point — -38.9 degrees Celsius or -37.9 degrees Fahrenheit — cannot form any bonds since it has zero electron affinity. A lot of nonmetals, like oxygen and chlorine are highly electronegative: they have high affinity for electrons and effectively pry them from the other atom, so the bond breaks easily. As a result, these nonmetals have subzero melting point temperatures. Auerbach, Scott. "Melting Points Of Metals Vs. Nonmetals" sciencing.com, . 30 April 2018. APA Auerbach, Scott. (2018, April 30). Melting Points Of Metals Vs. Nonmetals. sciencing.com. Retrieved from Chicago Auerbach, Scott. Melting Points Of Metals Vs. Nonmetals last modified March 24, 2022. The elements of the periodic table fall into three different groups: metals, metalloids, and nonmetals.This periodic table shows the three different groups of elements. The metalloid group separates the metals from the nonmetals. Elements to the left are metals and nonmetals are to the right. The exception is the element hydrogen. Hydrogen has properties of a nonmetal at normal temperatures and pressures and characteristics of an alkali metal under extremely high pressure.Some periodic tables include a zig-zag line that distinguishes between metals and metalloids. The line begins below boron (B) and extends between bismuth (Bi) and polonium (Po) or down between livermorium (Lv) and tennessine (Ts). In reality, the metals near the line often display nonmetallic properties while the nonmetals have some metallic character.Elements are classified as metals, metalloids, or nonmetals based on their physical and chemical properties.Metals are generally shiny, good conductors of heat and electricity, malleable, ductile, and have high melting and boiling points.Nonmetals are usually dull, poor conductors of heat and electricity, brittle when solid, and often have lower melting and boiling points.Metalloids have properties that are intermediate between metals and nonmetals, making them useful in semiconductor applications.Metals tend to lose electrons (forming cations), while nonmetals gain electrons (forming anions); metalloids behave either way depending on the reaction.Metals dominate the periodic table, occupying the left and center, while nonmetals are found on the right, and metalloids form a staircase-like boundary between them.Most of the elements are metals. Metals include the alkali metal, alkaline earth, transition metal, basic metal (post-transition metal), lanthanide, and actinide groups. These elements have metallic character, which means atoms easily lose electrons. Metals display the following properties:Solid at room temperature (with the exception of mercury)Usually shiny, with metallic lusterHigh melting pointGood conductor of heatGood conductor of electricityMalleable – able to be pounded into sheetsDuctile – can be pulled into wireHigh density (exceptions: lithium, potassium and sodium)Closely packed crystal structuresLow ionization energies and electronegativitiesCorrode in air or seawaterLose electrons in reactionsExamples of elements on the periodic table that are metals include lithium, titanium, silver, lead, and uranium.Metalloids or semimetals possess some properties of metals and some of nonmetals. Metalloids typically have several forms or allotropes with very different properties. Characteristics of metalloids include:Dull or shinyConduct heat and electricity, but not as well as metalsGood semiconductorsUsually malleableUsually ductileIntermediate ionization energies and electronegativity valuesCan both gain and lose electrons in reactionsExamples of elements that are metalloids include boron, silicon, arsenic, and antimony.The nonmetals include the nonmetals element group, plus the halogens, and noble gases. Properties of nonmetals include:Dull, not shiny or metallicPoor conductor of heatPoor conductor of electricityNot malleable or ductile, usually brittleLower density (when compared to metals)Lower melting point and boiling points (when compared to metals) – Most are gases at room temperature.Relatively high ionization energies and electronegativitiesGain electrons in reactionsExamples of nonmetals include helium, nitrogen, sulfur, and chlorine.Check your understanding of metals, metalloids, and nonmetals with this quick 10-question quiz:Which category of elements is the best conductor of electricity?a) Metalsb) Metalloidsc) Nonmetalsd) Noble gases(Answer: a) Metals)Which element is a metalloid?a) Oxygenb) Siliconc) Irond) Neon(Answer: b) Silicon)What is a key characteristic of most nonmetals?a) They are ductileb) They conduct electricity wellc) They tend to be brittle in solid formd) They have high melting points(Answer: c) They tend to be brittle in solid form)Which of the following elements is a metal?a) Sulfurb) Carbonc) Copperd) Arsenic(Answer: c) Copper)What type of elements are found along the 'stair-step' line on the periodic table?a) Metalsb) Metalloidsc) Nonmetalsd) Noble gases(Answer: b) Metalloids)Which statement is true about metalloids?a) They are never conductiveb) They can have properties of both metals and nonmetalsc) They are always highly reactived) They only exist as gases(Answer: b) They can have properties of both metals and nonmetals)Which of the following elements is most likely to gain electrons in a chemical reaction?a) Sodium (Na)b) Aluminum (Al)c) Fluorine (F)d) Iron (Fe)(Answer: c) Fluorine (F))What is a common use for metalloids like silicon?a) Electrical wiringb) Semiconductor devicesc) Making steel alloysd) Fuel production(Answer: b) Semiconductor devices)Which element is liquid at room temperature and classified as a metal?a) Mercury (Hg)b) Bromine (Br)c) Gallium (Ga)d) Argon (Ar)(Answer: a) Mercury (Hg))Which of the following is NOT a property of most metals?a) Malleabilityb) High conductivityc) Low densityd) Luster(Answer: c) Low density (most metals have relatively high density)Askeland, D.R.; Fulay, P.P.; Wright, J.W. (2011). The Science and Engineering of Materials (6th ed.). Stamford, CT: Cengage Learning. ISBN 0-495-66802-8.Brown, T.L.; LeMay, H.E.; et al. (2009). Chemistry: The Central Science (11th ed.). Pearson Education. ISBN 978-0-13-235-848-4.Edwards, Peter P.; Sienko, M. J. (1983). "On the occurrence of metallic character in the periodic table of the elements". Journal of Chemical Education. 60 (9). American Chemical Society (ACS): 691–696. doi:10.1021/ed060p691Herzfeld, K. F. (1927). "On Atomic Properties which make an Element a Metal". Physical Review. 29 (5): 701–705. doi:10.1103/PhysRev.29.701Related Posts Category of chemical elements This article is about the chemical elements that are not metals. For other meanings, see Nonmetal (disambiguation). This article may contain citations that do not verify the text. The reason given is: Checking of criteria section[broken anchor] indicated that many were incorrect, so everything needs to be checked. (That section was deleted in April 2025, but other sources still need verification.) Please check for citation inaccuracies. (August 2024) (Learn how and when to remove this message) A periodic table extract highlighting nonmetals 17 always/usually considered nonmetals[1][2][3] 6 metalloids, sometimes considered nonmetals 3 status as nonmetal or metal unconfirmed[4] Part of a series on thePeriodic table Periodic table forms 18-column 32-column Alternative and extended forms Periodic table history D. Mendeleev 1871 table 1869 predictions Discovery of elements Naming and etymology for people for places controversies (in East Asia) Systematic element names Sets of elements By periodic table structure Groups (1–18) 1 (alkali metals) 2 (alkaline earth metals) 3 4 5 6 7 8 9 10 11 12 13 14 15 (pnictogens) 16 (chalcogens) 17 (halogens) 18 (noble gases) Periods (1–7, ...) 1 2 3 4 5 6 7 8+ Blocks (s, p, d, f, ...) Atomic orbitals Aufbau principle By metallic classification Metals alkali alkaline earth transition post-transition lanthanide actinide Metalloids dividing metals and nonmetals Nonmetals nonmetal halogen noble gas By other characteristics Coinage metals Platinum-group metals Precious metals Refractory metals Heavy metals Light metals Native metals Noble metals Main-group elements Rare-earth elements Transuranium elements Major, minor and trans- actinides Elements List of chemical elements by abundance (in human body) by atomic properties by isotope stability by symbol Properties of elements Relative atomic mass Crystal structure Electron affinity configuration Electronegativity (Allen, Pauling) Goldschmidt classification Nutrition Valence Data pages for elements Abundance Atomic radius Boiling point Critical point Density Elasticity Electrical resistivity Electron affinity / configuration Electronegativity Hardness Heat capacity / of fusion / of vaporization Ionization energy Melting point Oxidation state Speed of sound Thermal conductivity / expansion coefficient Vapor pressure Category Chemistry Portal vte In the context of the periodic table, a nonmetal is a chemical element that mostly lacks distinctive metallic properties. They range from colorless gases like hydrogen to shiny crystals like iodine. Physically, they are usually lighter (less dense) than elements that form metals and are often poor conductors of heat and electricity. Chemically, nonmetals have relatively high electronegativity or usually attract electrons in a chemical bond with another element, and their oxides tend to be acidic. Seventeen elements are widely recognized as nonmetals. Additionally, some or all of six borderline elements (metalloids) are sometimes counted as nonmetals. The two lightest nonmetals, hydrogen and helium, together account for about 98% of the mass of the observable universe. Five nonmetallic elements—hydrogen, carbon, nitrogen, oxygen, and silicon—form the bulk of Earth's atmosphere, biosphere, crust and oceans, although metallic elements are believed to be slightly more than half of the overall composition of the Earth. Chemical compounds and alloys involving multiple elements including nonmetals are widespread. Industrial uses of nonmetals as the dominant component include in electronics, combustion, lubrication and machining. Most nonmetallic elements were identified in the 18th and 19th centuries. While a distinction between metals and other minerals had existed since antiquity, a classification of chemical elements as metallic or nonmetallic emerged only in the late 18th century. Since then about twenty properties have been suggested as criteria for distinguishing nonmetals from metals. In contemporary research usage it is common to use a distinction between metal and not-a-metal based upon the electronic structure of the solids; the elements carbon, arsenic and antimony are then semimetals, a subclass of metals. The rest of the nonmetallic elements are insulators, some of which such as silicon and germanium can readily accommodate dopants that change the electrical conductivity leading to semiconducting behavior. Unless otherwise noted, this article describes the stable form of an element at standard temperature and pressure (STP).[a] While arsenic (here sealed in a container to prevent tarnishing) has a shiny appearance and is a reasonable conductor of heat and electricity, it is soft and brittle and its chemistry is predominately nonmetallic.[6] Nonmetallic chemical elements are often broadly defined as those that mostly lack properties commonly associated with metals—namely shininess, pliability, good thermal and electrical conductivity (due to their band structure), and a general capacity to form basic oxides.[7][8] There is no widely accepted precise definition in terms of these properties;[9] any list of nonmetals is open to debate and revision.[1] Fourteen elements are almost always recognized as nonmetals:[1][2] HydrogenNitrogenOxygenSulfur FluorineChlorineBromineIodine HeliumNeonArgonKryptonXenonRadon Three more are commonly classed as nonmetals, but some sources list them as "metalloids",[3] a term which refers to elements intermediate between metals and nonmetals:[10] CarbonPhosphorusSelenium One or more of the six elements most commonly recognized as metalloids are sometimes instead counted as nonmetals: BoronSiliconGermaniumArsenicAntimonyTellurium About 15–20% of the 118 known elements[11] are thus classified as nonmetals.[b] See also § Physical properties by element type Variety in color and formof some nonmetallic elementsBoron in its β-rhombohedral phaseMetallic appearance of carbon as graphiteBlue color of liquid oxygenPale yellow liquid fluorine in a cryogenic bathSulfur as yellow chunksLiquid bromine at room temperatureMetallic appearance of iodine under white lightLiquefied xenon Nonmetals vary greatly in appearance, being colorless, colored or shiny. For the colorless nonmetals (hydrogen, nitrogen, oxygen, and the noble gases), no absorption of light happens in the visible part of the spectrum, and all visible light is transmitted.[14] The colored nonmetals (sulfur, fluorine, chlorine, bromine) absorb some colors (wavelengths) and transmit the complementary or opposite colors. For example, chlorine's "familiar yellow-green colour ... is due to a broad region of absorption in the violet and blue regions of the spectrum".[15][c] The shininess of boron, graphite (carbon), silicon, black phosphorus, germanium, arsenic, selenium, antimony, tellurium, and iodine[d] is a result of the electrons reflecting incoming visible light.[18] About half of nonmetallic elements are gases under standard temperature and pressure; most of the rest are solids. Bromine, the only liquid, is usually topped by a layer of its reddish-brown fumes. The gaseous and liquid nonmetals have very low densities, melting and boiling points, and are poor conductors of heat and electricity.[19] The solid nonmetals have low densities and low mechanical strength (being either hard and brittle, or soft and crumbly),[20] and a wide range of electrical conductivity.[e] This diversity stems from variability in crystallographic structures and bonding arrangements. Covalent nonmetals existing as discrete atoms like xenon, or as small molecules, such as oxygen, sulfur, and bromine, have low melting and boiling points; many are gases at room temperature, as they are held together by weak London dispersion forces acting between their atoms or molecules, although the molecules themselves have strong covalent bonds.[24] In contrast, nonmetals that form extended structures, such as long chains of selenium atoms,[25] sheets of carbon atoms in graphite,[26] or three-dimensional lattices of silicon atoms[27] have higher melting and boiling points, and are all solids. Nonmetals closer to the left or bottom of the periodic table (and so closer to the metals) often have metallic interactions between their molecules, chains, or layers; this occurs in boron,[28] carbon,[29] phosphorus,[30] arsenic,[31] selenium,[32] antimony,[33] tellurium[34] and iodine.[35] Some general physical differencesbetween elemental metals and nonmetals[19] Aspect Metals Nonmetals Appearanceand form Shiny if freshly preparedor fractured; few colored;[36]all but one solid[37] Shiny, colored ortransparent;[38] all butone solid or gaseous[37] Density Often higher Often lower Plasticity Mostly malleableand ductile Often brittle solids Electricalconductivity[39] Good Poor to good Electronicstructure[40] Metal or semimetallic Semimetal,semiconductor,or insulator Covalently bonded nonmetals often share only the electrons required to achieve a noble gas electron configuration.[41] For example, nitrogen forms diatomic molecules featuring a triple bonds between each atom, both of which thereby attain the configuration of the noble gas neon. In contrast antimony has buckled layers in which each antimony atom is singly bonded with three other nearby atoms.[42] Good electrical conductivity occurs when there is metallic bonding,[43] however the electrons in some nonmetals are not metallic.[43] Good electrical and thermal conductivity associated with metallic electrons is seen in carbon (as graphite, along its planes), arsenic, and antimony.[f] Good thermal conductivity occurs in boron, silicon, phosphorus, and germanium;[21] such conductivity is transmitted though vibrations of the crystalline lattices (phonons of these elements.[44] Moderate electrical conductivity is observed in the semiconductors[45] boron, silicon, phosphorus, germanium, selenium, tellurium, and iodine. Many of the nonmetallic elements are hard and brittle,[20] where dislocations cannot readily move so they tend to undergo brittle fracture rather than deforming.[46] Some do deform such as white phosphorus (soft as wax, pliable and can be cut with a knife at room temperature),[47] plastic sulfur,[48] and selenium which can be drawn into wires from its molten state.[49] Graphite is a standard solid lubricant where dislocations move very easily in the basal planes.[50] Three allotropes of carbonA transparent electrical insulatorA brownish semiconductorA blackish semimetalFrom left to right, diamond, buckminsterfullerene, and graphite For a more comprehensive list, see Allotropy § Non-metals, and Single-layer materials. Over half of the nonmetallic elements exhibit a range of less stable allotropic forms, each with distinct physical properties.[51] For example, carbon, the most stable form of which is graphite, can manifest as diamond, buckminsterfullerene,[52] amorphous[53] and paracrystalline[54] variations. Allotropes also occur for nitrogen, oxygen, phosphorus, sulfur, selenium and iodine.[55] See also § Chemical properties by element type Some general chemistry-baseddifferences between metals and nonmetals[19] Aspect Metals Nonmetals Reactivity[56] Wide range: very reactive to noble Oxides lower Basic Acidic; never basic[57] higher Increasingly acidic Compoundswith metals[58] Alloys Covalent or Ionic Ionization energy[59] Low to high Moderate to very high Electronegativity[60] Low to high Moderate to very high Nonmetals have relatively high values of electronegativity, and their oxides are usually acidic. Exceptions may occur if a nonmetal is not very electronegative, or if its oxidation state is low, or both. These non-acidic oxides of nonmetals may be amphoteric (like water, H_2O[61]) or neutral (like nitrous oxide, N_2O[62][g]), but never basic. They tend to gain electrons during chemical reactions, in contrast to metallic elements which tend to donate electrons. This behavior is related to the stability of electron configurations in the noble gases, which have complete outer shells, empirically described by the duet and octet rules of thumb, more correctly explained in terms of valence bond theory.[65] The chemical differences between metals and nonmetals stem from variations in how strongly atoms attract and retain electrons. Across a period of the periodic table, the nuclear charge increases as more protons are added to the nucleus.[66] However, because the number of inner electron shells remains constant, the effective nuclear charge experienced by the outermost electrons also increases, pulling them closer to the nucleus. This leads to a corresponding reduction in atomic radius,[67] and a greater tendency of these elements to gain electrons during chemical reactions, forming negatively charged ions.[68] Nonmetals, which occupy the right-hand side of the periodic table, exemplify this behavior. Nonmetals typically exhibit higher ionization energies, electron affinities, and standard electrode potentials than metals. The higher these values are (including electronegativity) the more nonmetallic the element tends to be.[69] For example, the chemically very active nonmetals fluorine, chlorine, bromine, and iodine have an average electronegativity of 3.19—a figure[h] higher than that of any metallic element. The number of compounds formed by nonmetals is vast.[70] The first 10 places in a "top 20" table of elements most frequently encountered in 895,501,834 compounds, as listed in the Chemical Abstracts Service register for November 2, 2021, were occupied by nonmetals. Hydrogen, carbon, oxygen, and nitrogen collectively appeared in most (80%) of compounds. Silicon, a metalloid, ranked 11th. The highest-rated metal, with an occurrence frequency of 0.14%, was iron, in 12th place.[71] Adding complexity to the chemistry of the nonmetals are anomalies occurring in the first row of each periodic table block; non-uniform periodic trends; higher oxidation states; multiple bond formation; and property overlaps with metals. Condensed periodic table highlightingthe first row of each block: s p d and f Period s-block 1 H 1 He2 p-block 2 Li3 Be4 B 5 C 6 N 7 O 8 F 9 Ne10 3 Na11 Mg12 d-block Al13 Si14 P 15 S 16 Cl17 Ar18 4 K 19 Ca20 Sc-Zn21-30 Ga31 Ge32 As33 Se34 Br35 Kr36 5 Rb37 Sr38 f-block Y-Cd39-48 In49 Sn50 Sb51 Te52 I 53 Xe54 6 Cs55 Ba56 La-Yb57-70 Lu-Hg71-80 Tl81 Pb82 Bi83 Po84 At85 Rn86 7 Fr87 Ra88 Ac-No89-102 Lr-Cn103-112 Nh113 Fl114 Mc115 Lv116 Ts117 Og118 Group (1) (2) (3-12) (13) (14) (15) (16) (17) (18) The first-row anomaly strength by block is s >> p > d > f.[72][i] Starting with hydrogen, the first row anomaly primarily arises from the electron configurations of the elements concerned. Hydrogen is notable for its diverse bonding behaviors. It most commonly forms covalent bonds, but it can also lose its single electron in an aqueous solution, leaving behind a bare proton with high polarizing power.[73] Consequently, this proton can attach itself to the lone electron pair of an oxygen atom in a water molecule, laying the foundation for acid-base chemistry.[74] Moreover, a hydrogen atom in a molecule can form a second, albeit weaker, bond with an atom or group of atoms in another molecule. Such bonding, "helps give snowflakes their hexagonal symmetry, binds DNA into a double helix; shapes the three-dimensional forms of proteins; and even raises water's boiling point high enough to make a decent cup of tea."[75] Hydrogen and helium, as well as boron through neon, have small atomic radii. The ionization energies and electronegativities among these elements are higher than the periodic trends would otherwise suggest. While it would normally be expected, on electron configuration consistency grounds, that hydrogen and helium would be placed atop the s-block elements, the significant first row anomaly shown by these two elements justifies alternative placements. Hydrogen is occasionally positioned above fluorine, in group 17, rather than above lithium in group 1. Helium is almost always placed above neon, in group 18, rather than above beryllium in group 2.[76] Electronegativity values of the group 16 chalcogen elements showing a W-shaped alternation or secondary periodicity going down the group An alternation in certain periodic trends, sometimes referred to as secondary periodicity, becomes evident when descending groups 13 to 15, and to a lesser extent, groups 16 and 17.[77][j] Immediately after the first row of d-block metals, from scandium to zinc, the 3d electrons in the p-block elements—specifically, gallium (a metal), germanium, arsenic, selenium, and bromine—prove less effective at shielding the increasing positive nuclear charge. The Soviet chemist Shchukarev [ru] gives two more tangible examples:[79] "The toxicity of some arsenic compounds, and the absence of this property in analogous compounds of phosphorus [P] and antimony [Sb]; and the ability of selenic acid [H_2SeO_4] to bring metallic gold [Au] into solution, and the absence of this property in sulfuric [H_2SO_4] and [H_2TeO_4] acids." Roman numerals such as III, V and VIII denote oxidation states Some nonmetallic elements exhibit oxidation states that deviate from those predicted by the octet rule, which typically results in an oxidation state of –3 in group 15, –2 in group 16, –1 in group 17, and 0 in group 18. Examples include ammonia NH_3, hydrogen sulfide H_2S, hydrogen fluoride HF, and elemental xenon Xe. Meanwhile, the maximum possible oxidation state increases from +5 in group 15, to +8 in group 18. The +5 oxidation state is observable from period 2 onward, in compounds such as nitric acid $HN(V)O_3$ and phosphorus pentafluoride PCl_5.[k] Higher oxidation states in later groups emerge from period 3 onwards, as seen in sulfur hexafluoride SF_6, iodine heptafluoride IF_7, and xenon(VIII) tetroxide XeO_4. For heavier nonmetals, their larger atomic radii and lower electronegativity values enable the formation of compounds with higher oxidation numbers, supporting higher bulk coordination numbers.[80] Molecular structure of pentazenium, a homopolyatomic cation of nitrogen with the formula N_5^+ and structure N−N−N−N−N.[81]Period 2 nonmetals, particularly carbon, nitrogen, and oxygen, show a propensity to form multiple bonds. The compounds formed by these elements often exhibit unique stoichiometries and structures, as seen in the various nitrogen oxides,[80] which are not commonly found in elements from later periods. While certain elements have traditionally been classified as nonmetals and others as metals, some overlapping of properties occurs. Writing early in the twentieth century, by which time the era of modern chemistry had been well-established[82] (although not as yet more precise quantum chemistry) Humphrey[83] observed that: ... these two groups, however, are not marked off perfectly sharply from each other; some nonmetals resemble metals in certain of their properties, and some metals approximate in some ways to the non-metals. Boron (here in its less stable amorphous form) shares some similarities with metals[l] Examples of metal-like properties occurring in nonmetallic elements include: Silicon has an electronegativity (1.9) comparable with metals such as cobalt (1.88), copper (1.9), nickel (1.91) and silver (1.93);[60] The electrical conductivity of graphite exceeds that of some metals;[m] Selenium can be drawn into a wire;[49] Radon is the most metallic of the noble gases and begins to show some cationic behavior, which is unusual for a nonmetal;[87] and In extreme conditions, just over half of nonmetallic elements can form homopolyatomic cations.[n] Examples of nonmetal-like properties occurring in metals are: Tungsten displays some nonmetallic properties, sometimes being brittle, having a high electronegativity, and forming only anions in aqueous solution,[89] and predominately acidic oxides.[8][90] Gold, the "king of metals" has the highest electrode potential among metals, suggesting a preference for gaining rather than losing electrons. Gold's ionization energy is one of the highest among metals, and its electron affinity and electronegativity are high, with the latter exceeding that of some nonmetals. It forms the Au– auride anion and exhibits a tendency to bond to itself, behaviors which are unexpected for metals. In aurides (MAu, where M = Li–Cs), gold's behavior is similar to that of a halogen.[91] The reason for this is that gold has a large enough nuclear potential that the electrons have to be considered with relativistic effects included, which changes some of the properties.[92] A relatively recent development involves certain compounds of heavier p-block elements, such as silicon, phosphorus, germanium, arsenic and antimony, exhibiting behaviors typically associated with transition metal complexes. This is linked to a small energy gap between their filled and empty molecular orbitals, which are the regions in a molecule where electrons reside and where they can be available for chemical reactions. In such compounds, this allows for unusual reactivity with small molecules like hydrogen (H_2), ammonia (NH_3), and ethylene (C_2H_4), a characteristic previously observed primarily in transition metal compounds. These reactions may open new avenues in catalytic applications.[93] Nonmetal classification schemes vary widely, with some accommodating as few as two subtypes and others up to seven. For example, the periodic table in the Encyclopaedia Britannica recognizes noble gases, halogens, and other nonmetals, and splits the elements commonly recognized as metalloids between "other metals" and "other nonmetals".[94] On the other hand, seven of twelve color categories on the Royal Society of Chemistry periodic table include nonmetals.[95][o] Group (1, 13−18) Period 13 14 15 16 1/17 18 (1−6) H He 1 B C N O F Ne 2 Si P S Cl Ar 3 Ge As Se Br Kr 4 Sb Te I Xe 5 Rn 6 Starting on the right side of the periodic table, three types of nonmetals can be recognized: the inert noble gases—helium, neon, argon, krypton, xenon, radon;[96] the reactive halogen nonmetals—fluorine, chlorine, bromine, iodine;[97] and the mixed reactivity "unclassified nonmetals", a set with no widely used collective name—hydrogen, carbon, nitrogen, oxygen, phosphorus, sulfur, selenium.[q] The descriptive phrase unclassified nonmetals is used here for convenience. The elements in a fourth set are sometimes recognized as nonmetals: the generally unreactive[s] metalloids,[115] sometimes considered a third category distinct from metals and nonmetals—boron, silicon, germanium, arsenic, antimony, tellurium. While many of the early workers attempted to classify elements none of their classifications were satisfactory. They were divided into metals and nonmetals, but some were soon found to have properties of both. These were called metalloids. This only added to the confusion by making two indistinct divisions where one existed before.[116] Whiteford & Coffin 1939, Essentials of College Chemistry The boundaries between these types are not sharp.[t] Carbon, phosphorus, selenium, and iodine border the metalloids and show some metallic character, as does hydrogen. The greatest discrepancy between authors occurs in metalloid "frontier territory".[118] Some consider metalloids distinct from both metals and nonmetals, while others classify them as nonmetals.[119] Some categorize certain metalloids as metals (e.g., arsenic and antimony due to their similarities to heavy metals).[120][u] Metalloids resemble the elements universally considered "nonmetals" in having relatively low densities, high electronegativity, and similar chemical behavior.[115][v] Main article: Noble gas A small (about 2 cm long) piece of rapidly melting argon ice Six nonmetals are classified as noble gases: helium, neon, argon, krypton, xenon, and the radioactive radon. In conventional periodic tables they occupy the rightmost column. They are called noble gases due to their exceptionally low chemical reactivity.[96] These elements exhibit similar properties, being colorlessness, odorless, and nonflammable. Due to their closed outer electron shells, noble gases possess weak interatomic forces of attraction, leading to exceptionally low melting and boiling points.[121] Chemically, the noble gases exhibit relatively high ionization energies, negligible or negative electron affinities, and high to very high electronegativities. The number of compounds formed by noble gases is in the hundreds and continues to expand,[122] with most of these compounds involving the combination of oxygen or fluorine with either krypton, xenon, or radon.[123] Main article: HalogenChemically, the halogen nonmetals have high ionization energies, electron affinities, and electronegativity values, and are relatively strong oxidizing agents.[124] All four elements tend to form primarily ionic compounds with metals,[125] in contrast to the remaining nonmetals (except for oxygen) which tend to form primarily covalent compounds with metals.[w] Selenium conducts electricity around 1,000 times better when light falls on it, a property used in light-sensing applications.[129] Hydrogen behaves in some respects like a metallic element and in others like a nonmetal.[130] Like a metallic element it can, for example, form a solvated cation in aqueous solution;[131] it can substitute for alkali metals in compounds such as the chlorides (NaCl cf. HCl) and nitrates (KNO_3 cf. HNO_3), and in certain alkali metal complexes[132][133] as a nonmetal.[134] It attains this configuration by forming a covalent or ionic bond[135] or by bonding as an ion to a lone pair of electrons.[136] Some or all of these nonmetals share several properties. Being generally less reactive than the halogens,[137] most of them can occur naturally in the environment.[138] Collectively, their physical and chemical characteristics can be described as "moderately non-metallic".[139] When combined with metals, the unclassified nonmetals can form interstitial or refractory compounds.[140] They also exhibit a tendency to bond to themselves, particularly in solid compounds.[141] Additionally, diagonal periodic table relationships among these nonmetals mirror similar relationships among the metalloids.[142] Approximate composition (top three components by weight; elements marked *nonmetal metal Universe[143] 75% *hydrogen 23% *helium 1% *oxygen Atmosphere[144] 78% *nitrogen 21% *oxygen 0.5% *argon Hydrosphere[145] 86% *oxygen 11% *hydrogen 2% *chlorine Biomass[146] 63% *oxygen 20% *carbon 10% *hydrogen Crust[145] 46% *oxygen 27% *silicon 8% aluminium Earth[147] 32% iron 30% *oxygen 14% magnesium The abundance of elements in the universe results from nuclear physics processes like nucleosynthesis and radioactive decay. The volatile noble gas nonmetal elements are less abundant in the atmosphere than expected based upon their overall abundance due to cosmic nucleosynthesis. Mechanisms to explain this difference is an important aspect of planetary science.[148] The element Xe is unexpectedly depleted, and a possible explanation comes from theoretical models of the high pressures in the Earth's core suggesting that there may be around 1013 tons of xenon in the form of stable $XeFe_3$ and $XeNi_3$ intermetallic compounds.[149] Five nonmetals—hydrogen, carbon, nitrogen, oxygen, and silicon—form the bulk of the directly observable structure of the Earth: about 73% of the crust, 93% of the biomass, 96% of the hydrosphere, and over 99% of the atmosphere, as shown in the accompanying table. Silicon and oxygen form stable tetrahedral structures, known as silicates. Here, "the powerful bond that unites the oxygen and silicon ions is the cement that holds the Earth's crust together."[150] However, they make up less than 50% of the total weight of the earth.[147] In the biomass, the relative abundance of the first four nonmetals (and phosphorus, sulfur, and selenium marginally) is attributed to a combination of relatively small atomic size, and sufficient spare electrons. These two properties enable them to bind to one another and "some other elements, to produce a molecular soup sufficient to build a self-replicating system."[151] Nine of the 23 nonmetallic elements are gases, or form compounds that are gases, and are extracted from natural gas or liquid air, including hydrogen, nitrogen, oxygen, sulfur, and most of the noble gases. For example, nitrogen and oxygen are extracted from liquid air through fractional distillation[152] and sulfur from the hydrogen sulfide in natural gas by reacting it with oxygen to yield water and sulfur.[153] Three nonmetals are extracted from seawater; the rest of the nonmetals – and almost all metals – from mining solid ores.[citation needed] Group (1, 13−18) Period 13 14 15 16 1/17 18 (1−6) H He 1 B C N O F Ne 2 Si P S Cl Ar 3 Ge As Se Br Kr 4 Sb Te I Xe 5 Rn 6 Nonmetallic elements are extracted from these sources:[138] 3 from natural gas components hydrogen (methane), helium, and sulfur (hydrogen sulfide) 6 from liquefied air nitrogen, oxygen, neon, argon, krypton, and xenon 3 from seawater brine chlorine, bromine, and iodine 12 from solid ores boron (borates), carbon (natural graphite), silicon (silica), phosphorus (phosphates), iodine (sodium iodate), radon (uranium ore decay product), fluorine (fluorite); and germanium, arsenic, selenium, antimony, and tellurium (from their sulfides). Cylinders containing argon gas for use in extinguishing fire without damaging computer server equipment Nonmetallic elements are present in combination with other elements in almost everything around us, from water to plastics and within metallic alloys. There are some specific uses of the elements themselves, although these are less common; extensive details can be found in the specific pages of the relevant elements. A few examples are: Hydrogen can be used in fuel cells, and is being explored for a possible future low-carbon hydrogen economy.[154] Carbon has many uses, ranging from decorative applications of diamond jewelry[155] to diamond in cutting blades[156] and graphite as a solid lubricant.[50] Liquid nitrogen is extensively used as a coolant.[157] Oxygen is a critical component of the air we breath. (While nitrogen is also present, it is less used from the air, mainly by certain bacteria.[158]) Oxygen gas and liquid is also heavily used for combustion in welding and cutting torches and as a component of rocket fuels.[159] Silicon is the most widely used semiconductor. While ultra-pure silicon is an insulator, by selectively adding electronic dopants it can be used as a semiconductor where the chemical potential of the electrons can be manipulated, this being exploited in a wide range of electronic devices.[160] The noble gases have a range of applications, including liquid helium for cryogenic cooling,[161] and argon to in gaseous fire suppression to -damp fires around sensitive electrical equipment where water cannot be used.[162] Radon is a potentially hazardous indoor pollutant.[163] Medieval chemical philosophers focused on metals, rarely investigating nonmetallic minerals.[164] French nobleman and chemist Antoine Lavoisier (1743–1794), with a page of the English translation of his 1789 Traité élémentaire de chimie,[165] listing the elemental gases oxygen, hydrogen and nitrogen (and erroneously including light and caloric); the nonmetallic substances sulfur, phosphorus, and carbon; and the chloride, fluoride and borate ions See also: Discovery of chemical elements In the late 1700s, French chemist Antoine Lavoisier published the first modern list of chemical elements in his revolutionary[166] 1789 Traité élémentaire de chimie. The 33 elements known to Lavoisier were categorized into four distinct groups, including gases, metallic substances, nonmetallic substances that form acids when oxidized,[167] and earths (heat-resistant oxides).[168] Lavoisier's work gained widespread recognition and was republished in twenty-three editions across six languages within its first seventeen years, significantly advancing the understanding of chemistry in Europe and America.[169] Lavoisier's chemistry was "dualistic",: "salts" were combinations of "acid" and "base"; acids where combinations of oxygen and metals while bases where combinations of oxygen and nonmetals. This view prevailed despite increasing evidence that chemicals like chlorine and ammonia contained no oxygen, in large part due the vigious if sometimes misguided defense by the Swedish chemist Berzelius.[167]:165 In 1802 the term "metalloids" was introduced for elements with the physical properties of metals but the chemical properties of non-metals.[170] In 1811 Berzelius used the term "metalloids"[171] to describe all nonmetallic elements, noting their ability to form negatively charged ions with oxygen in aqueous solutions.[172][173] Drawing on this, in 1864 the "Manual of Metalloids" divided all elements into either metals or metalloids, with the latter group including elements now called nonmetals.[174]:31 Reviews of the book indicated that the term "metalloids" was still endorsed by leading authorities,[175] but there were reservations about its appropriateness. While Berzelius' terminology gained significant acceptance,[176] it later faced criticism from some who found it counterintuitive,[173] misapplied,[177] or even invalid.[178] The idea of designating elements like arsenic as metalloids had been considered.[175] The use of the term "metalloids" persisted in France as textbooks of chemistry appeared in the 1800s. During this period, "metals" as a chemical category were characterized by a single property, their affinity for oxygen, while "metalloids" were organized by comparison of many characteristic analogous to the approach of naturalists.[179] Bust of Dupasquier (1793–1848) in the Monument aux Grands Hommes de la Martinière [fr] in Lyon, France. In 1844, Alphonse Dupasquier [fr], a French doctor, pharmacist, and chemist,[180] established a basic taxonomy of nonmetals to aid in their study. He wrote:[181] They will be divided into four groups or sections, as in the following: Organogens—oxygen, nitrogen, hydrogen, carbon Sulphuroids—sulfur, selenium, phosphorus Chloroides—fluorine, chlorine, bromine, iodine Boroids—boron, silicon. Dupasquier's quartet parallels the modern nonmetal types. The organogens and sulphuroids are akin to the unclassified nonmetals. The chloroides were later called halogens.[182] The boroids eventually evolved into the metalloids, with this classification beginning from as early as 1864.[175] The then unknown noble gases were recognized as a distinct nonmetal group after being discovered in the late 1800s.[183] This taxonomy was noted as a "natural classification" of the substance considering all aspects rather than an single characteristic like oxygen affinity.[184] It was a significant departure from other contemporary classifications, since it grouped together oxygen, nitrogen, hydrogen, and carbon.[185] In 1828 and 1859, the French chemist Dumas classified nonmetals as (1) hydrogen; (2) fluorine to iodine; (3) oxygen to sulfur; (4) nitrogen to arsenic; and (5) carbon, boron and silicon,[186] thereby anticipating the vertical groupings of Mendeleev's 1871 periodic table. Dumas' five classes fall into modern groups 1, 17, 16, 15, and 14 to 13 respectively. By as early as 1866, some authors began preferring the term "nonmetal" over "metalloid" to describe nonmetallic elements.[187] In 1875, Kemshead[188] observed that elements were categorized into two groups: non-metals (or metalloids) and metals. He noted that the term "non-metal", despite its compound nature, was more precise and had become universally accepted as the nomenclature of choice. The early terminologies were empirical categorizations based upon observables. As the 20th century started there were significant changes in understanding. The first was due to methods, mainly x-ray crystallography, for determining how atoms are arranged in the various

materials. As early as 1784 René Just Haüy discovered that every face of a crystal could be described by simple stacking patterns of blocks of the same shape and size (law of decrements).[189] Haüy's study led to the idea that crystals are a regular three-dimensional array (a Bravais lattice) of atoms and molecules, with a single unit cell repeated indefinitely, along with other developments in the early days of physical crystallography. After Max von Laue demonstrated in 1912 that x-rays diffract,[190] fairly quickly William Lawrence Bragg and his father William Henry Bragg were able to solve previously unknown structures.[191][192][193] Building on this, it became clear that most of the simple elemental metals had close packed structures. With this determined the concept of dislocations originally developed by Vito Volterra in 1907[194] became accepted, for instance being used to explain the ductility of metals by G. I. Taylor in 1934.[195] The second was the advent of quantum mechanics. In 1924 Louis de Broglie in his PhD thesis Recherches sur la théorie des quanta[196] introduced his theory of electron waves. This rapidly became part of what was called by Erwin Schrödinger undulatory mechanics,[197] now called the Schrödinger equation, wave mechanics or more commonly in contemporary usage quantum mechanics. While it was not so easy to solve the mathematics in the early days, fairly rapidly ideas such as the chemical bond terminology of Linus Pauling[198] as well as electronic band structure concepts were developed.[160]Filling of the electronic states in various types of materials at equilibrium. Here, height is energy while width is the density of available states for a certain energy in the material listed. The shade follows the Fermi–Dirac distribution (black: all states filled, white: no state filled). In metals and semimetals the Fermi level EF lies inside at least one band. In insulators and semiconductors the Fermi level is inside a band gap; however, in semiconductors the bands are near enough to the Fermi level to be thermally populated with electrons or holes. "intrin." indicates intrinsic semiconductors. editFrom this the concept of nonmetals as "not-a-metal" originates. The original approach to describe metals and nonmetals was a band-structure with delocalized electrons (i.e. spread out in space). A nonmetal has a gap in the energy levels of the electrons at the Fermi level.[160]:Chpt 8 & 19 In contrast, a metal would have at least one partially occupied band at the Fermi level;[160] in a semiconductor or insulator there are no delocalized states at the Fermi level, see for instance Ashcroft and Mermin.[160] (A semimetal is similar to a metal, with a slightly more complex band structure.) These definitions are equivalent to stating that metals conduct electricity at absolute zero, as suggested by Nevill Francis Mott,[199]:257 and the equivalent definition at other temperatures is also commonly used as in textbooks such as Chemistry of the Non-Metals by Ralf Steudel[200] and work on metal–insulator transitions.[201][202] Originally[203][204] this band structure interpretation was based upon a single-electron approach with the Fermi level in the band gap as illustrated in the Figure, not including a complete picture of the many-body problem where both exchange and correlation terms matter, as well as relativistic effects such as spin-orbit coupling. For instance, the passivity of gold is typically associated with relativistic terms.[205] A key addition by Mott and Rudolf Peierls was that these could not be ignored.[206] For instance, nickel oxide would be a metal if a single-electron approach was used, but in fact has quite a large band gap.[207] As of 2024 it is more common to use an approach based upon density functional theory where the many-body terms are included.[208][209] Although accurate calculations remain a challenge, reasonable results are now available in many cases.[210][211] It is common to nuance the early definition of Alan Herries Wilson and Mott which was for a zero temperature. As discussed by Peter Edwards and colleagues,[212] as well as Fumiko Yonezawa,[199]:257–261it is important to consider the temperatures at which both metals and nonmetals are used. Yonezawa provides a general definition for both general temperatures and conditions (such as standard temperature and pressure):[199]:260 When a material conducts and at the same time the temperature coefficient of the electric conductivity of that material is not positive under a certain environmental condition, the material is metallic under that environmental condition. A material which does not satisfy these requirements is not metallic under that environmental condition. The precise meaning of semiconductor needs a little care. In terms of the temperature dependence of their conductivity they are all classified as insulators; the pure forms are intrinsic semiconductors. When they are doped their conductivity continues to increase with temperature,[160] and can become substantial; hence the ambiguities with an empirical categorisation using conductivity described earlier. Indeed, some elements that are normally considered as insulators have been exploited as semiconductors. For instance diamond, which has the largest band gap of the elements that are solids under normal conditions,[213] has a number of semiconductor applications.[214][215] Band structure definitions of metals and nonmetals are widely used in current research into materials, and apply both to single elements such as insulating boron[216] as well as compounds such as strontium titanate.[217] The characteristics associated with metals and nonmetals in early work such as their appearance and mechanical properties are now understood to be consequences of how the atoms and electrons are arranged. The two tables in this section list some of the properties of five types of elements (noble gases, halogen nonmetals, unclassified nonmetals, metalloids and, for comparison, metals) based on their most stable forms at standard temperature and pressure. The dashed lines around the columns for metalloids signify that the treatment of these elements as a distinct type can vary depending on the author, or classification scheme in use. See also § Physical Physical properties are listed in loose order of ease of their determination. Property Element type Metals Metalloids Unc. nonmetals Halogen nonmetals Noble gases General physical appearance lustrous[19] lustrous[218] ◇ lustrous: carbon, phosphorus, selenium[219] ◇ colored: sulfur[220] ◇ colorless: hydrogen, nitrogen, oxygen[221] ◇ lustrous: iodine[3] ◇ colored: fluorine, chlorine, bromine[222] colorless[223] Form and density[224] solid (Hg liquid) solid solid or gas solid or gas (bromine liquid) gas often high density such as iron, lead, tungsten low to moderately high density low density low density some light metals including beryllium, magnesium, aluminium all lighter than iron hydrogen, nitrogen lighter than air[225] helium, neon lighter than air[226] Plasticity mostly malleable and ductile[19] often brittle[218] phosphorus, sulfur, selenium, brittle[x] iodine brittle[230] not applicable Electrical conductivity good[y] ◇ moderate: boron, silicon, germanium, tellurium ◇ good: arsenic, antimony[z] ◇ poor: hydrogen, nitrogen, oxygen, sulfur ◇ moderate: phosphorus, selenium ◇ good: carbon[aa] ◇ poor: fluorine, chlorine, bromine ◇ moderate: I[ab] poor[ac] Electronic structure[40] metal (beryllium, strontium, α-tin, ytterbium, bismuth are semimetals) semimetal (arsenic, antimony) or semiconductor ◇ semimetal: carbon ◇ semiconductor: phosphorus ◇ insulator: hydrogen, nitrogen, oxygen, sulfur semiconductor (I) or insulator insulator See also § Chemical Chemical properties are listed from general characteristics to more specific details. Property Element type Metals Metalloids Unc. nonmetals Halogen nonmetals Noble gases General chemical behavior ◇ strong to weakly metallic[234] ◇ noble metals are relatively inert[235] weakly nonmetallic[ad] moderately nonmetallic[236] strongly nonmetallic[237] ◇ inert to nonmetallic[238] ◇ radon shows some cationic behavior[239] Oxides basic; some amphoteric or acidic[8] amphoteric or weakly acidic[240][ae] acidic[af] or neutral[ag] acidic[ah] metastable XeO3 is acidic;[247] stable XeO4 strongly so[248] few glass formers[ai] all glass formers[250] some glass formers[aj] no glass formers reported no glass formers reported ionic, polymeric, layer, chain, and molecular structures[252] polymeric in structure[253] ◇ mostly molecular[253] ◇ carbon, phosphorus, sulfur, selenium have 1+ polymeric forms ◇ mostly molecular ◇ iodine has a polymeric form, I2O5[254] ◇ mostly molecular ◇ XeO2 is polymeric[255] Compounds with metals alloys[19] or intermetallic compounds[256] tend to form alloys or intermetallic compounds[257] ◇ salt-like to covalent or metallic: hydrogen†, carbon, nitrogen, phosphorus, sulfur, selenium[10] ◇ mainly ionic: oxygen[258] mainly ionic[125] simple compounds at STP not known[ak] Ionization energy (kJ mol−1)[59]‡ low to high moderate moderate to high high high to very high 376 to 1,007 762 to 947 941 to 1,402 1,008 to 1,681 1,037 to 2,372 average 643 average 833 average 1,152 average 1,270 average 1,589 Electronegativity (Pauling)[al][60]‡ low to high moderate moderate to high high high (radon) to very high 0.7 to 2.54 1.9 to 2.18 2.19 to 3.44 2.66 to 3.98 ca. 2.43 to 4.7 average 1.5 average 2.05 average 2.65 average 3.19 average 3.3 † Hydrogen can also form alloy-like hydrides[133] ‡ The labels low, moderate, high, and very high are arbitrarily based on the value spans listed in the table CHON (carbon, hydrogen, oxygen, nitrogen) List of nonmetal monographs Metallization pressure Nonmetal (astrophysics) Period 1 elements (hydrogen & helium) Properties of nonmetals (and metalloids) by group ^ The most stable forms are: diatomic hydrogen H2; β-rhombohedral boron; graphite for carbon; diatomic nitrogen N2; diatomic oxygen O2; tetrahedral silicon; black phosphorus; orthorhombic sulfur S8; α-germanium; gray arsenic; gray selenium; gray antimony; gray tellurium; and diatomic iodine I2. All other nonmetallic elements have only one stable form at STP.[5] ^ At higher temperatures and pressures the numbers of nonmetals can be called into question. For example, when germanium melts it changes from a semiconductor to a metallic conductor with an electrical conductivity similar to that of liquid mercury.[12] At a high enough pressure, sodium (a metal) becomes a non-conducting insulator.[13] ^ The absorbed light may be converted to heat or re-emitted in all directions so that the emission spectrum is thousands of times weaker than the incident light radiation.[16] ^ Solid iodine has a silvery metallic appearance under white light at room temperature. At ordinary and higher temperatures it sublimes from the solid phase directly into a violet-colored vapor.[17] ^ The solid nonmetals have electrical conductivity values ranging from 10−18 S•cm−1 for sulfur[21] to 3 × 104 in graphite[22] or 3.9 × 104 for arsenic;[23] cf. 0.69 × 104 for manganese to 63 × 104 for silver, both metals.[21] The conductivity of graphite and arsenic (both semimetals) exceed that of manganese. ^ Thermal conductivity values for metals range from 6.3 W m−1 K−1 for neptunium to 429 for silver; cf. antimony 24.3, arsenic 50, and carbon 2000.[21] Electrical conductivity values of metals range from 0.69 S•cm−1 × 104 for manganese to 63 × 104 for silver; cf. carbon 3 × 104,[22] arsenic 3.9 × 104 and antimony 2.3 × 104.[21] ^ While CO and NO are commonly referred to as being neutral, CO is a slightly acidic oxide, reacting with bases to produce formates (CO + OH− → HCOO−);[63] and in water, NO reacts with oxygen to form nitrous acid HNO2 (4NO + O2 + 2H2O → 4HNO2).[64] ^ Electronegativity values of fluorine to iodine are: 3.98 + 3.16 + 2.96 + 2.66 = 12.76/4 3.19. ^ Helium is shown above beryllium for electron configuration consistency purposes; as a noble gas it is usually placed above neon, in group 18. ^ The net result is an even-odd difference between periods (except in the s-block): elements in even periods have smaller atomic radii and prefer to lose fewer electrons, while elements in odd periods (except the first) differ in the opposite direction. Many properties in the p-block then show a zigzag rather than a smooth trend along the group. For example, phosphorus and antimony in odd periods of group 15 readily reach the +5 oxidation state, whereas nitrogen, arsenic, and bismuth in even periods prefer to stay at +3.[78] ^ Oxidation states do not reflect the actual net charge of atoms in molecules or ions, they represent the valence which refers more to how many bonds there are. For instance carbon typically has a valence of +4, but that only means that it forms three bonds. Electronegative elements such as fluorine are conventionally associated with negative valence, while electropositive ones have positive valence. ^ Greenwood[84] commented that: "The extent to which metallic elements mimic boron (in having fewer electrons than orbitals available for bonding) has been a fruitful cohering concept in the development of metalloborane chemistry ... Indeed, metals have been referred to as "honorary boron atoms" or even as "flexiboron atoms". The converse of this relationship is clearly also valid." ^ For example, the conductivity of graphite is 3 × 104 S•cm−1.[85] whereas that of manganese is 6.9 × 103 S•cm−1.[86] ^ A homopolyatomic cation consists of two or more atoms of the same element bonded together and carrying a positive charge, for example, N5+, O2+ and Cl4+. This is unusual behavior for nonmetals since cation formation is normally associated with metals, and nonmetals are normally associated with anion formation. Homopolyatomic cations are further known for carbon, phosphorus, antimony, sulfur, selenium, tellurium, bromine, iodine and xenon.[88] ^ Of the twelve categories in the Royal Society periodic table, five only show up with the metal filter, three only with the nonmetal filter, and four with both filters. Interestingly, the six elements marked as metalloids (boron, silicon, germanium, arsenic, antimony, and tellurium) show under both filters. Six other elements (113–118: nihonium, flerovium, moscovium, livermorium, tennessine, and oganesson), whose status is unknown, also show up under both filters but are not included in any of the twelve color categories. ^ The quote marks are not found in the source; they are used here to make it clear that the source employs the word non-metals as a formal term for the subset of chemical elements in question, rather than applying to nonmetals generally. ^ Varying configurations of these nonmetals have been referred to as, for example, basic nonmetals,[98] bioelements,[99] central nonmetals,[100] CHNOPS,[101] essential elements,[102] "non-metals",[103][p] orphan nonmetals,[104] or redox nonmetals.[105] ^ Arsenic is stable in dry air. Extended exposure in moist air results in the formation of a black surface coating. "Arsenic is not readily attacked by water, alkaline solutions or non-oxidizing acids".[110] It can occasionally be found in nature in an uncombined form.[111] It has a positive standard reduction potential (As → As3+ + 3e = +0.30 V), corresponding to a classification of semi-noble metal.[112] ^ "Crystalline boron is relatively inert."[106] Silicon "is generally highly unreactive."[107] "Germanium is a relatively inert semimetal."[108] "Pure arsenic is also relatively inert."[109][r] "Metallic antimony is ... inert at room temperature."[113] "Compared to S and Se, Te has relatively low chemical reactivity."[114] ^ Boundary fuzziness and overlaps often occur in classification schemes.[117] ^ Jones takes a philosophical or pragmatic view to these questions. He writes: "Though classification is an essential feature of all branches of science, there are always hard cases at the boundaries. The boundary of a class is rarely sharp ... Scientists should not lose sleep over the hard cases. As long as a classification system is beneficial to economy of description, to structuring knowledge and to our understanding, and hard cases constitute a small minority, then keep it. If the system becomes less than useful, then scrap it and replace it with a system based on different shared characteristics."[117] ^ For a related comparison of the properties of metals, metalloids, and nonmetals, see Rudakiya & Patel (2021), p. 36. ^ Metal oxides are usually somewhat ionic, depending upon the metal element electropositivity.[126] On the other hand, oxides of metals with high oxidation states are often either polymeric or covalent.[127] A polymeric oxide has a linked structure composed of multiple repeating units.[128] ^ All four have less stable non-brittle forms: carbon as exfoliated (expanded) graphite,[227][228] and as carbon nanotube wire;[229] phosphorus as white phosphorus (soft as wax, pliable and can be cut with a knife, at room temperature);[47] sulfur as plastic sulfur;[48] and selenium as selenium wires.[49] ^ Metals have electrical conductivity values of from 6.9×103 S•cm−1 for manganese to 6.3×105 for silver.[231] ^ Metalloids have electrical conductivity values of from 1.5×10−6 S•cm−1 for boron to 3.9×104 for arsenic.[232] ^ Unclassified nonmetals have electrical conductivity values of from ca. 1×10−18 S•cm−1 for the elemental gases to 3×104 in graphite.[85] ^ Halogen nonmetals have electrical conductivity values of from ca. 1×10−18 S•cm−1 for F and Cl to 1.7×10−8 S•cm−1 for iodine.[85][233] ^ Elemental gases have electrical conductivity values of ca. 1×10−18 S•cm−1.[85] ^ Metalloids always give "compounds less acidic in character than the corresponding compounds of the [typical] nonmetals."[218] ^ Arsenic trioxide reacts with sulfur trioxide, forming arsenic "sulfate" As2(SO4)3.[241] This substance is covalent in nature rather than ionic;[242] it is also given as As2O3·3SO3.[243] ^ NO2, N2O5, SO3, SeO3 are strongly acidic.[244] ^ H2O, CO, NO, N2O are neutral oxides; CO and N2O are "formally the anhydrides of formic and hyponitrous acid, respectively viz. CO + H2O → H2CO2 (HCOOH, formic acid); N2O + H2O → H2N2O2 (hyponitrous acid)."[245] ^ ClO2, Cl2O7, I2O5 are strongly acidic.[246] ^ Metals that form glasses are: vanadium; molybdenum, tungsten; alumnium, indium, thallium; tin, lead; and bismuth.[249] ^ Unclassified nonmetals that form glasses are phosphorus, sulfur, selenium;[249] CO2 forms a glass at 40 GPa.[251] ^ Disodium helide (Na2He) is a compound of helium and sodium that is stable at high pressures above 113 GPa. Argon forms an alloy with nickel, at 140 GPa and close to 1,500 K, however at this pressure argon is no longer a noble gas.[259] ^ Values for the noble gases are from Rahm, Zeng and Hoffmann.[260] ^ a b c Larrañaga, Lewis & Lewis 2016, p. 988 ^ a b Steudel 2020, p. 43: Steudel's monograph is an updated translation of the fifth German edition of 2013, incorporating the literature up to Spring 2019. ^ a b c Vernon 2013 ^ At: Restrepo et al. 2006, p. 411; Thornton & Burdette 2010, p. 86; Hermann, Hoffmann & Ashcroft 2013, pp. 11604–1–11604–5; Ts: [citation needed] Og: Smits et al. 2020 ^ Wismer 1997, p. 72: H, He, C, N, O, F, Ne, S, Cl, Ar, As, Se, Br, Kr, Sb, I, Xe; Powell 1974, pp. 174, 182: P, Te; Greenwood & Earnshaw 2002, p. 143: B; Field 1979, p. 403: Si, Ge; Addison 1964, p. 120: Rn ^ Pascoe 1982, p. 3[broken anchor] ^ Malone & Dolter 2010, pp. 110–111 ^ a b c Porterfield 1993, p. 336 ^ Godovikov & Nenasheva 2020, p. 4; Morely & Muir 1892, p. 241 ^ a b Vernon 2020, p. 220; Rochow 1966, p. 4 ^ IUPAC Periodic Table of the Elements ^ Berger 1997, pp. 71–72 ^ Gatti, Tokatly & Rubio 2010 ^ Wibaut 1951, p. 33: "Many substances ...are colourless and therefore show no selective absorption in the visible part of the spectrum." ^ Elliot 1929, p. 629 ^ Fox 2010, p. 31 ^ Tidy 1887, pp. 107–108; Koenig 1962, p. 108 ^ Wiberg 2001, p. 416; Wiberg is here referring to iodine. ^ a b c d e f Kneen, Rogers & Simpson 1972, pp. 261–264 ^ a b Johnson 1966, p. 4 ^ a b c d e Aylward & Findlay 2008, pp. 6–12 ^ a b Jenkins & Kawamura 1976, p. 88 ^ Carapella 1968, p. 30 ^ Zumdahl & DeCoste 2010, pp. 455, 456, 469, A40; Earl & Wilford 2021, p. 3-24 ^ Corb, B.W.; Wei, W.D.; Averbach, B.L. (1982). "Atomic models of amorphous selenium". Journal of Non-Crystalline Solids. 53 (1–2): 29–42. Bibcode:1982JNCS...53...29C. doi:10.1016/0022-3093(82)90016-3. ^ Wiberg 2001, pp. 780 ^ Wiberg 2001, pp. 824, 785 ^ Siekierski & Burgess 2002, p. 86 ^ Charlier, Gonze & Michenaud 1994 ^ Taniguchi et al. 1984, p. 867: "... black phosphorus ... [is] characterized by the wide valence bands with rather delocalized nature."; Carmalt & Norman 1998, p. 7: "Phosphorus ... should therefore be expected to have some metalloid properties."; Du et al. 2010: Interlayer interactions in black phosphorus, which are attributed to van der Waals-Keesom forces, are thought to contribute to the smaller band gap of the bulk material (calculated 0.19 eV; observed 0.3 eV) as opposed to the larger band gap of a single layer (calculated ~0.75 eV). ^ Wiberg 2001, pp. 742 ^ Evans 1966, pp. 124–25 ^ Wiberg 2001, pp. 758 ^ Stuke 1974, p. 178; Donohue 1982, pp. 386–87; Cotton et al. 1999, p. 501 ^ Steudel 2020, p. 601: "... Considerable orbital overlap can be expected. Apparently, intermolecular multicenter bonds exist in crystalline iodine that extend throughout the layer and lead to the delocalization of electrons akin to that in metals. This explains certain physical properties of iodine: the dark color, the luster and a weak electric conductivity, which is 3400 times stronger within the layers then perpendicular to them. Crystalline iodine is thus a two-dimensional semiconductor."; Segal 1989, p. 481: "Iodine exhibits some metallic properties ..." ^ Taylor 1960, p. 207; Brannt 1919, p. 34 ^ a b Green 2012, p. 14 ^ Spencer, Bodner & Rickard 2012, p. 178 ^ Redmer, Hensel & Holst 2010, preface ^ a b Keeler & Wothers 2013, p. 293 ^ DeKock & Gray 1989, pp. 423, 426—427 ^ Boreskov 2003, p. 45 ^ a b Ashcroft and Mermin ^ Yang 2004, p. 9 ^ Wiberg 2001, pp. 416, 574, 681, 824, 895, 930; Siekierski & Burgess 2002, p. 129 ^ Weertman, Johannes; Weertman, Julia R. (1992). Elementary dislocation theory. New York: Oxford University Press. ISBN 978-0-19-506900-6. ^ a b Faraday 1853, p. 42; Holderness & Berry 1979, p. 255 ^ a b Partington 1944, p. 405 ^ a b c Regnault 1853, p. 208 ^ a b Scharf, T. W.; Prasad, S. V. (January 2013). "Solid lubricants: a review". Journal of Materials Science. 48 (2): 511–531. Bibcode:2013JMatS..48..511S. doi:10.1007/s10853-012-7038-2. ISSN 0022-2461. ^ Barton 2021, p. 200 ^ Wiberg 2001, p. 796 ^ Shang et al. 2021 ^ Tang et al. 2021 ^ Steudel 2020, passim; Carrasco et al. 2023; Shanabrook, Lannin & Hisatsune 1981, pp. 130–133 ^ Weller et al. 2018, preface ^ Abbott 1966, p. 18 ^ Ganguly 2012, p. 1-1 ^ a b Aylward & Findlay 2008, p. 132 ^ a b c Aylward & Findlay 2008, p. 126 ^ Eagleson 1994, 1169 ^ Moody 1991, p. 365 ^ House 2013, p. 427 ^ Lewis & Deen 1994, p. 568 ^ Smith 1990, pp. 177–189 ^ Young et al. 2018, p. 753 ^ Brown et al. 2014, p. 227 ^ Moore 2016; Burford, Passmore & Sanders 1989, p. 54 ^ Yoder, Suydam & Snavely 1975, p. 58 ^ Brady & Senese 2009, p. 69 ^ Chemical Abstracts Service 2021 ^ Jensen 1986, p. 506 ^ Lee 1996, p. 240 ^ Greenwood & Earnshaw 2002, p. 43 ^ Cressey 2010 ^ Petruševski & Cvetković 2018; Grochala 2018 ^ Kneen, Rogers & Simpson 1972, pp. 226, 360; Siekierski & Burgess 2002, pp. 52, 101, 111, 124, 194 ^ Scerri 2020, pp. 407–420 ^ Shchukarev 1977, p. 229 ^ a b Cox 2004, p. 146 ^ Vij et al. 2001 ^ Dorsey 2023, pp. 12–13 ^ Humphrey 1908 ^ Greenwood 2001, p. 2057 ^ a b c d Bogoroditskii & Pasynkov 1967, p. 77; Jenkins & Kawamura 1976, p. 88 ^ Desai, James & Ho 1984, p. 1160 ^ Stein 1983, p. 165 ^ Engesser & Krossing 2013, p. 947 ^ Schweitzer & Pesterfield 2010, p. 305 ^ Rieck 1967, p. 97: Tungsten trioxide dissolves in hydrofluoric acid to give an oxyfluoride complex. ^ Wiberg 2001, p. 1279 ^ Pyper, N. C. (2020-09-18). "Relativity and the periodic table". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 378 (2180): 20190305. Bibcode:2020RSPTA.37890305P. doi:10.1098/rsta.2019.0305. ISSN 1364-503X. PMID 32811360. ^ Power 2010; Crow 2013; Weetman & Inoue 2018 ^ Encyclopaedia Britannica 2021 ^ Royal Society of Chemistry 2021 ^ a b Matson & Orbaek 2013, p. 203 ^ Kernion & Mascetta 2019, p. 191; Cao et al. 2021, pp. 20–21; Hussain et al. 2023; also called "nonmetal halogens": Chambers & Holliday 1982, pp. 273–274; Bohlmann 1992, p. 213; Jentzsch & Matile 2015, p. 247 or "stable halogens": Vassilakis, Kalemos & Mavridis 2014, p. 1; Hanley & Koga 2018, p. 24; Kaiho 2017, ch. 2, p. 1 ^ Williams 2007, pp. 1550–1561: H, C, N, P, O, S ^ Wächtershäuser 2014, p. 5: H, C, N, P, O, S, Se ^ Hengeveld & Fedonkin 2007, pp. 181–226: C, N, P, O, S ^ Wakeman 1899, p. 562 ^ Fraps 1913, p. 11: H, C, Si, N, P, O, S, Cl ^ Parameswaran at al. 2020, p. 210: H, C, N, P, O, S, Se ^ Knight 2002, p. 148: H, C, N, P, O, S, Se ^ Fraústo da Silva & Williams 2001, p. 500: H, C, N, O, S, Se ^ Zhu et al. 2022 ^ Graves 2022 ^ Rosenberg 2013, p. 847 ^ Obodovskiy 2015, p. 151 ^ Greenwood & Earnshaw 2002, p. 552 ^ Eagleson 1994, p. 91 ^ Huang 2018, pp. 30, 32 ^ Orisakwe 2012, p. 000 ^ Yin et al. 2018, p. 2 ^ a b Moeller et al. 1989, p. 742 ^ Whiteford & Coffin 1939, p. 239 ^ a b Jones 2010, pp. 169–71 ^ Russell & Lee 2005, p. 419 ^ Goodrich 1844, p. 264; The Chemical News 1897, p. 189; Hampel & Hawley 1976, pp. 174, 191; Lewis 1993, p. 835; Hérold 2006, pp. 149–50 ^ Tyler 1948, p. 105; Reilly 2002, pp. 5–6 ^ Jolly 1966, p. 20 ^ Maosheng 2020, p. 962 ^ Mazej 2020 ^ Rudolph 1973, p. 133: "Oxygen and the halogens in particular ... are therefore strong oxidizing agents." ^ a b Cotton et al. 1999, p. 554 ^ Woodward et al. 1999, pp. 133–194 ^ Phillips & Williams 1965, pp. 478–479 ^ Moeller et al. 1989, p. 314 ^ Emsley 2011, p. 478 ^ Seese & Daub 1985, p. 65 ^ MacKay, MacKay & Henderson 2002, pp. 209, 211 ^ Cousins, Davidson & García-Vivó 2013, pp. 11809–11811 ^ a b Cao et al. 2021, p. 4 ^ Liptrot 1983, p. 161; Malone & Dolter 2008, p. 255 ^ Wiberg 2001, pp. 255–257 ^ Scott & Kanda 1962, p. 153 ^ Taylor 1960, p. 316 ^ a b Emsley 2011, passim ^ Cao et al. 2021, p. 20 ^ Messler 2011, p. 10 ^ King 1994, p. 1344; Powell & Tims 1974, pp. 189–191; Cao et al. 2021, pp. 20–21 ^ Vernon 2020, pp. 221–223; Rayner-Canham 2020, p. 216 ^ Chandra X-ray Center 2018 ^ Chapin, Matson & Vitousek 2011, p. 27 ^ a b Fortescue 1980, p. 56 ^ Georgievskii 1982, p. 58 ^ a b Morgan & Anders 1980, p. 6975 ^ Pepin, R. O.; Porcelli, D. (2002-01-01). "Origin of Noble Gases in the Terrestrial Planets". Reviews in Mineralogy and Geochemistry. 47 (1): 191–246. Bibcode:2002RvMG...47..191P. doi:10.2138/rmg.2002.47.7. ISSN 1529-6466. ^ Zhu et al. 2014, pp. 644–648 ^ Klein & Dutrow 2007, p. 435[broken anchor] ^ Cockell 2019, p. 212, 208–211 ^ Emsley 2011, pp. 363, 379 ^ Emsley 2011, p. 516 ^ Cheng, Xuan; Shi, Zheng; Glass, Nancy; Zhang, Lu; Zhang, Jiujun; Song, Datong; Liu, Zhong-Sheng; Wang, Haijiang; Shen, Jun (2007-03-20). "A review of PEM hydrogen fuel cell contamination: Impacts, mechanisms, and mitigation". Journal of Power Sources. IBA – HBC 2006. 165 (2): 739–756. Bibcode:2007JPS...165..739C. doi:10.1016/j.jpowsour.2006.12.012. ISSN 0378-7753. ^ Purbrick, L. (2011-02-22). "Brilliant Effects: A Cultural History of Gem Stones and Jewellery". Journal of Design History. 24 (1): 88–90. doi:10.1093/jdh/epq052. ISSN 0952-4649. ^ Harlow, George E. (1997). The nature of diamonds. American museum of natural history. Cambridge: Cambridge University Press in association with the American Museum of Natural History. ISBN 978-0-521-62083-3. ^ Beteta, Oscar; Ivanova, Svetlana (September 2015). "Cool down with liquid nitrogen" (PDF). American Institute of Chemical Engineers. ^ Franche, Claudine; Lindström, Kristina; Elmerich, Claudine (2009). "Nitrogen-fixing bacteria associated with leguminous and non-leguminous plants". Plant and Soil. 321 (1–2): 35–59. Bibcode:2009PlSoi.321...35F. doi:10.1007/s11104-008-9833-8. ISSN 0032-079X. ^ "Basics of Space Flight: Rocket Propellants". www.braeunig.us. Retrieved 2025-04-24. ^ a b c d e f Ashcroft, Neil W.; Mermin, N. David (1976). Solid state physics. Fort Worth Philadelphia San Diego [etc.]: Saunders college publ. ISBN 978-0-03-083993-1. ^ "4 Ways Cryogenic Applications of Helium Can Be Used". www.cryogenicsociety.org. Retrieved 2025-04-24. ^ Peters, M. J. "Which Gases Are Used in Fire Suppression Systems?". www.firetrace.com. Retrieved 2025-04-24. ^ Maroni 1995, pp. 108–123 ^ Stillman 1924, p. 213 ^ Lavoisier 1790, p. 175 ^ Strathern 2000, p. 239 ^ a b Moore, F. J.; Hall, William T. (1918). A History Of Chemistry. McGraw-Hill. p. 99. Retrieved 2024-08-01. Lavoisier's Table is reproduced on page 99. ^ Criswell 2007, p. 1140 ^ Salzberg 1991, p. 204 ^ Friend JN 1953, Man and the Chemical Elements, 1st ed., Charles Scribner's Sons, New York ^ Berzelius 1811, p. 258 ^ Partington 1964, p. 168 ^ a b Bache 1832, p. 250 ^ Apjohn, J. (1864). Manual of the Metalloids. United Kingdom: Longman. ^ a b c The Chemical News and Journal of Physical Science 1864 ^ Goldsmith 1982, p. 526 ^ Roscoe & Schormlemmer 1894, p. 4 ^ Glinka 1960, p. 76 ^ Bertomeu-Sánchez et al. 2002, pp. 235 ^ Bertomeu-Sánchez et al. 2002, pp. 248–249 ^ Dupasquier 1844, pp. 66–67 ^ Bache 1832, pp. 248–276 ^ Renouf 1901, pp. 268 ^ Bertomeu-Sánchez et al. 2002, p. 236 ^ Hoefer 1845, p. 85 ^ Dumas 1828; Dumas 1859 ^ Oxford English Dictionary 1989 ^ Kemshead 1875, p. 13 ^ Authier, André (2013). Early days of X-ray crystallography. Oxford: Oxford university press. ISBN 978-0-19-965984-5. ^ von Laue M (1914). "Concerning the detection of x-ray interferences" (PDF). Nobel Lectures, Physics. 1901–1921. Archived (PDF) from the original on 2010-12-07. Retrieved 2009-02-18. ^ Bragg WL (1913). "The Structure of Some Crystals as Indicated by their Diffraction of X-rays". Proc. R. Soc. Lond. A89 (610): 248–277. Bibcode:1913RSPSA..89..248B. doi:10.1098/rspa.1913.0083. JSTOR 93488. ^ Bragg WL, James RW, Bosanquet CH (1921). "The Intensity of Reflexion of X-rays by Rock-Salt". Phil. Mag. 41 (243): 309. doi:10.1080/14786442108636225. Archived from the original on 2020-03-29. Retrieved 2019-09-10. ^ Bragg WL, James RW, Bosanquet CH (1921). "The Intensity of Reflexion of X-rays by Rock-Salt. Part II". Phil. Mag. 42 (247): 1. doi:10.1080/14786442108633730. Archived from the original on 2020-03-29. Retrieved 2019-09-10. ^ Vito Volterra (1907) "Sur l'équilibre des corps élastiques multiplement connexes", Annales Scientifiques de l'École Normale Supérieure, Vol. 24, pp. 401–517 ^ G. I. Taylor (1934). "The Mechanism of Plastic Deformation of Crystals. Part I. Theoretical". Proceedings of the Royal Society of London. Series A. 145 (855): 362–87. Bibcode:1934RSPSA.145..362T. doi:10.1098/rspa.1934.0106. JSTOR 2935509. ^ de Broglie, Louis Victor. "On the Theory of Quanta" (PDF). Foundation of Louis de Broglie (English translation by A.F. Kracklauer, 2004. ed.). Retrieved 25 February 2023. ^ Schrödinger, E. (1926). "An Undulatory Theory of the Mechanics of Atoms and Molecules". Physical Review. 28 (6): 1049–1070. Bibcode:1926PhRv...28.1049S. doi:10.1103/PhysRev.28.1049. ISSN 0031-899X. ^ Pauling, Linus (2010). The nature of the chemical bond and the structure of molecules and crystals: an introduction to modern structural chemistry (3. ed., 17. print ed.). Ithaca, NY: Cornell Univ. Press. ISBN 978-0-8014-0333-0. ^ a b c Yonezawa, Fumiko (2017). Physics of metal-nonmetal transitions. Washington, DC: IOS Press. ISBN 978-1-61499-786-3. ^ Steudel, Ralf (2020). Chemistry of the Non-Metals: Syntheses - Structures - Bonding - Applications. De Gruyter. p. 154. doi:10.1515/9783110578065. ISBN 978-3-11-057806-5. ^ MOTT, N. F. (1968-10-01). "Metal-Insulator Transition". Reviews of Modern Physics. 40 (4): 677–683. Bibcode:1968RvMP...40..677M. doi:10.1103/RevModPhys.40.677. ^ Imada, Masatoshi; Fujimori, Atsushi; Tokura, Yoshinori (1998-10-01). "Metal-insulator transitions". Reviews of Modern Physics. 70 (4): 1039–1263. Bibcode:1998RvMP...70.1039I. doi:10.1103/RevModPhys.70.1039. ^ Wilson, A. H. (1931). "The theory of electronic semi-conductors". Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character. 133 (822): 458–491. Bibcode:1931RSPSA.133..458W. doi:10.1098/rspa.1931.0162. ISSN 0950-1207. ^ Wilson, A. H. (1931). "The theory of electronic semi-conductors. - II". Proceedings of the Royal Society of London. Series A, Containing Papers of a Mathematical and Physical Character. 134 (823): 277–287. Bibcode:1931RSPSA.134..277W. doi:10.1098/rspa.1931.0196. ISSN 0950-1207. ^ Pyykkö, Pekka (2012-05-05). "Relativistic Effects in Chemistry: More Common Than You Thought". Annual Review of Physical Chemistry. 63 (1): 45–64. Bibcode:2012ARPC...63...45P. doi:10.1146/annurev-physchem-032511-143755. ISSN 0066-426X. PMID 22404585. ^ Mott, N F; Peierls, R (1937). "Discussion of the paper by de Boer and Verwey". Proceedings of the Physical Society. 49 (4S): 72–73. Bibcode:1937PPS....49...72M. doi:10.1088/0959-5309/49/4S/308. ISSN 0959-5309. ^ Boer, J H de; Verwey, E J W (1937). "Semi-conductors with partially and with completely filled 3 d -lattice bands". Proceedings of the Physical Society. 49 (4S): 59–71. Bibcode:1937PPS....49...59B. doi:10.1088/0959-5309/49/4S/307. ISSN 0959-5309. ^ Burke, Kieron (2007). "The ABC of DFT" (PDF). ^ Gross, Eberhard K. U.; Dreizler, Reiner M. (2013). Density Functional Theory. Springer Science & Business Media. ISBN 978-1-4757-9975-0. ^ Ferreira, Luiz G.; Marques, Marcelo; Teles, Lara K. (2008). "Approximation to density functional theory for the calculation of band gaps of semiconductors". Physical Review B. 78 (12): 125116. arXiv:0808.0729. Bibcode:2008PhRvB..78l5116F. doi:10.1103/PhysRevB.78.125116. ISSN 1098-0121. ^ Tran, Fabien; Blaha, Peter (2017). "Importance of the Kinetic Energy Density for Band Gap Calculations in Solids with Density Functional Theory". The Journal of Physical Chemistry A. 121 (17): 3318–3325. Bibcode:2017JPCA..121.3318T. doi:10.1021/acs.jpca.7b02882. ISSN 1089-5639. PMC 5423078. PMID 28402113. ^ Edwards, P. P.; Lodge, M. T. J.; Hensel, F.; Redmer, R. (2010). "'... a metal conducts and a non-metal doesn't'". Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences. 368 (1914): 941–965. Bibcode:2010RSPTA.368..941E. doi:10.1098/rsta.2009.0282. ISSN 1364-503X. PMC 3263814. PMID 20123742. ^ Strehlow, W. H.; Cook, E. L. (1973-01-01). "Compilation of Energy Band Gaps in Elemental and Binary Compound Semiconductors and Insulators". Journal of Physical and Chemical Reference Data. 2 (1): 163–200. Bibcode:1973JPCRD...2..163S. doi:10.1063/1.3253115. ISSN 0047-2689. ^ Collins, Alan T. (1997). "The optical and electronic properties of semiconducting diamond". Philosophical Transactions of the Royal Society of London, Series A. 342 (1664): 233–244. doi:10.1098/rsta.1993.0017. ^ Umezawa, Hitoshi (2018-05-01). "Recent advances in diamond power semiconductor devices". Materials Science in Semiconductor Processing. Wide band gap semiconductors technology for next generation of energy efficient power electronics. 78: 147–156. doi:10.1016/j.mssp.2018.01.007. ISSN 1369-8001. ^ Ogitsu, Tadashi; Schwegler, Eric; Galli, Giulia (2013). "β-Rhombohedral Boron: At the Crossroads of the Chemistry of Boron and the Physics of Frustration". Chemical Reviews. 113 (5): 3425–3449. doi:10.1021/cr300356t. ISSN 0009-2665. OSTI 1227014. PMID 23472640. ^ Reihl, B.; Bednorz, J. G.; Müller, K. A.; Jugnet, Y.; Landgren, G.; Morar, J. F. (1984). "Electronic structure of strontium titanate". Physical Review B. 30 (2): 803–806. Bibcode:1984PhRvB..30..803R. doi:10.1103/PhysRevB.30.803. ISSN 0163-1829. ^ a b c Rochow 1966, p. 4 ^ Wiberg 2001, p. 780; Emsley 2011, p. 397; Rochow 1966, pp. 23, 84 ^ Kneen, Rogers & Simpson 1972, p. 439 ^ Kneen, Rogers & Simpson 1972, pp. 321, 404, 436 ^ Kneen, Rogers & Simpson 1972, p. 465 ^ Kneen, Rogers & Simpson 1972, p. 308 ^ Tregarthen 2003, p. 10 ^ Lewis 1993, pp. 28, 827 ^ Lewis 1993, pp. 28, 813 ^ Chung 1987 ^ Godfrin & Lauter 1995, pp. 216–218 ^ Janas, Cabrero-Vilatela & Bulmer 2013 ^ Wiberg 2001, p. 416 ^ Desai, James & Ho 1984, p. 1160; Matula 1979, p. 1260 ^ Schaefer 1968, p. 76; Carapella 1968, pp. 29–32 ^ Greenwood & Earnshaw 2002, p. 804 ^ Kneen, Rogers & Simpson 1972, p. 264 ^ Rayner-Canham 2018, p. 203 ^ Welcher 2009, p. 3–32: "The elements change from ... metalloids, to moderately active nonmetals, to very active nonmetals, and to a noble gas." ^ Mackin 2014, p. 80 ^ Johnson 1966, pp. 105–108 ^ Stein 1969, pp. 5396–5397; Pitzer 1975, pp. 760–761 ^ Rochow 1966, p. 4; Atkins et al. 2006, pp. 8, 122–123 ^ Wiberg 2001, p. 750. ^ Douglade & Mercier 1982, p. 723 ^ Gillespie & Robinson 1959, p. 418 ^ Sanderson 1967, p. 172; Mingos 2019, p. 27 ^ House 2008, p. 441 ^ Mingos 2019, p. 27; Sanderson 1967, p. 172 ^ Wiberg 2001, p. 399 ^ Kläning & Appelman 1988, p. 3760 ^ a b Rao 2002, p. 22 ^ Sidorov 1960, pp. 599–603 ^ McMillan 2006, p. 823 ^ Wells 1984, p. 534 ^ a b Puddephatt & Monaghan 1989, p. 59 ^ King 1995, p. 182 ^ Ritter 2011, p. 10 ^ Yamaguchi & Shirai 1996, p. 3 ^ Vernon 2020, p. 223 ^ Woodward et al. 1999, p. 134 ^ Dalton 2019 ^ Rahm, Zeng & Hoffmann 2019, p. 345 Abbott D 1966, An Introduction to the Periodic Table, J. M. Dent & Sons, London Addison WE 1964, The Allotropy of the Elements, Oldbourne Press, London Atkins PA et al. 2006, Shriver & Atkins' Inorganic Chemistry, 4th ed., Oxford University Press, Oxford, ISBN 978-0-7167-4878-6 Aylward G and Findlay T 2008, SI Chemical Data, 6th ed., John Wiley & Sons Australia, Milton, ISBN 978-0-470-81638-7 Bache AD 1832, "An essay on chemical nomenclature, prefixed to the treatise on chemistry; by J. J. Berzelius", American Journal of Science, vol. 22, pp. 248–277 Baker et al. PS 1962, Chemistry and You, Lyons and Carnahan, Chicago Barton AFM 2021, States of Matter, States of Mind, CRC Press, Boca Raton, ISBN 978-0-7503-0418-4 Beach FC (ed.) 1911, The Americana: A universal reference library, vol. XIII, Mel–New, Metalloid, Scientific American Compiling Department, New York Beard A, Battenberg, C & Sutker BJ 2021, "Flame retardants", in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.a11_123.pub2 Beiser A 1987, Concepts of modern physics, 4th ed., McGraw-Hill, New York, ISBN 978-0-07-004473-9 Benner SA, Ricardo A & Carrigan MA 2018, "Is there a common chemical model for life in the universe?", in Cleland CE & Bedau MA (eds.), The Nature of Life: Classical and Contemporary Perspectives from Philosophy and Science, Cambridge University Press, Cambridge, ISBN 978-1-108-72206-3 Benzhen et al. 2020, Metals and non-metals in the periodic table, Philosophical Transactions of the Royal Society A, vol. 378, 20200213 Berger LI 1997, Semiconductor Materials, CRC Press, Boca Raton, ISBN 978-0-8493-8912-2 Bertomeu-Sánchez JR, Garcia-Belmar A & Bensaude-Vincent B 2002, "Looking for an order of things: Textbooks and chemical classifications in nineteenth century France", Ambix, vol. 49, no. 3, doi:10.1179/amb.2002.49.3.227 Berzelius JJ 1811, 'Essai sur la nomenclature chimique', Journal de Physique, de Chimie, d'Histoire Naturelle, vol. LXXIII, pp. 253–286 Bhuwalka et al. 2021, "Characterizing the changes in material use due to vehicle electrification", Environmental Science & Technology vol. 55, no. 14, doi:10.1021/acs.est.1c00970 Bogoroditskii NP & Pasynkov VV 1967, Radio and Electronic Materials, Iliffe Books, London Bohlmann R 1992, "Synthesis of halides", in Winterfeldt E (ed.), Heteroatom manipulation, Pergamon Press, Oxford, ISBN 978-0-08-091249-3 Boreskov GK 2003, Heterogeneous Catalysis, Nova Science, New York, ISBN 978-1-59033-864-3 Brady JE & Senese F 2009, Chemistry: The study of Matter and its Changes, 5th ed., John Wiley & Sons, New York, ISBN 978-0-470-57642-7 Brande WT 1821, A Manual of Chemistry, vol. II, John Murray, London Brandt HG & Weiler H, 2000, "Welding and cutting", in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.a28_203 Brannt WT 1919, Metal Worker's Handy-book of Receipts and Processes, HC Baird & Company, Philadelphia Brown TL et al. 2014, Chemistry: The Central Science, 3rd ed., Pearson Australia: Sydney, ISBN 978-1-4425-5460-3 Burford N, Passmore J & Sanders JCP 1989, "The preparation, structure, and energetics of homopolyatomic cations of groups 16 (the chalcogens) and 17 (the halogens)", in Liebman JF & Greenberg A (eds.), From atoms to polymers: isoelectronic analogies, VCH, New York, ISBN 978-0-89573-711-3 Bynum WF, Browne J & Porter R 1981 (eds), Dictionary of the History of Science, Princeton University Press, Princeton, ISBN 978-0-691-08287-5 Cahn RW & Haasen P, Physical Metallurgy: Vol. 1, 4th ed., Elsevier Science, Amsterdam,ISBN 978-0-444-89875-3 Cao C et al. 2021, "Understanding periodic and non-periodic chemistry in periodic tables", Frontiers in Chemistry, vol. 8, no. 813, doi:10.3389/fchem.2020.00813 Carapella SC 1968, "Arsenic" in Hampel CA (ed.), The Encyclopedia of the Chemical Elements, Reinhold, New York Carmalt CJ & Norman NC 1998, "Arsenic, antimony and bismuth: Some general properties and aspects of periodicity", in Norman NC (ed.), Chemistry of Arsenic, Antimony and Bismuth, Blackie Academic & Professional, London, pp. 1–38, ISBN 0-7514-0389-X Carrasco et al. 2023, "Antimonene: a tuneable post-graphene material for advanced applications in optoelectronics, catalysis, energy and biomedicine", Chemical Society Reviews, vol. 52, no. 4, p. 1288–1330, doi:10.1039/d2cs00570k Challoner J 2014, The Elements: The New Guide to the Building Blocks of our Universe, Carlton Publishing Group, ISBN 978-0-233-00436-5 Chambers E 1743, in "Metal", Cyclopedia: Or an Universal Dictionary of Arts and Sciences (etc.), vol. 2, D Midwinter, London Chambers C & Holliday AK 1982, Inorganic Chemistry, Butterworth & Co., London, ISBN 978-0-408-10822-5 Chandra X-ray Observatory 2018, Abundance Pie Chart, accessed 26 October 2023 Chapin FS, Matson PA & Vitousek PM 2011, Earth's climate system, in Principles of Terrestrial Ecosystem Ecology, Springer, New York, ISBN 978-1-4419-9503-2 Charlier J-C, Gonze X, Michenaud J-P 1994, "First-principles study of the stacking effect on the electronic properties of graphite(s)", Carbon, vol. 32, no. 2, pp. 289–99, doi:10.1016/0008-6223(94)90192-9 Chedd G 1969, Half-way elements: The technology of metalloids, Double Day, Garden City, NY Chemical Abstracts Service 2021, CAS REGISTRY database as of November 2, Case #01271182 Chen K 1990, Industrial Power Distribution and Illuminating Systems, Marcel Dekker, New York, ISBN 978-0-8247-8237-5 Chung DD 1987, "Review of exfoliated graphite", Journal of Materials Science, vol. 22, doi:10.1007/BF01132008 Clugston MJ & Flemming R 2000, Advanced Chemistry, Oxford University Press, Oxford, ISBN 978-0-19-914633-8 Cockell C 2019, The Equations of Life: How Physics Shapes Evolution, Atlantic Books, London, ISBN 978-1-78649-304-0 Cook CG 1923, Chemistry in Everyday Life: With Laboratory Manual, D Appleton, New York Cotton A et al. 1999, Advanced Inorganic Chemistry, 6th ed., Wiley, New York, ISBN 978-0-471-19957-1 Cousins DM, Davidson MG & García-Vivó D 2013, "Unprecedented participation of a four-coordinate hydrogen atom in the cubane core of lithium and sodium phenolates", Chemical Communications, vol. 49, doi:10.1039/C3CC47393G Cox PA 1997, The Elements: Their Origins, Abundance, and Distribution, Oxford University Press, Oxford, ISBN 978-0-19-855298-7 Cox T 2004, Inorganic Chemistry, 2nd ed., BIOS Scientific Publishers, London, ISBN 978-1-85996-289-3 Crawford FH 1968, Introduction to the Science of Physics, Harcourt, Brace & World, New York Cressey D 2010, "Chemists re-define hydrogen bond" Archived 2019-01-24 at the Wayback Machine, Nature newsblog, accessed August 23, 2017 Crichton R 2012, Biological Inorganic Chemistry: A New Introduction to Molecular Structure and Function, 2nd ed., Elsevier, Amsterdam, ISBN 978-0-444-53783-6 Criswell B 2007, "Mistake of having students be Mendeleev for just a day", Journal of Chemical Education, vol. 84, no. 7, pp. 1140–1144, doi:10.1021/ed084p1140 Crow JM 2013, Main group renaissance, Chemistry World, 31 May, accessed 26 December 2023 Csele M 2016, Lasers, in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.a15_165.pub2 Dalton L 2019, "Argon reacts with nickel under pressure-cooker conditions", Chemical & Engineering News, accessed November 6, 2019 de Clave E 1651, Nouvelle Lumière philosophique des vrais principes et élémens de nature, et qualité d'iceux, contre l'opinion commune, Olivier de Varennes, Paris Daniel PL & Rapp RA 1976, "Halogen corrosion of metals", in Fontana MG & Staehle RW (eds.), Advances in Corrosion Science and Technology, Springer, Boston, doi:10.1007/978-1-4615-9062-0_2 de L'Aunay L 1566, Responce au discours de maistre Iacques Grevin, docteur de Paris, qu'il a escript contre le livre de maistre Loys de L'Aunay, medecin en la Rochelle, touchant la faculté de l'antimoine (Response to the Speech of Master Jacques Grévin,... Which He Wrote Against the Book of Master Loys de L'Aunay,... Touching the Faculty of Antimony), De l'Imprimerie de Barthelemi Berton, La Rochelle Davis et al. 2006, "Atomic iodine lasers", in Endo M & Walter RF (eds) 2006, Gas Lasers, CRC Press, Boca Raton, Florida, ISBN 978-0-470-19565-9 DeKock RL & Gray HB 1989, Chemical structure and bonding, University Science Books, Mill Valley, CA, ISBN 978-0-935702-61-3 Desai PD, James HM & Ho CY 1984, "Electrical resistivity of aluminum and manganese", Journal of Physical and Chemical Reference Data, vol. 13, no. 4, doi:10.1063/1.555725 Donohue J 1982, The Structures of the Elements, Robert E. Krieger, Malabar, Florida, ISBN 978-0-89874-230-5 Dorsey MG 2023, Holding Their Breath: How the Allies Confronted the Threat of Chemical Warfare in World War II, Cornell University Press, Ithaca, New York, pp. 12–13, ISBN 978-1-5017-6837-8 Douglade J, Mercier R 1982, Structure cristalline et covalence des liaisons dans le sulfate d'arsenic(III), As2(SO4)3, Acta Crystallographica Section B, vol. 38, no, 3, 720–723, doi:10.1107/s056774088200394x Du Y, Ouyang C, Shi S & Lei M 2010, Ab initio studies on atomic and electronic structures of black phosphorus, Journal of Applied Physics, vol. 107, no. 9, pp. 093718–1–4, doi:10.1063/1.3386509 Duffus JH 2002, " 'Heavy metals'—A meaningless term?", Pure and Applied Chemistry, vol. 74, no. 5, pp. 793–807, doi:10.1351/pac200274050793 Dumas JBA 1828, Traité de Chimie Appliquée aux Arts, Béchet Jeune, Paris Dumas JBA 1859, Mémoire sur les Équivalents des Corps Simples, Mallet-Bachelier, Paris Dupasquier A 1844, Traité élémentaire de chimie industrielle, Charles Savy Juene, Lyon Eagleson M 1994, Concise Encyclopedia Chemistry, Walter de Gruyter, Berlin, ISBN 3-11-011451-8 Earl B & Wilford D 2021, Cambridge O Level Chemistry, Hodder Education, London, ISBN 978-1-3983-1059-9 Edwards PP 2000, "What, why and when is a metal?", in Hall N (ed.), The New Chemistry, Cambridge University, Cambridge, pp. 85–114, ISBN 978-0-521-45224-3 Edwards PP et al. 2010, "... a metal conducts and a non-metal doesn't", Philosophical Transactions of the Royal Society A, 2010, vol, 368, no. 1914, doi:10.1098/rsta.2009.0282 Edwards PP & Sienko MJ 1983, "On the occurrence of metallic character in the periodic table of the elements", Journal of Chemical Education, vol. 60, no. 9, doi:10.1021/ed060p691, PMID 25666074 Elliot A 1929, "The absorption band spectrum of chlorine", Proceedings of the Royal Society A, vol. 123, no. 792, pp. 629–644, doi:10.1098/rspa.1929.0088 Emsley J 1971, The Inorganic Chemistry of the Non-metals, Methuen Educational, London, ISBN 978-0-423-86120-4 Emsley J 2011, Nature's Building Blocks: An A–Z Guide to the Elements, Oxford University Press, Oxford, ISBN 978-0-19-850341-5 Encyclopaedia Britannica, 2021, Periodic table, accessed September 21, 2021 Engesser TA & Krossing I 2013, "Recent advances in the syntheses of homopolyatomic cations of the non metallic elements C, N, P, S, Cl, Br, I and Xe", Coordination Chemistry Reviews, vol. 257, nos. 5–6, pp. 946–955, doi:10.1016/j.ccr.2012.07.025 Erman P & Simon P 1808, "Third report of Prof. Erman and State Architect Simon on their joint experiments", Annalen der Physik, vol. 28, no. 3, pp. 347–367 Evans RC 1966, An Introduction to Crystal Chemistry, 2nd ed., Cambridge University, Cambridge Faraday M 1853, The Subject Matter of a Course of Six Lectures on the Non-metallic Elements, (arranged by John Scoffern), Longman, Brown, Green, and Longmans, London Field JE (ed.) 1979, The Properties of Diamond, Academic Press, London, ISBN 978-0-12-255350-9 Florez et al. 2022, "From the gas phase to the solid state: The chemical bonding in the superheavy element flerovium", The Journal of Chemical Physics, vol. 157, 064304, doi:10.1063/5.0097642 Fortescue JAC 2012, Environmental Geochemistry: A Holistic Approach, Springer-Verlag, New York, ISBN 978-1-4612-6047-9 Fox M 2010, Optical Properties of Solids, 2nd ed., Oxford University Press, New York, ISBN 978-0-19-957336-3 Fraps GS 1913, Principles of Agricultural Chemistry, The Chemical Publishing Company, Easton, PA Fraústo da Silva JJR & Williams RJP 2001, The Biological Chemistry of the Elements: The Inorganic Chemistry of Life, 2nd ed., Oxford University Press, Oxford, ISBN 978-0-19-850848-9 Gaffney J & Marley N 2017, General Chemistry for Engineers, Elsevier, Amsterdam, ISBN 978-0-12-810444-6 Ganguly A 2012, Fundamentals of Inorganic Chemistry, 2nd ed., Dorling Kindersley (India), New Delhi ISBN 978-81-317-6649-1 Gargaud M et al. (eds.) 2006, Lectures in Astrobiology, vol. 1, part 1: The Early Earth and Other Cosmic Habitats for Life, Springer, Berlin, ISBN 978-3-540-29005-6 Gatti M, Tokatly IV & Rubio A, 2010, Sodium: a charge-transfer insulator at high pressures, Physical Review Letters, vol. 104, no. 21, doi:10.1103/PhysRevLett.104.216404 Georgievskii VI 1982, Mineral compositions of bodies and tissues of animals, in Georgievskii VI, Annenkov BN & Samokhin VT (eds), Mineral Nutrition of Animals: Studies in the Agricultural and Food Sciences, Butterworths, London, ISBN 978-0-408-10770-9 Gillespie RJ, Robinson EA 1959, The sulfuric acid solvent system, in Emeléus HJ, Sharpe AG (eds), Advances in Inorganic Chemistry and Radiochemistry, vol. 1, pp. 386–424, Academic Press, New York Gillham EJ 1956, A semi-conducting antimony bolometer, Journal of Scientific Instruments, vol. 33, no. 9, doi:10.1088/0950-7671/33/9/303 Glinka N 1960, General chemistry, Sobolev D (trans.), Foreign Languages Publishing House, Moscow Godfrin H & Lauter HJ 1995, "Experimental properties of 3He adsorbed on graphite", in Halperin WP (ed.), Progress in Low Temperature Physics, volume 14, Elsevier Science B.V., Amsterdam, ISBN 978-0-08-053993-5 Godovikov AA & Nenasheva N 2020, Structural-chemical Systematics of Minerals, 3rd ed., Springer, Cham, Switzerland, ISBN 978-3-319-72877-3 Goldsmith RH 1982, "Metalloids", Journal of Chemical Education, vol. 59, no. 6, pp. 526–527, doi:10.1021/ed059p526 Goldwhite H & Spielman JR 1984, College Chemistry, Harcourt Brace Jovanovich, San Diego, ISBN 978-0-15-601561-5 Goodrich BG 1844, A Glance at the Physical Sciences, Bradbury, Soden & Co., Boston Gresham et al. 2015, Lubrication and lubricants, in Kirk-Othmer Encyclopedia of Chemical Technology, John Wiley & Sons, doi:10.1002/0471238961.1221021802151519.a01.pub3, accessed Jun 3, 2024 Grondzik WT et al. 2010, Mechanical and Electrical Equipment for Buildings, 11th ed., John Wiley & Sons, Hoboken, ISBN 978-0-470-19565-9 Government of Canada 2015, Periodic table of the elements, accessed August 30, 2015 Graves Jr JL 2022, A Voice in the Wilderness: A Pioneering Biologist Explains How Evolution Can Help Us Solve Our Biggest Problems, Basic Books, New York, ISBN 978-1-6686-1610-9, Green D 2012, The Elements, Scholastic, Southam, Warwickshire, ISBN 978-1-4071-3155-9 Greenberg A 2007, From alchemy to chemistry in picture and story, John Wiley & Sons, Hoboken, NJ, 978-0-471-75154-0 Greenwood NN 2001, Main group element chemistry at the millennium, Journal of the Chemical Society, Dalton Transactions, no. 14, pp. 2055–66, doi:10.1039/b103917m Greenwood NN & Earnshaw A 2002, Chemistry of the Elements, 2nd ed., Butterworth-Heinemann, ISBN 978-0-7506-3365-9 Grochala W 2018, "On the position of helium and neon in the Periodic Table of Elements", Foundations of Chemistry, vol. 20, pp. 191–207, doi:10.1007/s10698-017-9302-7 Hall RA 2021, Pop Goes the Decade: The 2000s, ABC-CLIO, Santa Barbara, California, ISBN 978-1-4408-6812-2 Haller EE 2006, "Germanium: From its discovery to SiGe devices", Materials Science in Semiconductor Processing, vol. 9, nos 4–5, accessed 9 October 2013 Hampel CA & Hawley GG 1976, Glossary of Chemical Terms, Van Nostrand Reinhold, New York, ISBN 978-0-442-23238-2 Hanley JJ & Koga KT 2018, "Halogens in terrestrial and cosmic geochemical systems: Abundances, geochemical behaviors, and analytical methods" in The Role of Halogens in Terrestrial and Extraterrestrial Geochemical Processes: Surface, Crust, and Mantle, Harlov DE & Aranovich L (eds.), Springer, Cham, ISBN 978-3-319-61667-4 Harbison RD, Bourgeois MM & Johnson GT 2015, Hamilton and Hardy's Industrial Toxicology, 6th ed., John Wiley & Sons, Hoboken, ISBN 978-0-470-92973-5 Hare RA & Bache F 1836, Compendium of the Course of Chemical Instruction in the Medical Department of the University of Pennsylvania, 3rd ed., JG Auner, Philadelphia Harris TM 1803, The Minor Encyclopedia, vol. III, West & Greenleaf, Boston Hein M & Arena S 2011, Foundations of College Chemistry, 13th ed., John Wiley & Sons, Hoboken, New Jersey, ISBN 978-0470-46061-0 Hengeveld R & Fedonkin MA 2007, "Bootstrapping the energy flow in the beginning of life", Acta Biotheoretica, vol. 55, doi:10.1007/s10441-007-9019-4 Herman ZS 1999, "The nature of the chemical bond in metals, alloys, and intermetallic compounds, according to Linus Pauling", in Maksić, ZB, Orville-Thomas WJ (eds.), 1999, Pauling's Legacy: Modern Modelling of the Chemical Bond, Elsevier, Amsterdam, doi:10.1016/S1380-7323(99)80030-2 Hermann A, Hoffmann R & Ashcroft NW 2013, "Condensed astatine: Monatomic and metallic", Physical Review Letters, vol. 111, doi:10.1103/PhysRevLett.111.116404 Hérold A 2006, "An arrangement of the chemical elements in several classes inside the periodic table according to their common properties", Comptes Rendus Chimie, vol. 9, no. 1, doi:10.1016/j.crci.2005.10.002 Herzfeld K 1927, "On atomic properties which make an element a metal", Physical Review, vol. 29, no. 5, doi:10.1103/PhysRev.29.701 Hill G, Holman J & Hulme PG 2017, Chemistry in Context, 7th ed., Oxford University Press, Oxford, ISBN 978-0-19-839618-5 Hoefer F 1845, Nomenclature et Classifications Chimiques, J.-B. Baillière, Paris Holderness A & Berry M 1979, Advanced Level Inorganic Chemistry, 3rd ed., Heinemann Educational Books, London, ISBN 978-0-435-65435-1 Horvath AL 1973, "Critical temperature of elements and the periodic system", Journal of Chemical Education, vol. 50, no. 5, doi:10.1021/ed050p335 House JE 2008, Inorganic Chemistry, Elsevier, Amsterdam, ISBN 978-0-12-356786-4 House JE 2013, Inorganic Chemistry, 2nd ed., Elsevier, Kidlington, ISBN 978-0-12-385110-9 Huang Y 2018, Thermodynamics of materials corrosion, in Huang Y & Zhang J (eds), Materials Corrosion and Protection, De Gruyter, Boston, pp. 25–58, doi:10.1515/9783110310054-002 Humphrey TPJ 1908, "Systematic course of study, Chemistry and physics", Pharmaceutical Journal, vol. 80, p. 58 Hussain et al. 2023, "Tuning the electronic properties of molybdenum di-sulphide monolayers via doping using first-principles calculations", Physica Scripta, vol. 98, no. 2, doi:10.1088/1402-4896/acacd1 Imberti C & Sadler PJ, 2020, "150 years of the periodic table: New medicines and diagnostic agents", in Sadler PJ & van Eldik R 2020, Advances in Inorganic Chemistry, vol. 75, Academic Press, ISBN 978-0-12-819196-5 IUPAC Periodic Table of the Elements, accessed October 11, 2021 Janas D, Cabrero-Vilatela, A & Bulmer J 2013, "Carbon nanotube wires for high-temperature performance", Carbon, vol. 64, pp. 305–314, doi:10.1016/j.carbon.2013.07.067 Jenkins GM & Kawamura K 1976, Polymeric Carbons—Carbon Fibre, Glass and Char, Cambridge University Press, Cambridge, ISBN 978-0-521-20693-8 Jentzsch AV & Matile S 2015, "Anion transport with halogen bonds", in Metrangolo P & Resnati G (eds.), Halogen Bonding I: Impact on Materials Chemistry and Life Sciences, Springer, Cham, ISBN 978-3-319-14057-5 Jensen WB 1986, Classification, symmetry and the periodic table, Computers & Mathematics with Applications, vol. 12B, nos. 1/2, pp. 487−510, doi:10.1016/0898-1221(86)90167-7 Johnson RC 1966, Introductory Descriptive Chemistry, WA Benjamin, New York Jolly WL 1966, The Chemistry of the Non-metals, Prentice-Hall, Englewood Cliffs, New Jersey Jones BW 2010, Pluto: Sentinel of the Outer Solar System, Cambridge University, Cambridge, ISBN 978-0-521-19436-5 Jordan JM 2016 " 'Ancient episteme' and the nature of fossils: a correction of a modern scholarly error", History and Philosophy of the Life Sciences, vol. 38, no, 1, pp. 90–116, doi:10.1007/s40656-015-0094-6 Kaiho T 2017, Iodine Made Simple, CRC Press, e-book, doi:10.1201/9781315158310 Keeler J & Wothers P 2013, Chemical Structure and Reactivity: An Integrated Approach, Oxford University Press, Oxford, ISBN 978-0-19-960413-5 Kemshead WB 1875, Inorganic chemistry, William Collins, Sons, & Company, London Kernion MC & Mascetta JA 2019, Chemistry: The Easy Way, 6th ed., Kaplan, New York, ISBN 978-1-4380-1210-0 King AH 2019, "Our elemental footprint", Nature Materials, vol. 18, doi:10.1038/s41563-019-0334-3 King RB 1994, Encyclopedia of Inorganic Chemistry, vol. 3, John Wiley & Sons, New York, ISBN 978-0-471-93620-6 King RB 1995, Inorganic Chemistry of Main Group Elements, VCH, New York, ISBN 978-1-56081-679-9 Kiiski et al. 2016, "Fertilizers, 1. General", in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.a10_323.pub4 Kläning UK & Appelman EH 1988, "Protolytic properties of perxenic acid", Inorganic Chemistry, vol. 27, no. 21, doi:10.1021/ic00294a018 Kneen WR, Rogers MJW & Simpson P 1972, Chemistry: Facts, Patterns, and Principles, Addison-Wesley, London, ISBN 978-0-201-03779-1 Knight J 2002, Science of Everyday Things: Real-life chemistry, Gale Group, Detroit, ISBN 9780787656324 Koenig SH 1962, in Proceedings of the International Conference on the Physics of Semiconductors, held at Exeter, July 16–20, 1962, The Institute of Physics and the Physical Society, London Kosanke et al. 2012, Encyclopedic Dictionary of Pyrotechnics (and Related Subjects), Part 3 – P to Z, Pyrotechnic Reference Series No. 5, Journal of Pyrotechnics, Whitewater, Colorado, ISBN 978-1-889526-21-8 Kubaschewski O 1949, "The change of entropy, volume and binding state of the elements on melting", Transactions of the Faraday Society, vol. 45, doi:10.1039/TF9494500931 Labinger JA 2019, "The history (and pre-history) of the discovery and chemistry of the noble gases", in Giunta CJ, Mainz VV & Girolami GS (eds.), 150 Years of the Periodic Table: A Commemorative Symposium, Springer Nature, Cham, Switzerland, ISBN 978-3-030-67910-1 Lanford OE 1959, Using Chemistry, McGraw-Hill, New York Larrañaga MD, Lewis RJ & Lewis RA 2016, Hawley's Condensed Chemical Dictionary, 16th ed., Wiley, Hoboken, New York, ISBN 978-1-118-13515-0 Lavoisier A 1790, Elements of Chemistry, R Kerr (trans.), William Creech, Edinburgh Lee JD 1996, Concise Inorganic Chemistry, 5th ed., Blackwell Science, Oxford, ISBN 978-0-632-05293-6 Lémery N 1699, Traité universel des drogues simples, mises en ordre alphabetique, L d'Houry, Paris, p. 118 Lewis RJ 1993, Hawley's Condensed Chemical Dictionary, 12th ed., Van Nostrand Reinhold, New York, ISBN 978-0-442-01131-4 Lewis RS & Deen WM 1994, "Kinetics of the reaction of nitric oxide with oxygen in aqueous solutions", Chemical Research in Toxicology, vol. 7, no. 4, pp. 568–574, doi:10.1021/tx00040a013 Liptrot GF 1983, Modern Inorganic Chemistry, 4th ed., Bell & Hyman, ISBN 978-0-7135-1357-8 Los Alamos National Laboratory 2021, Periodic Table of Elements: A Resource for Elementary, Middle School, and High School Students, accessed September 19, 2021 Lundgren A & Bensaude-Vincent B 2000, Communicating chemistry: textbooks and their audiences, 1789–1939, Science History, Canton, MA, ISBN 0-88135-274-8 MacKay KM, MacKay RA & Henderson W 2002, Introduction to Modern Inorganic Chemistry, 6th ed., Nelson Thornes, Cheltenham, ISBN 978-0-7487-6420-4 Mackin M 2014, Study Guide to Accompany Basics for Chemistry, Elsevier Science, Saint Louis, ISBN 978-0-323-14652-4 Malone LJ & Dolter T 2008, Basic Concepts of Chemistry, 8th ed., John Wiley & Sons, Hoboken, ISBN 978-0-471-74154-1 Mann et al. 2000, Configuration energies of the d-block elements, Journal of the American Chemical Society, vol. 122, no. 21, pp. 5132–5137, doi:10.1021/ja9928677 Maosheng M 2020, "Noble gases in solid compounds show a rich display of chemistry with enough pressure", Frontiers in Chemistry, vol. 8, doi:10.3389/fchem.2020.570492 Maroni M, Seifert B & Lindvall T (eds) 1995, "Physical pollutants", in Indoor Air Quality: A Comprehensive Reference Book, Elsevier, Amsterdam, ISBN 978-0-444-81642-9 Martin JW 1969, Elementary Science of Metals, Wykeham Publications, London Matson M & Orbaek AW 2013, Inorganic Chemistry for Dummies, John Wiley & Sons: Hoboken, ISBN 978-1-118-21794-8 Matula RA 1979, "Electrical resistivity of copper, gold, palladium, and silver", Journal of Physical and Chemical Reference Data, vol. 8, no. 4, doi:10.1063/1.555614 Mazej Z 2020, "Noble-gas chemistry more than half a century after the first report of the noble-gas compound", Molecules, vol. 25, no. 13, doi:10.3390/molecules25133014, PMID 32630333, PMC 7412050 McMillan P 2006, "A glass of carbon dioxide", Nature, vol. 441, doi:10.1038/441823a Mendeléeff DI 1897, The Principles of Chemistry, vol. 2, 5th ed., trans. G Kamensky, AJ Greenaway (ed.), Longmans, Green & Co., London Messler Jr RW 2011, The Essence of Materials for Engineers, Jones and Bartlett Learning, Sudbury, Massachusetts, ISBN 978-0-7637-7833-0 Mewes et al. 2019, "Copernicium: A relativistic noble liquid", Angewandte Chemie International Edition, vol. 58, pp. 17964–17968, doi:10.1002/anie.201906966 Mingos DMP 2019, "The discovery of the elements in the Periodic Table", in Mingos DMP (ed.), The Periodic Table I. Structure and Bonding, Springer Nature, Cham, doi:10.1007/978-3-030-40025-5 Moeller T 1958, Qualitative Analysis: An Introduction to Equilibrium and Solution Chemistry, McGraw-Hill, New York Moeller T et al. 1989, Chemistry: With Inorganic Qualitative Analysis, 3rd ed., Academic Press, New York, ISBN 978-0-12-503350-3 Moody B 1991, Comparative Inorganic Chemistry, 3rd ed., Edward Arnold, London, ISBN 978-0-7131-3679-1 Moore JT 2016, Chemistry for Dummies, 2nd ed., ch. 16, Tracking periodic trends, John Wiley & Sons: Hoboken, ISBN 978-1-119-29728-4 Morgan JW, & Anders E 1980, "Chemical composition of earth, venus, and mercury", Proceedings of the National Academy of Sciences, vol. 77, no. 12, pp. 6973–6977 Morely HF & Muir MM 1892, Watt's Dictionary of Chemistry, vol. 3, Longman's Green, and Co., London Moss, TS 1952, Photoconductivity in the Elements, Butterworths Scientific, London Myers RT 1979, "Physical and chemical properties and bonding of metallic elements", Journal of Chemical Education, vol. 56, no. 11, pp. 712–73, doi:10.1021/ed056p71 Obodovskiy I 2015, Fundamentals of Radiation and Chemical Safety, Elsevier, Amsterdam, ISBN 978-0-12-802026-5 Oderberg DS 2007, Real Essentialism, Routledge, New York, ISBN 978-1-134-34885-5 Ostriker JP & Steinhardt PJ 2001, "The quintessential universe", Scientific American, vol. 284, no. 1, pp. 46–53 PMID 11132422, doi:10.1038/scientificamerican0101-46 Oxford English Dictionary 1989, "nonmetal" Orisakwe OE 2012, Other heavy metals: antimony, cadmium, chromium and mercury, in Pacheco-Torgal F, Jalali S & Fucic A (eds), Toxicity of Building Materials, Woodhead Publishing, Oxford, pp. 297–333, doi:10.1533/9780857096357.297 Parameswaran P et al. 2020, "Phase evolution and characterization of mechanically alloyed hexanary Al16.6Mg16.6Ni16.6Cr16.6Ti16.6Mn16.6 high entropy alloy", Metal Powder Report, vol. 75, no. 4, doi:10.1016/j.mprp.2019.08.001 Parish RV 1977, The Metallic Elements, Longman, London, ISBN 978-0-582-44278-8 Partington JR 1944, A Text-book of Inorganic Chemistry, 5th ed., Macmillan & Co., London Partington JR 1964, A history of chemistry, vol. 4, Macmillan, London Pascoe KJ 1982, An Introduction to the Properties of Engineering Materials, 3rd ed., Von Nostrand Reinhold (UK), Wokingham, Berkshire, ISBN 978-0-442-30233-7 Pauling L 1947, General chemistry: An introduction to descriptive chemistry and modern chemical theory, WH Freeman, San Francisco Pawlicki T, Scanderbeg DJ & Starkschall G 2016, Hendee's Radiation Therapy Physics, 4th ed., John Wiley & Sons, Hoboken, NJ, p. 228, ISBN 978-0-470-37651-5 Petruševski VM & Cvetković J 2018, "On the 'true position' of hydrogen in the Periodic Table", Foundations of Chemistry, vol. 20, pp. 251–260, doi:10.1007/s10698-018-9306-y Phillips CSG & Williams RJP 1965, Inorganic Chemistry, vol. 1, Principles and non-metals, Clarendon Press, Oxford Pitzer K 1975, "Fluorides of radon and elements 118", Journal of the Chemical Society, Chemical Communications, no. 18, doi:10.1039/C3975000760B Porterfield WW 1993, Inorganic Chemistry, Academic Press, San Diego, ISBN 978-0-12-562980-5 Povh B & Rosina M 2017, Scattering and Structures: Essentials and Analogies in Quantum Physics, 2nd ed., Springer, Berlin, doi:10.1007/978-3-662-54515-7 Powell P & Timms P 1974, The Chemistry of the Non-Metals, Chapman and Hall, London, ISBN 978-0-412-12200-2 Power PP 2010, Main-group elements as transition metals, Nature, vol. 463, 14 January 2010, pp. 171–177, doi:10.1038/nature08634 Puddephatt RJ & Monaghan PK 1989, The Periodic Table of the Elements, 2nd ed., Clarendon Press, Oxford, ISBN 978-0-19-855516-2 Rahm M, Zeng T & Hoffmann R 2019, "Electronegativity seen as the ground-state average valence electron binding energy", Journal of the American Chemical Society, vol. 141, no. 1, pp. 342–351, doi:10.1021/jacs.8b10246 Ramdohr P 1969, The Ore Minerals and Their Intergrowths, Pergamon Press, Oxford Rao CNR & Ganguly PA 1986, "New criterion for the metallicity of elements", Solid State Communications, vol. 57, no. 1, pp. 5–6, doi:10.1016/0038-1098(86)90659-9 Rao KY 2002, Structural chemistry of glasses, Elsevier, Oxford, ISBN 0-08-043958-6 Rayner-Canham G 2018, "Organizing the transition metals", in Scerri E & Restrepo G (Ed's.) Mendeleev to Oganesson: A multidisciplinary perspective on the periodic table, Oxford University, New York, ISBN 978-0-190-668532 Rayner-Canham G 2020, The Periodic Table: Past, Present and Future, World Scientific, New Jersey, ISBN 978-981-121-850-7 Redmer R, Hensel F & Holst B (eds) 2010, "Metal-to-Nonmetal Transitions", Springer, Berlin, ISBN 978-3-642-03952-2 Regnault MV 1853, Elements of Chemistry, vol. 1, 2nd ed., Clark & Hesser, Philadelphia Reilly C 2002, Metal Contamination of Food, Blackwell Science, Oxford, ISBN 978-0-632-05927-0 Reinhardt et al. 2015, Inerting in the chemical industry, Linde, Pullach, Germany, accessed October 19, 2021 Remy H 1956, Treatise on Inorganic Chemistry, Anderson JS (trans.), Kleinberg J (ed.), vol. II, Elsevier, Amsterdam Renouf E 1901, "Lehrbuch der Anorganischen Chemie", Science, vol. 13, no. 320, doi:10.1126/science.13.320.268 Restrepo G, Llanos EJ & Mesa H 2006, "Topological space of the chemical elements and its properties", Journal of Mathematical Chemistry, vol. 39, doi:10.1007/s10910-005-9041-1 Rieck GD 1967, Tungsten and its Compounds, Pergamon Press, Oxford Ritter SK 2011, "The case of the missing xenon", Chemical & Engineering News, vol. 89, no. 9, ISSN 0009-2347 Rochow EG 1966, The Metalloids, DC Heath and Company, Boston Rosenberg E 2013, Germanium-containing compounds, current knowledge and applications, in Kretsinger RH, Uversky VN & Permyakov EA (eds), Encyclopedia of Metalloproteins, Springer, New York, doi:10.1007/978-1-4614-1533-6_582 Roscoe HE & Schorlemmer FRS 1894, A Treatise on Chemistry: Volume II: The Metals, D Appleton, New York Royal Society of Chemistry 2021, Periodic Table: Non-metal, accessed September 3, 2021 Rudakiya DM & Patel Y 2021, Bioremediation of metals, metalloids, and nonmetals, in Panpatte DG & Jhala YK (eds), Microbial Rejuvenation of Polluted Environment, vol. 2, Springer Nature, Singapore, pp. 33–49, doi:10.1007/978-981-15-7455-9_2 Rudolph J 1973, Chemistry for the Modern Mind, Macmillan, New York Russell AM & Lee KL 2005, Structure-Property Relations in Nonferrous Metals, Wiley-Interscience, New York, ISBN 0-471-64952-X Salinas JT 2019 Exploring Physical Science in the Laboratory, Moreton Publishing, Englewood, Colorado, ISBN 978-1-61731-753-8 Salzberg HW 1991, From Caveman to Chemist: Circumstances and Achievements, American Chemical Society, Washington, DC, ISBN 0-8412-1786-6 Sanderson RT 1967, Inorganic Chemistry, Reinhold, New York Scerri E (ed.) 2013, 30-Second Elements: The 50 Most Significant Elements, Each Explained In Half a Minute, Ivy Press, London, ISBN 978-1-84831-616-4 Scerri E 2020, The Periodic Table: Its Story and Its Significance, Oxford University Press, New York, ISBN 978-0-19091-436-3 Schaefer JC 1968, "Boron" in Hampel CA (ed.), The Encyclopedia of the Chemical Elements, Reinhold, New York Schmedt auf der Günne J, Mangstl M & Kraus F 2012, "Occurrence of difluorine F2 in nature—In situ proof and quantification by NMR spectroscopy", Angewandte Chemie International Edition, vol. 51, no. 31, doi:10.1002/anie.201203515 Schweitzer GK & Pesterfield LL 2010, Aqueous Chemistry of the Elements, Oxford University Press, Oxford, ISBN 978-0-19-539335-4 Scott D 2014, Around the World in 18 Elements, Royal Society of Chemistry, e-book, ISBN 978-1-78262-509-4 Scott EC & Kanda FA 1962, The Nature of Atoms and Molecules: A General Chemistry, Harper & Row, New York Scott WAH 2001, Chemistry Basic Facts, 5th ed., HarperCollins, Glasgow, ISBN 978-0-00-710321-8 Seese WS & Daub GH 1985, Basic Chemistry, 4th ed., Prentice-Hall, Englewood Cliffs, NJ, ISBN 978-0-13-057811-2 Segal BG 1989, Chemistry: Experiment and Theory, 2nd ed., John Wiley & Sons, New York, ISBN 0-471-84929-4 Shanabrook BV, Lannin JS & Hisatsune IC 1981, "Inelastic light scattering in a onefold-coordinated amorphous semiconductor", Physical Review Letters, vol. 46, no. 2, 12 January, doi:10.1103/PhysRevLett.46.130 Shang et al. 2021, "Ultrahard bulk amorphous carbon from collapsed fullerene", Nature, vol. 599, pp. 599–604, doi:10.1038/s41586-021-03882-9 Shchukarev SA 1977, New views of D. I. Mendeleev's system. I. Periodicity of the stratigraphy of atomic electronic shells in the system, and the concept of Kainosymmetry", Zhurnal Obshchei Kimii, vol. 47, no. 2, pp. 246–259 Shkol'nikov EV 2010, "Thermodynamic characterization of the amphoterism of oxides M2O3 (M = AS, Sb, Bi) and their hydrates in aqueous media, Russian Journal of Applied Chemistry, vol. 83, no. 12, pp. 2121–2127, doi:10.1134/S1070427210120104 Sidorov TA 1960, "The connection between structural oxides and their tendency to glass formation", Glass and Ceramics, vol. 17, no. 11, doi:10.1007BF00670116 Siekierski S & Burgess J 2002, Concise Chemistry of the Elements, Horwood Press, Chichester, ISBN 978-1-898563-71-6 Slye OM Jr 2008, "Fire extinguishing agents", in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.a11_113.pub2 Smith A 1906, Introduction to Inorganic Chemistry, The Century Co., New York Smith A & Dwyer C 1991, Key Chemistry: Investigating Chemistry in the Contemporary World: Book 1: Materials and Everyday Life, Melbourne University Press, Carlton, Victoria, ISBN 978-0-522-84450-4 Smith DW 1990, Inorganic Substances: A Prelude to the Study of Descriptive Chemistry, Cambridge University Press, Cambridge, ISBN 978-0-521-33136-4 Smits et al. 2020, "Oganesson: A noble gas element that is neither noble nor a gas", Angewandte Chemie International Edition, vol. 59, pp. 23636–23640, doi:10.1002/anie.202011976 Smulders E & Sung E 2011, "Laundry Detergents, 2, Ingredients and Products", In Ullmann's Encyclopedia of

Industrial Chemistry, doi:10.1002/14356007.o15_o13 Spencer JN, Bodner GM, Rickard LY 2012, Chemistry: Structure & Dynamics, 5th ed., John Wiley & Sons, Hoboken, ISBN 978-0-470-58711-9 Stein L 1969, "Oxidized radon in halogen fluoride solutions", Journal of the American Chemical Society, vol. 19, no. 19, doi:10.1021/ja01047a042 Stein L 1983, "The chemistry of radon", Radiochimica Acta, vol. 32, doi:10.1524/ract.1983.32.13.163 Steudel R 2020, Chemistry of the Non-metals: Syntheses – Structures – Bonding – Applications, in collaboration with D Scheschkewitz, Berlin, Walter de Gruyter, doi:10.1515/9783110578065 Still B 2016 The Secret Life of the Periodic Table, Cassell, London, ISBN 978-1-84403-885-5 Stillman JM 1924, The Story of Early Chemistry, D. Appleton, New York Stott RWA 1956, Companion to Physical and Inorganic Chemistry, Longmans, Green and Co, London Stuke J 1974, "Optical and electrical properties of selenium", in Zingaro RA & Cooper WC (eds.), Selenium, Van Nostrand Reinhold, New York, pp. 174 Strathern P 2000, Mendeleyev's dream: The Quest for the Elements, Hamish Hamilton, London, ISBN 9780425184677 Suresh CH & Koga NA 2001, "A consistent approach toward atomic radii", Journal of Physical Chemistry A, vol. 105, no. 24. doi:10.1021/jp010432b Tang et al. 2021, "Synthesis of paracrystalline diamond", Nature, vol. 599, pp. 605–610, doi:10.1038/s41586-021-04122-w Taniguchi M, Suga S, Seki M, Sakamoto H, Kanzaki H, Akahama Y, Endo S, Terada S & Narita S 1984, "Core-exciton induced resonant photoemission in the covalent semiconductor black phosphorus", Solid State Communications, vo1. 49, no. 9, pp. 867–7, doi:10.1016/0038-1098(84)90441-1 Taylor MD 1960, First Principles of Chemistry, Van Nostrand, Princeton The Chemical News and Journal of Physical Science 1864, "Notices of books: Manual of the Metalloids", vol. 9, p. 22 The Chemical News and Journal of Physical Science 1897, "Notices of books: A Manual of Chemistry, Theoretical and Practical", by WA Tilden", vol. 75, pp. 188–189 Thornton BF & Burdette SC 2010, "Finding eka-iodine: Discovery priority in modern times", Bulletin for the History of Chemistry, vol. 35, no. 2, accessed September 14, 2021 Tidy CM 1887, Handbook of Modern Chemistry, 2nd ed., Smith, Elder & Co., London Timberlake KC 1996, Chemistry: An Introduction to General, Organic, and Biological Chemistry, 6th ed., HarperCollinsCollege, ISBN 978-0-673-99054-9 Toon R 2011, "The discovery of fluorine", Education in Chemistry, Royal Society of Chemistry, accessed 7 October 2023 Tregarthen L 2003, Preliminary Chemistry, Macmillan Education: Melbourne, ISBN 978-0-7329-9011-4 Tyler PM 1948, From the Ground Up: Facts and Figures of the Mineral Industries of the United States, McGraw-Hill, New York Vassilakis AA, Kalemos A & Mavridis A 2014, "Accurate first principles calculations on chlorine fluoride ClF and its ions ClF±", Theoretical Chemistry Accounts, vol. 133, no. 1436, doi:10.1007/s00214-013-1436-7 Vernon R 2013, "Which elements are metalloids?", Journal of Chemical Education, vol. 90, no. 12, pp. 1703–1707, doi:10.1021/ed3008457 Vernon R 2020, "Organising the metals and nonmetals", Foundations of Chemistry, vol. 22, pp. 217–233doi:10.1007/s10698-020-09356-6 (open access) Vij et al. 2001, Polynitrogen chemistry. Synthesis, characterization, and crystal structure of surprisingly stable fluoroantimonate salts of N5+. Journal of the American Chemical Society, vol. 123, no. 26, pp. 6308−6313, doi:10.1021/ja010141g Wächtershäuser G 2014, "From chemical invariance to genetic variability", in Weigand W and Schollhammer P (eds.), Bioinspired Catalysis: Metal Sulfur Complexes, Wiley-VCH, Weinheim, doi:10.1002/9783527664160.ch1 Wakeman TH 1899, "Free thought—Past, present and future", Free Thought Magazine, vol. 17 Wang HS, Lineweaver CH & Ireland TR 2018, The elemental abundances (with uncertainties) of the most Earth-like planet, Icarus, vol. 299, pp. 460–474, doi:10.1016/j.icarus.2017.08.024 Wasewar KL 2021, "Intensifying approaches for removal of selenium", in Devi et al. (eds.), Selenium contamination in water, John Wiley & Sons, Hoboken, pp. 319–355, ISBN 978-1-119-69354-3 Weeks ME & Leicester HM 1968, Discovery of the Elements, 7th ed., Journal of Chemical Education, Easton, Pennsylvania Weetman C & Inoue S 2018, The road travelled: After main-group elements as transition metals, ChemCatChem, vol. 10, no. 19, pp. 4213–4228, doi:10.1002/cctc.201800963 Welcher SH 2009, High marks: Regents Chemistry Made Easy, 2nd ed., High Marks Made Easy, New York, ISBN 978-0-9714662-0-3 Weller et al. 2018, Inorganic Chemistry, 7th ed., Oxford University Press, Oxford, ISBN 978-0-19-252295-5 Wells AF 1984, Structural Inorganic Chemistry, 5th ed., Clarendon Press, Oxford, ISBN 978-0-19-855370-0 White JH 1962, Inorganic Chemistry: Advanced and Scholarship Levels, University of London Press, London Whiteford GH & and Coffin RG 1939, Essentials of College Chemistry, 2nd ed., Mosby Co., St Louis Whitten KW & Davis RE 1996, General Chemistry, 5th ed., Saunders College Publishing, Philadelphia, ISBN 978-0-03-006188-2 Wibaut P 1951, Organic Chemistry, Elsevier Publishing Company, New York Wiberg N 2001, Inorganic Chemistry, Academic Press, San Diego, ISBN 978-0-12-352651-9 Williams RPJ 2007, "Life, the environment and our ecosystem", Journal of Inorganic Biochemistry, vol. 101, nos. 11–12, doi:10.1016/j.jinorgbio.2007.07.006 Windmeier C & Barron RF 2013, "Cryogenic technology", in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.b03_20.pub2 Winstel G 2000, "Electroluminescent materials and devices", in Ullmann's Encyclopedia of Industrial Chemistry, doi:10.1002/14356007.a09_255 Wismer RK 1997, Student Study Guide, General Chemistry: Principles and Modern Applications, 7th ed., Prentice Hall, Upper Saddle River, ISBN 978-0-13-281990-9 Woodward et al. 1999, "The electronic structure of metal oxides", In Fierro JLG (ed.), Metal Oxides: Chemistry and Applications, CRC Press, Boca Raton, ISBN 1-4200-2812-X World Economic Forum 2021, Visualizing the abundance of elements in the Earth's crust, accessed 21 March 2024 Wulfsberg G 2000, Inorganic Chemistry, University Science Books, Sausalito, California, ISBN 978-1-891389-01-6 Yamaguchi M & Shirai Y 1996, "Defect structures", in Stoloff NS & Sikka VK (eds.), Physical Metallurgy and Processing of Intermetallic Compounds, Chapman & Hall, New York, ISBN 978-1-4613-1215-4 Yang J 2004, "Theory of thermal conductivity", in Tritt TM (ed.), Thermal Conductivity: Theory, Properties, and Applications, Kluwer Academic/Plenum Publishers, New York, pp. 1–20, ISBN 978-0-306-48327-1 Yin et al. 2018, Hydrogen-assisted post-growth substitution of tellurium into molybdenum disulfide monolayers with tunable compositions, Nanotechnology, vol. 29, no 14, doi:10.1088/1361-6528/aaabe8 Yoder CH, Suydam FH & Snavely FA 1975, Chemistry, 2nd ed, Harcourt Brace Jovanovich, New York, ISBN 978-0-15-506470-6 Young JA 2006, "Iodine", Journal of Chemical Education, vol. 83, no. 9, doi:10.1021/ed083p1285 Young et al. 2018, General Chemistry: Atoms First, Cengage Learning: Boston, ISBN 978-1-337-61229-6 Zhao J, Tu Z & Chan SH 2021, "Carbon corrosion mechanism and mitigation strategies in a proton exchange membrane fuel cell (PEMFC): A review", Journal of Power Sources, vol. 488, #229434, doi:10.1016/j.jpowsour.2020.229434 Zhigal'skii GP & Jones BK 2003, The Physical Properties of Thin Metal Films, Taylor & Francis, London, ISBN 978-0-415-28390-8 Zhu W 2020, Chemical Elements In Life, World Scientific, Singapore, ISBN 978-981-121-032-7 Zhu et al. 2014, "Reactions of xenon with iron and nickel are predicted in the Earth's inner core", Nature Chemistry, vol. 6, doi:10.1038/nchem.1925, PMID 24950336 Zhu et al. 2022, Introduction: basic concept of boron and its physical and chemical properties, in Fundamentals and Applications of Boron Chemistry, vol. 2, Zhu Y (ed.), Elsevier, Amsterdam, ISBN 978-0-12-822127-3 Zumdahl SS & DeCoste DJ 2010, Introductory Chemistry: A Foundation, 7th ed., Cengage Learning, Mason, Ohio, ISBN 978-1-111-29601-8 Media related to Nonmetals at Wikimedia Commons Retrieved from "
How can financial brands set themselves apart through visual storytelling? Our experts explain how.Learn MoreThe Motorsport Images Collections captures events from 1895 to today’s most recent coverage.Discover The CollectionCurated, compelling, and worth your time. Explore our latest gallery of Editors’ Picks.Browse Editors' FavoritesHow can financial brands set themselves apart through visual storytelling? Our experts explain how.Learn MoreThe Motorsport Images Collections captures events from 1895 to today’s most recent coverage.Discover The CollectionCurated, compelling, and worth your time. Explore our latest gallery of Editors’ Picks.Browse Editors' FavoritesHow can financial brands set themselves apart through visual storytelling? Our experts explain how.Learn MoreThe Motorsport Images Collections captures events from 1895 to today’s most recent coverage.Discover The CollectionCurated, compelling, and worth your time. Explore our latest gallery of Editors’ Picks.Browse Editors' Favorites