

The Chemical Context of Life

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Slide 1

Any chemical reaction involves some number of reactants that are transformed into some number of products. As a reaction proceeds, some chemical bonds are broken, and some new chemical bonds are formed. The result is that reactants are consumed and products are produced. No matter is created or destroyed in this process, but a rearrangement of electrons results in products that have different properties compared to the reactants from which they are produced.

Slide 2

A chemical reaction is represented by a chemical equation, using an arrow to separate reactants (on the left) from products (on the right). Reactants and products can be represented in various ways, including names, pictures, structural diagrams, and chemical formulae.

Slide 3

Organisms, like all material things, are made of atoms. Though there are more than a hundred different elements, organisms are made mostly of a small number of the smallest of these elements. Most of the human body, for instance, is made up of just four kinds of atoms: carbon, hydrogen, nitrogen, and oxygen.

Slide 4

All material things are made up of tiny subunits called atoms, which in turn are made up of even smaller subatomic particles. There are three primary types of subatomic particles:

- Protons are found only in the nucleus of an atom. Each proton has a +1 electrostatic charge. The number of protons in an atomic nucleus determines which kind of element that atom represents.
- Neutrons are found only in the nucleus, along with some number of protons. While every atom has at least one proton in its nucleus, not every atom includes neutrons. A neutron is nearly identical in mass to a proton, but it has no electrostatic charge.
- Electrons are much smaller than protons and neutrons, and they are not part of the nucleus. Instead, electrons are found orbiting the nucleus. Each electron has a -1 electrostatic charge. Despite the drastic difference in size between an electron and a proton, the negative charge of an electron is just as big as the positive charge of a proton.

Slide 5

Though electrons are often depicted as orbiting an atomic nucleus in a well defined path (like a planet around a star), this is an oversimplification. At any given moment, an electron is found some distance from the nucleus, so an alternative depiction of electrons is as a cloud surrounding the nucleus.

Slide 6

The position of an electron at any given moment is unpredictable; however, electrons reside in spaces called energy levels, or electron shells, that are discrete (i.e., an electron must be in one energy level or another, not between two levels). Levels increase in energy as distance from the nucleus increases. Therefore, when an atom receives energy, its electrons can become excited and move to a higher energy level. When an excited electron returns to a lower energy level, energy will be released from the atom.

Slide 7

The spaces we call energy levels (electron shells) are divided into subspaces called orbitals, in which electrons can be located. Each level contains a characteristic number of orbitals. There are different types of orbitals (e.g., *s*, *p*, *d*, etc.) each with its own shape, but regardless of type, any single orbital can contain at most two electrons.

Slide 8

Every level contains a single *s* orbital. Starting with level two, each level also contains three different *p* orbitals. Starting with level three, each level also contains five different *d* orbitals, and so on. The second energy level, therefore, has four total orbitals: one *s* orbital (called $2s$, because it's in level two), and three *p* orbitals (called $2p_x$, $2p_y$, and $2p_z$, because they are situated at right angles to each other). Each of these orbitals can contain up to two electrons, so the whole shell (level) can contain up to eight electrons.

Slide 9

The period table is an ordered arrangement of the known elements. An element is a substance made up of only one kind of atom. Though all electrons are alike, all neutrons are alike, and all protons are alike, there are different types of atoms, because atoms can contain different numbers of protons. An atom's number of protons is called its atomic number, and that determines what kind of element that kind of atom makes up. Each element has its own properties that depend on that number of protons. The elements are listed in the periodic table in increasing order of atomic number, starting with hydrogen, the simplest type of atom (1 proton). The rows in the table are called periods. Periods represent energy levels. The columns are called groups. Elements within groups have similar properties to each other. In the abbreviated periodic table shown in the slide, energy levels are depicted as circles around nuclei (orbitals are not shown), and electrons are depicted as dots in the levels. Any neutral atom contains the same number of electrons as it contains protons. The positive charges of the protons are neutralized by the same number of negative charges of the electrons, making the overall atom neutral. The number of protons an atom contains depends on the type of element, and that number does not change under normal circumstances. Therefore, a neutral atom has a number of electrons that equals its atomic number. However, the number of electrons can be changed (increased or decreased) under normal circumstances, resulting in an ion. An ion is charged, because it contains either more electrons than protons or fewer electrons than protons, so the negative charges and the positive charges do not add up to zero. An ion with more electrons than protons is negatively charged, and it is called an anion. An ion with fewer electrons than protons is positively charged, and it is called a cation. The elements on the left side of the periodic table (except hydrogen) are called metals, whereas those on the right side are called non-metals (there are more metals than non-metals). An atom becomes most stable when its outer shell (called the valence shell) is full of electrons. Metals have valence shells that are more empty than full. They gain stability by losing those outer (valence) electrons, so they form cations. Non-metals have valence shells that are more full than empty. They gain stability by gaining enough electrons to fill the outer shell, so they form anions. The elements in the rightmost column (group) are the noble gases. They already have full valence shells, so they're as stable as they can be, and they do not form ions.

Slide 10

Though there are only slightly more than a hundred elements, these elements can be combined in endless ways to form new substances called compounds. Compounds form when atoms of unlike elements form chemical bonds. Atoms of the same type of element can also form chemical bonds, though the resulting substance is then still an element. In this course, we will restrict our attention to two types of chemical bonds, called ionic bonds and covalent bonds. The formation of an ionic bond is shown in this slide. An ionic bond forms between a metal and a non-metal. A metal forms a cation by losing its outermost electron or electrons. This gives it a positive charge. Meanwhile, a non-metal is likely to receive one or more electrons (depending on the number of electrons needed to fill its outer shell), so it forms an anion. This gives it a negative charge. Since opposite charges attract each other, a positively charged, metal cation is electrostatically attracted to a negatively charged, non-metal anion. This attraction is called an ionic bond, and it holds the two ions together to form a compound. The compound has properties all its own, unlike the properties of either of the elements from which it is formed. Since each cation is attracted to anions from all sides (and vice versa), collections of cations and anions form crystals of indefinite size. The smallest possible piece of an ionic compound is called a formula unit.

Slide 11

A salt is an ionic compound. There are many kinds of salt, including sodium chloride (table salt), shown here. A single piece can be indefinitely large.

Slide 12

A second kind of chemical bond forms when electrons are shared by two atoms rather than being completely transferred from one atom to the other. When a pair of electrons (one from each of two atoms) is shared by those two atoms, that bond is covalent. The shared electrons spend some time around the nucleus of one of the atoms and some time around the nucleus of the other atom. The sharing of the electrons keeps the two atoms together. A covalent bond is much stronger than an ionic bond. A covalent bond forms between two non-metal atoms (either the same element or different). For each pair of electrons shared, each atom counts those two electrons as its own, so they contribute to that atom's stability. For example, any hydrogen atom has one electron (to counteract the charge of its one proton). Hydrogen's valence shell is its only shell (level one), which contains only one orbital (the $1s$ orbital). Hydrogen will gain stability if that outer shell is full, which in this case will happen if it contains two electrons (since that shell has only one orbital). The same is true for any other hydrogen atom. Therefore, hydrogen atoms pair up, and each atom shares its only electron with the other atom. In this way, a pair of electrons is shared, and each atom "gets credit" for both of the electrons; therefore each is stable (like helium). The formation of a covalent bond creates a larger structure called a molecule. The added stability of having full valence shells is why molecules form. Unlike ionic compounds, which can occur as indefinitely large chunks, each molecule is its own particle, independent of any other molecules around it. A molecule can be elemental (when atoms of the same type are covalently bonded), or it can be a covalent compound (when different types of atoms are covalently bonded).

Slide 13

Each pair of shared electrons forms a single covalent bond. But for atoms with higher valences, multiple (double or triple) covalent bonds can form. A double bond involves four shared electrons (two pairs), and a triple bond involves six shared electrons (three pairs).

Slide 14

Molecules can be depicted in various ways, including formulae and diagrams. In a chemical formula, subscripts (other than 1) are written below chemical symbols for the atoms involved. Each subscript indicates how many of that type of atom are included in the molecule. For example, water has H_2O as its chemical formula, because each water molecule includes two hydrogen atoms and one oxygen atom. Notice that each of the atoms in a molecule has a full valence shell. For water, each hydrogen gets credit for two shared electrons, which brings its outer level (number 1) to fullness (2). At the same time, oxygen gets credit for four shared electrons (two for each bond with a hydrogen). Along with the four electrons that remain (unshared) in oxygen's second level, that brings the number in the outer shell to fullness (8).

Slide 15

All covalent bonds involve the sharing of electrons; however, the electrons that are shared are not shared equally in all cases. Unequal sharing results when a pair of shared electrons spends more time associated with the nucleus of one of the bonded atoms than that pair spends associated with the other nucleus. This happens because different types of atoms attract electrons to different degrees. A measure of an atom's degree to which it attracts electrons is called its electronegativity. If a covalent bond is formed between two atoms that have drastically different electronegativities, the shared electrons will be more strongly attracted to the atom with the higher electronegativity, so the sharing will be unequal. The result is a polar covalent bond. On the other hand, equal sharing (which happens when the two bonded atoms have equal or nearly equal electronegativities) results in a non-polar bond. A compound that includes a polar covalent bond is called a polar compound. The extra time that shared electrons spend with the atom of high electronegativity makes that atom slightly negative within the molecule (since electrons are negative). Conversely, the smaller amount of time the electrons spend with the atom of low electronegativity makes that atom slightly positive within the molecule. Since a polar molecule has a slightly positive side and a slightly negative side, when a number of those molecules are near each other, they tend to orient themselves so that the positive side of one molecule is close to the negative side of another molecule. This gives polar compounds different properties compared to non-polar compounds. Polar substances mix readily with other polar substance, and non-polar substances mix readily with other non-polar substances; however, polar substance and non-polar substance tend to avoid each other. Water is just one example of a polar substance.

Slide 16

The slight attraction between two polar molecules is called a hydrogen bond (because hydrogen is often involved). A hydrogen bond is much weaker than an ionic bond (and therefore much, much weaker than a covalent bond), and a hydrogen bond does not form a new compound (it just affects the interaction between molecules of the same or different compounds). However, hydrogen bonds are so important to the way substances interact that hydrogen bonding is the reason that life was made possible on earth.

Slide 17

Molecules have their characteristic shapes because atoms and unpaired electrons in a molecule tend to distance themselves from each other as much as possible.

Slide 18

The function of a biological molecule often depends on the shape of that molecule, and sometimes it depends on the shape of just a part of that molecule. A signal molecule (like endorphin) operates by having part of its shape bind temporarily to a receptor molecule. If a different molecule (like the drug, morphine), has a part with a similar shape, it will operate similarly and cause a similar effect.