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ON THE POSSIBILITY
OF EXOTIC BIOCHEMISTRIES

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ABSTRACT

The likelihood of abiogenesis and extraterrestrial life based upon chemical structures other than the usual proteins, nucleic acids, water and other organic molecules common to terrestrial biochemistry is examined from the viewpoint of the chemical, physical and mechanical features of the alternative structures and their constituent atoms.

High cosmic abundance and small size are found to be desirable features of atoms comprising the large molecules of living systems. Polarity, abundance, and good solvating properties are found to be the requirements for a suitable biological solvent.

It is concluded that hydrogen and the elements in the second row of the Periodic Table--namely carbon, nitrogen and oxygen, are necessary major components of biologically significant molecules, although some variation from the terrestrial biomolecules is possible under different pressure, temperature and concentration conditions. Ammonia is found to be a possible replacement for water, as a biological solvent, under conditions where water is frozen but ammonia is a liquid.

ON THE POSSIBILITY OF EXOTIC BIOCHEMISTRIES

I. INTRODUCTION

The possibility of abiogenesis and extraterrestrial life based upon chemical structures other than the usual proteins, nucleic acids, carbohydrates, water and other organic molecules common to terrestrial biochemistry has been considered by several authors (Refs. 1, 2 and 3). Too often the conclusions of these studies are unjustifiably prejudiced toward terrestrial molecules (Ref. 3) or to the other extreme--an "anything goes" attitude (Ref. 1). This is primarily due to the absence of a careful chemical consideration of the mechanical aspects of living systems.

It is the purpose of the present study to describe the most important structural and dynamic requirements of living systems, from the chemical point of view, and to consider the types of chemical compounds compatible with these requirements. In particular, it is desired to learn whether carbon, hydrogen, nitrogen and oxygen, the predominant elements in all terrestrial organisms, as well as water, the universal solvent of terrestrial biochemistry, are necessary components of living systems or whether other substances under the same or different environmental conditions could occupy their respective places and thereby give rise to exotic biochemistries.

II. SOME IMPORTANT FEATURES OF LIVING SYSTEMS

Living systems are characterized by their ability to carry out a set of interdependent chemical reactions which result in the perpetuation of the living condition of the system. They are distinguishable from other naturally occurring chemical systems in that their chemical reactions do not drive them toward the lowest state of free energy compatible with their environment. This apparent violation of the second law of thermodynamics is circumvented by the coupling of highly exentropic chemical reactions to the negentropic processes which characterize the living state. The net result is that while the entropy of the living system itself may not increase, the entropy of the universe does increase as a result of the spontaneous chemical reactions of life.

The processes of living systems consist of acquisition of structural and functional molecules, reproduction, utilization of energy in life processes and disposal of waste materials. These processes must occur continuously and harmoniously if the living system is to avoid chemical equilibration with the environment. This requires that the living system be isolated, to some extent, from its environment, in order that extraneous chemical species in the environment do not interfere with the functioning of the living system. At the same time, the living system must be able to acquire raw materials from the environment and discharge waste materials to the environment. Consequently, "selective isolation" is a necessary property characteristic of living systems.

Given the foregoing properties of living systems, we are now confronted with the problem of deciding which types of atoms and molecules can participate in: (1) a medium for mass transport and chemical reactions in living systems, (2) selectively permeable membranes, (3) structurally and functionally significant molecules, (4) transmission of genetic and structural information, and (5) the release of energy to drive biochemical reactions. Since the biological properties derive from the chemical features of the molecular participants in all life processes, a brief review on the nature of interactions between atoms to form molecules and between molecules to form other molecules or molecular complexes is included as an Appendix.

III. SOME PHYSICAL LIMITATIONS ON THE EXISTENCE OF LIVING SYSTEMS

The origin and perpetuation of living systems on a planet will depend upon the existence and organization of some rather specialized types of chemical substances. Before considering the details of the natures of these substances and their respective places in a biochemistry, it is pertinent to consider whether or not they can exist in the physical environment of that planet. This section will consider three of the most important factors determining the condition of matter in a planetary environment--namely, the relative natural occurrences of the elements on the planet, the temperature of the environment and the presence of high energy radiation fluxes.

A. Elemental Abundances

Assuming that the origin of life on a planet occurs as a result of abiogenesis, the chemical species which eventually become the molecules of life are formed in accordance with the laws of chemical kinetics (Ref. 4) and near-equilibrium thermodynamics (Ref. 4). This means that the rates of production of the potentially biochemically significant species will depend upon the concentrations of their precursors and, also, that the concentrations of species not favored by equilibrium will be appreciable only if the initial concentrations of the precursor species are high.

The concentrations of biochemical precursor molecules can be related, in large part, to the relative abundances of their component atoms at the time of the formation of these compounds. Because of the high degree of organization and ordering required by all biologically important compounds, chemical kinetics and thermodynamics should be against the formation of such compounds in appreciable quantities from any but the most abundant elements present. Consequently, it is reasonable to conclude that only the most abundant elements can comprise the bulk of the atoms in a living system. As planetary life evolves from an abiogenetic to a biogenetic condition, the developed biochemistry demands that the more abundant elements at the time of abiogenesis continue to comprise the majority of the atoms of which the living systems are composed.

Hydrogen is believed to account for about 90% of the atoms in the universe (Ref. 5) while helium comprises about 9.5% of the cosmic atoms. All other elements make up the remaining 0.5% of the atoms. If we assume that the initial composition of a planet is similar to the distribution of elements in the universe, hydrogen and helium will predominate tremendously in concentration over all other elements. Since helium is chemically inert and hydrogen is univalent, the only compounds which could reasonably be expected on such a planet are simple hydrides of the higher elements with helium and hydrogen still in tremendous excess. However, due to the low atomic weight of both hydrogen and helium, the bulk of these elements are lost by thermal escape from all but the coldest, most massive planets. In our own solar system only the large cold planets like Jupiter and Saturn are known to retain large excesses of hydrogen while the detection of considerable quantities of ammonia (NH_3) and methane (CH_4) on these planets indicates that the other elements are present largely as hydrides. Since only rather small, hydride type molecules are likely to form on these planets, it is not probable that the complex, highly ordered molecules which characterize living systems would form under such conditions.

After hydrogen and helium, the next most plentiful elements are, in order of cosmic abundance: oxygen, nitrogen, carbon, iron, neon, silicon, magnesium and sulfur. Together these make up better than 99% of the remaining 0.5% of the atoms in the universe. Since all of these elements, except neon, form compounds which are capable of being retained by planets of all sizes and under almost any thermal conditions, it is reasonably safe to conclude that the majority of the atoms constituting biomolecules will come from this group. Excepted is neon, due to its chemical inertness. Hydrogen could still be present in the form of chemical compounds.

B. The Temperature Environment

The thermal conditions of a given planet are extremely important in determining which molecules could function as components of living systems and ultimately whether or not life is possible there at all. Life depends upon the highly controlled functioning of highly ordered molecules. High temperatures act to disrupt molecular order and may even destroy or prevent the synthesis of biomolecules. It is well known that above a few hundred degrees centigrade, most covalent bonds and all weak attractive interactions (charge-transfer, hydrogen bonding, etc.) are broken irrespective of ambient pressure. Above 1000° C even ionic compounds dissociate.

The resistance of a chemical bond to thermal rupture is determined by the bond dissociation energy which is in turn determined predominantly by the sizes of the atoms forming the bond. The larger the atoms, the less stable is the bond. Consequently, the smallest atoms form the most thermostable bonds. Since terrestrial organisms employ the smallest atoms available, it is doubtful that structures based upon atoms in the third row of the periodic table and beyond would offer any advantage over hydrogen and the second row elements in biomolecules at higher environmental temperatures than those found on the Earth.

Temperature also determines the rates of chemical reactions. The higher the temperature, the greater, in general, will be the rates of reaction. Also, high temperatures may accelerate unfavorable reactions and result in vitiation of biomolecular processes. Very low temperatures, on the other hand, may retard the rates of chemical reactions to the extent that biological processes are impossible.

The existence of life on a planet will depend upon the fluid properties of a liquid for mass transport and assistance in chemical reactions. The presence of such a liquid will be strongly dependent upon temperature. If the temperature of the environment is above the boiling point of the solvent under the prevailing atmospheric pressure, no liquid state will be present. If the temperature exceeds the critical temperature of the solvent, no liquid state will be present under any pressure conditions. If the temperature is below the freezing point of the solvent, again no liquid phase will normally be present. Thus, given a planet favoring the existence of a biological solvent, the temperature conditions will ultimately determine whether the solvent can be effectively utilized as part of a biological system.

C. High Energy Radiations

The molecular absorption of energy from high frequency electromagnetic radiations and fast moving charged particles produces electronically excited states and frequently results in non-thermal chemical reactions. The products of these reactions are not in thermodynamic equilibrium with their environment and are subsequently degraded through reactions involving the release of energy. Consequently, it is reasonable to expect that radiation induced chemical reactions will have some bearing on the existence of life on a planet exposed to space radiation. Radiation is believed to have played a large part in the synthesis of terrestrial biomolecules (Ref. 6). It is the most abundant source of the energy necessary to produce the non-equilibrium chemical species which comprise living systems. There is good reason to believe that abiogenesis on other planets, regardless of the elements involved, would rely heavily on radiation for its inception. On the other hand, high energy radiations can be detrimental to the existence of living systems.

Particulate radiations and electromagnetic radiation of wavelengths shorter than 2000 Å are capable of breaking chemical bonds and producing highly reactive species such as ions and free radicals. These species are capable of destroying the molecules comprising living systems and are therefore hazardous to the living state. Consequently, the perpetuation of life on a planet must involve some means of protection of living systems from high energy radiations. The presence of a thick fluid medium, such as an atmosphere or an ocean, on a planet would permit radiosynthesis to occur at the outer regions of the medium while shielding the inner regions from primary cosmic radiations and reactive, radiation-produced intermediates. The higher molecular weight radiosynthesized molecules could then settle, gravitationally, to inner regions and thereby be shielded from further interactions with radiations. Radiosynthesis on solid surfaces precludes the settling mechanism and subjects radiosynthesized species to radiation damage. Consequently, it is doubtful that any planet not containing a thick atmosphere or deep oceans could sustain life in the presence of a high cosmic radiation flux.

IV. BIOLOGICAL SOLVENTS

Living systems require a medium for mass transport and assistance in chemical reactions. To this end the liquid state is indispensible. Mass transport in solids is exceedingly slow--too slow to sustain biochemical reactions.

Transport of macromolecules in gases is almost impossible, except in the case of superdense gases. Chemical reactions usually involve both bond breaking and bond making steps. The rupture of chemical bonds in isolated molecules often requires more energy than the environment can supply in thermal collisions. Sometimes interaction of a biochemical reactant with a liquid solvent assists the breaking of bonds at thermal energies. The ensuing reactions might be impossible in the absence of such a solvent-solute interaction.

A biological solvent must be capable of dissolving small molecules but not macromolecular biological structures. Since the molecules of importance to living systems must be chemically active, they will necessarily be polar molecules. Because the dissolution of polar molecules as well as their reactivities are assisted by polar solvents, biological solvents will necessarily be composed of polar molecules. Consequently, liquified elements and molecules having three dimensional symmetry will not be capable of functioning as biological solvents. The importance of this is that hydrogen and methane, as well as other hydrocarbons, which are among the most abundant materials in the universe, are immediately eliminated from consideration.

A biological solvent must be abundant on a life-bearing planet if living systems are to exist there for a substantial portion of the planet's lifetime. For this reason the solvent molecules must be composed of relatively abundant elements and must be produced through very short synthetic mechanisms. Resistance to oxidation and reduction by the environment contributes to the stability of a solvent over long periods of time and is therefore a desirable property of biochemical solvents. Furthermore, if extensive acid-base and oxidation-reduction reactions occur in the biochemical processes, the solvent must have very weak acid, base, oxidizing and reducing properties relative to the reactants dissolved in it. Since living systems will have to be enclosed in selectively permeable membranes, the free passage of the solvent through the membrane, in either direction, requires that the solvent molecules be rather small. Finally, since all planets are expected to demonstrate periodic variations of temperature, both on a daily and seasonal basis, a good biological solvent should have as wide a freezing point to boiling point temperature range as possible.

Most of the small compounds of the more abundant elements (Ref. 7) do not satisfy several of the above criteria. The carbides, oxides, nitrides and sulfides of silicon, iron and magnesium are all ionic crystals, even at very high temperatures. The hydrides of iron and magnesium are unstable while those of carbon and silicon are non-polar. The hydride of sulfur has a 21° melting to boiling point range, is a very weak Bronsted acid, a very strong Lewis base, is unstable to oxidation and does not solvate charged species well. Many metal ions which may be essential as trace components of living systems will therefore be extremely insoluble in H_2S. It is therefore not a good biological solvent.

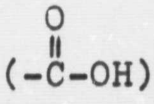
Carbon and nitrogen form a compound, cyanogen, which is non-polar due to its dimerization and is unstable to a wide variety of conditions. Carbon forms three oxides: C_3O_2, CO_2 and CO, which are, respectively, unstable, non-polar and of narrow and low (critical temp. = -139°) liquid temperature range. Nitrogen forms six oxides, all of which are either unstable, strong oxidizing agents, liquids at very low temperatures and within narrow ranges or poor solvating agents. Sulfur has two oxides. Sulfur dioxide is highly susceptible to oxidation and less so to reduction while sulfur trioxide is an extremely strong Lewis acid so that an extensive acid-base chemistry would not be possible in it. Sulfur also forms an unstable, solid nitride (S_4N_4) and a non-polar compound with carbon (CS_2).

Hydrogen forms two oxides (H_2O and H_2O_2) and three nitrides (NH_3, N_2H_4 and N_2H_2). One of the oxides (H_2O_2) and two of the nitrides (N_2H_4 and N_2H_2) are unstable under a wide variety of conditions due to the instability of the O-O single bond and the great stability of the N≡N triple bond. The remaining oxide and nitride of hydrogen have the properties desirable of biological solvents and will be discussed further.

In addition to the above binary compounds of the more common elements, there are several ternary compounds which might be expected to form in some quantity on a planet containing the hydrides of these elements. Among these are compounds like hydrogen cyanide (HCN), methanol (CH_3OH) and methyl amine (CH_3NH_2), all of which have several of the properties desirable for a biological solvent. These compounds are, however, relatively reactive and tend to form a wide variety of polymerization, oxidation and reduction products so that they would not be very stable in a dynamic planetary environment.

The substances most capable of satisfying all of the above requirements of a biological solvent are liquid water and ammonia. Both are small, highly polar molecules which are composed of some of the most abundant elements in the universe: hydrogen and oxygen in the case of water, and hydrogen and nitrogen in the case of ammonia. Both substances are extensively hydrogen-bonded in the liquid state. This results in their being liquids at much higher temperatures than are molecules of similar size but no hydrogen bonding.

The chemical behaviors of water and ammonia are qualitatively similar. Both can act as either Bronsted acids, Bronsted bases, Lewis acids or Lewis bases and are capable of dissolving a wide variety of polar and ionic substances. The principal differences between these two solvents are that ammonia is less polar, more basic, less acidic and less resistant to oxidation than water. Their differences are therefore of degree rather than kind. At one earth atmosphere pressure water has a freezing point to boiling point range of 100° C, while ammonia has only a 44° C range (-77.7°C to -33.4°C). Due to its greater susceptibility to oxidation, ammonia would probably not be a good biological solvent in a highly oxidizing environment, such as one containing molecular oxygen. Neither water nor ammonia exhibit very strong oxidizing or reducing properties relative to compounds composed of other elements. This is due to the small atomic sizes of hydrogen, oxygen and nitrogen and the already high states of reduction of oxygen and nitrogen in these compounds.

Due to its lower dipole moment, ammonia is a liquid at lower temperatures than is water. This, coupled with the differences in acidity and basicity of these substances, implies that if life exists in liquid ammonia, its chemical makeup might be somewhat different from that observed on Earth, with water as a solvent. For example, the carbamidine group  $(-\overset{H}{\overset{|}{\overset{N}{\overset{\|}{C}}}}-NH_2)$ might replace the carboxyl group  $(-\overset{O}{\overset{\|}{C}}-OH)$ common to terrestrial biochemical molecules.

It may be concluded that on a planet somewhat colder than Earth and with not too strongly oxidizing conditions, it would be chemically feasible for ammonia to serve as a biological solvent in place of water.

V. FUNCTIONAL MACROMOLECULES

Several of the processes which characterize living systems require very large molecules for their execution. Selective isolation, the discriminatory acquisition and rejection of environmental materials and the retention and rejection of systemic materials, requires large molecules with chemically active groups to participate in systemic membranes which act as highly selective two-way filters for the living systems. The retention and transmission of structural and genetic information is effected through macromolecular templates whose information is contained in the arrangement of chemically active groups affixed to the templates.

Since templates and membranes, as well as other macromolecular structures, are constructed according to the informational bits contained in template macromolecules, the biological macromolecules must be constructed, in vivo, from small molecules which can be acquired from the environment and whose chemical properties are complementary to those of the functional groups forming the informational bits.

The ability of atoms to form large but finite molecules whose skeletal structures will be stable in a polar medium depends upon the bonding properties of these atoms. In order to form extended structures, the component atoms must be capable of forming several covalent bonds of low polarity and high bonding strength. High covalence contributes to extension of structure while low bond polarity protects the structure from rupture due to attack by polar reactants. High bonding strengh assures thermal stability of the structure. High covalence is a property common to elements in the central groups of the periodic table (Ref. 7): the elements having three, four, five and six electrons in their outermost electronic shells. Low bond polarity is observed in bonds formed by atoms of identical or very similar size and nuclear charge. High bond strength is favored by small size of the bonded atoms due to their high orbital overlap, high attractive electrostatic interactions and low repulsive electrostatic interactions. Since the macromolecules constitute major fractions of the masses of living systems, the atoms which comprise the bulk of these macromolecules should be among the cosmically more abundant elements. Carbon, nitrogen, oxygen, magnesium, silicon, sulfur and iron will therefore be the elements of interest in the consideration of macromolecular skeletons.

Carbon and nitrogen are known to be capable of participating in the formation of biomacromolecules as these are the principal components of the skeletons of proteins and nucleic acids, the biopolymers of terrestrial biochemistry. Carbon is tetracovalent while nitrogen is tricovalent. Carbon atoms form bonds of low polarity by bonding to other carbon atoms. Nitrogen atoms can bond to other nitrogen atoms but the molecules containing nitrogen-nitrogen covalent bonds are generally thermodynamically unstable due to the very great stability of the nitrogen-nitrogen triple bond. These compounds usually decompose, with the evolution of molecular nitrogen Carbon-nitrogen bonds, however, are quite stable and the small size and charge differences between carbon and nitrogen result in their low polarity. Due to the very small sizes of the carbon and nitrogen atoms, both carbon-carbon and carbon-nitrogen bonds are quite strong. Both carbon and nitrogen demonstrate π-bond formation. In structures where this occurs carbon-carbon and carbon-nitrogen σ-bonding is reinforced by the formation of π-bonds (Ref. 8).

Due to the presence of non-bonded electron pairs in its valence shell, nitrogen also behaves as a functional, as well as a structural atom. These non-bonded electrons permit nitrogen to act as either a Bronsted base or a Lewis base. These activities are important in the functioning of proteins and nucleic acids. Carbon has no non-bonded electron pairs and while it is in a macromolecule, it is usually chemically active only when it participates in π-bonds.

Oxygen is also known to occur in the skeletons of terrestrial biomacromolecules, where it is usually bonded to carbon. The oxygen-oxygen single bond is inherently unstable. Because of the difference in nuclear charge between carbon and oxygen, the carbon-oxygen bond is rather polar. Both carbon and oxygen are, however, very small atoms and the carbon-oxygen bond is, therefore, very strong. Additionally, neither carbon nor oxygen have vacant valence shell orbitals to provide an easy pathway for polar attack on the carbon-oxygen bond via a coordination mechanism. To be sure, oxygen, like nitrogen, has lone pair electrons which are capable of being employed in coordination covalent bond formation. Donation of non-bonded pairs, however, generally strengthens covalent bonds due to minimization of valence shell electron pair repulsions. Acceptance of non-bonded pairs into vacant orbitals, on the other hand, increases valence shell electronic repulsions and generally weakens covalent bonding. Consequently, in spite of its polarity, the carbon-oxygen bond is relatively stable in polar media. The presence of carbon-oxygen or carbon-nitrogen single bonds in a terrestrial biopolymer usually indicates the places where small molecules have been joined to form the polymer.

It is interesting that in spite of the ability of carbon to catenate indefinitely, biopolymers make little use of this affinity of carbon atoms for each other. While synthetic concatamers of carbon are known, containing thousands of uninterrupted carbon-carbon bonds, biopolymers rarely contain groups of more than six continuously joined carbon atoms. For example, the fundamental monomeric unit of all protein skeletons consists of two carbon atoms and a nitrogen atom $(-\overset{|}{C}-\overset{\parallel}{C}-N-)$. This appears to be related to the great abundances of both carbon and nitrogen on the prebiotic earth. Long chain carbon concatamers would be likely to form in a system containing carbon as the only chemically active, polyvalent element. The presence of any other element with combining properties similar to carbon would tend to compete with carbon atoms for places in the molecular chains. The synthesis of long chain carbon concatamers on a warm planet is not likely because of dilution of carbon by oxygen and nitrogen. On a cold planet where oxygen and nitrogen are condensed as water and ammonia, hydrocarbon synthesis is possible, by radiolytic means, in the upper atmosphere. Even so, life based upon hydrocarbon macromolecules is extremely unlikely. In a cold environment, it would be extremely difficult for a living system to rely upon thermal energy to assist it in breaking down hydrocarbon chains into small units and then reassembling them, in vivo, into biopolymers. Furthermore, the insolubility of even small hydrocarbon molecules in polar solvents appears to represent an insurmountable problem.

Magnesium and iron are the only metallic elements among those we have arbitrarily designated the most abundant and it is precisely this fact which prevents them from being important structural atoms in biomacromolecules. Metallic elements are characterized by a small binding energy per valence electron compared with other elements in their periodic groups. This is a result of their having lower nuclear charges and slightly greater radii than other elements in the same periodic group. As a result, metallic elements are electropositive and tend to form bonds which have a great deal of ionic character. Ionic compounds either dissociate into ions in polar solvents or form insoluble infinite ionic crystals. Neither property is contributory to the formation of large but discrete molecules which retain their structure in polar solvents. Consequently, magnesium and iron are not suitable atoms to compose the skeletons of biomacromolecules.

Silicon, about one-eighth as abundant, cosmically, as carbon, is in the same periodic group with carbon. It therefore has four electrons in its valence shell. There, however, the similarity to carbon ends. Because of its nuclear charge and atomic radius, silicon is much more electropositive than is carbon. Its covalent bonds with other elements therefore tend to be highly polar. In addition, silicon has vacant orbitals in its valence shell which carbon does not. Consequently, covalent silicon compounds are readily susceptible to spontaneous coordination and reaction with polar molecules. With electronegative elements like oxygen and nitrogen, silicon forms ionic bonds which, due to the inability of silicon to form conventional π-bonds, result in the formation of infinite ionic lattices (e.g., silicon dioxide). Hence, even though silicon shows some ability to catenate, extended covalent silicon compounds would not be able to exist in a polar solvent like water or ammonia.

Silicon does form some molecular polymers when it is partially combined with hydrocarbon radicals and is put into a polar solvent like water or ammonia. These polymers have a skeleton of alternating silicon and either oxygen or nitrogen atoms and are extraordinarily stable to heat and to polar solvents as long as there are organic groups (e.g., CH_3-) occupying all non-skeletal covalent bonding sites. These polymers are called silicones (or siloxanes) if oxygen alternates with silicon in the molecular skeleton, and silazanes if nitrogen alternates with silicon. The thermal stabilities of the silicones and the silazanes appear to derive from the ionic nature of the Si-O and Si-N bonds, while the stability to coordination by polar solvents seems to be due to $p\pi \rightarrow d\pi$ back-bonding involving skeletal oxygen or nitrogen non-bonded electrons and silicon vacant d orbitals. The silicones are insoluble in polar solvents. Unfortunately, so are their small fragments. Further, the small fragments are only stable if they are capped off at the ends of the chain by organic groups. This situation does not favor the condensation of these small fragments into large polymers. Consequently, it is doubtful that the silicones or silazanes, or any silicon compounds, for that matter, could serve as biomacromolecules.

Sulfur is in the same periodic group with oxygen and is cosmically only about 0.7% as abundant as oxygen. It is known to occur in terrestrial macromolecules (proteins) in both a skeletal and a functional capacity. Skeletally it appears in the divalent state as does oxygen. Sulfur is very similar to oxygen chemically except that it does have valence shell acceptor orbitals and, due to its greater size, it is easier to oxidize than oxygen. Sulfur is not, however, a strongly electropositive element and is not nearly as susceptible to polar solvolysis as is silicon. In environments which are not strongly oxidizing, divalent sulfur is reasonably stable and many of its covalent compounds are structurally and reactively analogous to the corresponding oxygen compounds. It is interesting that sulfur would serve well in place of oxygen in the same type of environment in which ammonia might replace water in a biological scheme. It may be concluded that divalent sulfur compounds could participate as principal structural atoms in the skeletons of biopolymers. Tetracovalent sulfur compounds, on the other hand, are too susceptible to oxidation, reduction and polar solvolysis while hexavalent sulfur compounds tend to form only very small molecules and ions.

It is in order, at this point, to mention a few words about the place of hydrogen in biomacromolecules. Because of its univalence, hydrogen can form only one covalent bond to any other atom. Consequently, the occurrence of hydrogen at a particular point in a molecule represents a termination of spatial extension of the molecule from the atom to which the hydrogen atom is bonded, in the direction of the line of the bond with the hydrogen atom. It is this bonding with a univalent element that affords a molecule the ability to achieve "finiteness" without imparting a high degree of chemical reactivity, which may be unfavorable for molecular stability, to the site of termination of extension. (Ionization and π-bond formation may also terminate molecular extension, but usually impart reactivity to the bonding site.)

There are other univalent elements besides hydrogen--namely, the alkali metals: lithium, sodium, potassium, rubidium, cesium and francium and the halogens: fluorine, chlorine, bromine, iodine and astatine. It is pertinent, therefore, to consider whether these elements could occupy the place of hydrogen in an exotic biochemistry.

The alkali metals are extremely electropositive and tend to form ionic bonds with all but the most electropositive elements. In a polar solvent compounds containing alkali metals are dissociated into ions. Thus macromolecules would be transformed into polynegative anions in polar media. The accumulation of large numbers of negative charges on macromolecular skeletons would induce electrostatic instability and would result in breakup of the macromolecules. In amphiprotic solvents like water or ammonia, acid-base reactions would occur in which the alkali metal ions would be replaced with hydrogen ions which would form covalent bonds with the skeletal atoms of the macromolecules. It is thus impossible for alkali metal atoms to fulfill the structural function of hydrogen in biomacromolecules.

The halogens are extremely electronegative and would form highly polar covalent bonds with skeletal atoms. These bonds would be susceptible to dissociation in polar solvents. Furthermore, all of the halogens except fluorine have vacant acceptor orbitals to facilitate polar solvolysis. Fluorine, aside from being very rare, is the most electronegative of all the halogens and its bonds with skeletal atoms would usually have considerable ionic character. There are certain organic compounds in which fluorine, through electronic delocalization, forms bonds with carbon which are stable in the presence of polar solvents. It is conceivable that such compounds could find their way into biomacromolecules. The cosmic rarity of fluorine, however, makes the likelihood of this extremely low.

The small size, intermediate electronegativity and great cosmic abundance of hydrogen result in its uniqueness to form stable, covalent, single bonds with skeletal atoms which themselves must be of intermediate electronegativity.

In this chapter we have attempted to deal with the chemical requirements of the mechanical structures of biological systems. These structures are responsible for carrying out important life processes which are dependent upon the chemical reactivities of atoms and groups of atoms contained therein and which entail acid-base, oxidation-reduction , hydrogen bonding and charge transfer reactions. While it has been possible to accept or reject certain atomic species having similar chemical properties as potential structural factors on the bases of elemental abundance, atomic size and electronic structure, it is beyond the scope of this study to perform a similar analysis for the dynamic chemical behavior of these structures. This unfortunate circumstance is brought about by the chemical similarities demonstrated by many elements which are not as easy to separate from the point of view of reactivity as from that of structure. Furthermore, elemental abundance is not as limiting in the case of functional groups as it is with gross structures. Hence, it is not clear that trivalent phosphorus or arsenic could not serve in place of nitrogen as basic atoms or that sulfonic acid groups could not replace the acidic function of the carboxyl group. Even in terrestrial organisms, there is some evidence that sulfhydryl groups perform some of the functions of hydroxyl groups while iron and copper are known to perform similar functions in respiratory enzymes. The differences in reactivity of similar functional groups are often of degree rather than kind. To evaluate the effect of replacing one functional group with another would probably require a detailed model of the biochemical system into which it would fit.

VI. CHEMICAL ENERGY AND LIVING SYSTEMS

Living organisms being dynamic systems, require a source of energy to drive their vital processes. In order that the living system controls the rates of its own processes, the energy for these processes must be generated from within the organism in exergonic chemical reactions which are coupled, through reactive intermediates, to the vital processes. Assuming that the living system does not consume itself in the bioenergetic process, the chemical species which are responsible for biological energy production will have to be acquired from the environment or synthesized in vivo from materials acquired from the environment. Since these species must release energy in the course of their reaction, they must have higher chemical potential energy than either the environment or the living system. Consequently, these species will not be in a state of thermodynamic equilibrium with the environment. The synthesis of such high energy species, either in the environment or in vivo, requires the utilization of an energy source which is external to the environment and the living system. This energy source could be thermal or electrical as in the cases of volcanoes, hot springs and lightning but a far more intense and constant source of energy is available to all planets, regardless of their geological features, in the forms of cosmic and stellar radiation. High energy radiations can excite environmentally equilibrated molecules to electronically excited states, in which they are capable of reacting to produce high energy chemical species. These species would be degraded back to equilibrium species by reactions in the environment or in the organism. In vivo synthesis has obvious advantages in this respect. Ultimately, the waste products of the bioenergetic reactions would be returned to the environment as equilibrium or near-equilibrium species.

The bioenergetic reactions could be either of the acid-base or oxidation-reduction type or a combination of these. Presumably, the rates of reactions would be regulated by biochemical catalysts whose structures and modes of reaction would depend upon the reactions they were catalyzing.

The origin of biochemical fuels is probably closely related to the availability of the precursor species in the environment and the tendencies of their component atoms to form energy-rich covalent bonds under the influence of thermal, electrical or radiative energy. Hence, it would be reasonable to expect that they would be composed of the more abundant, covalent bonding elements--namely, carbon, hydrogen, oxygen, nitrogen and sulfur. Although iron does not show a strong tendency to form covalent compounds in polar media, the oxidation of Fe(II) to Fe(III) or the reduction of Fe(III) to Fe(II) could conceivably serve as a bioenergetic reaction. Silicon and magnesium, on the other hand, tend to form ionic species which are not amenable to the production of energy-rich molecules.

It is impossible to predict, a priori, which molecules could serve as the fuels for bioenergetic processes without detailed knowledge of planetary conditions. It is certain, however, that the energy-rich compounds must have reasonably long lifetimes if they are to exist long enough to be utilized by living systems. In water or ammonia as a solvent, it is doubtful that free radicals or small, unconjugated, π-bonded molecules could serve as fuels in oxidation-reduction processes. Similarly, ionic species could not serve as primary bioenergetic species in acid-base reactions. Such reactions would have to proceed through species containing covalent bonds with ionic character. In general, the reactive groups or atoms of the fuel molecules will have to be shielded from the environment by being trapped in the shallow potential wells of metastable covalent bonds (or inner atomic orbits in the case of iron).

The accelerated release of biologically useful chemical energy, in vivo, from these metastable bonds, would be accomplished by the intervention of biological catalysts. Those catalysts promoting oxidation-reduction reactions would themselves have to be capable of being reversibly oxidized or reduced or of conducting electronic charge. The presence of a delocalized π-electron system in these molecules is indispensible in this sense. Since only the elements in the second row of the periodic table show the ability to form extensively delocalized π-systems, oxidation-reduction catalysts would have to be composed primarily of carbon and nitrogen. Occasionally, certain reversibly reducible metal ions, like iron, may be useful in oxidation-reduction catalysts, as they permit the binding of bioenergetic molecules to the catalyst by coordinate covalent bonding without disruption of the π-system of the catalyst.

Catalysts for acid-base reactions would have to be capable of polarizing an already polar covalent bond until almost complete charge separation occurred. This requires the presence of strong electron acceptor and donor groups on the catalyst. As there are many chemical species which could fulfull this requirement, it is not possible to be very restrictive in this case.

VII. CONCLUSIONS

In order for living systems to exist on a given planet, certain chemical conditions must be met. These chemical conditions impose physical conditions on the biological environment.

A polar solvent must be available, in large quantities, to act as a medium for mass transport and mechanistic assistance in sustaining the chemical reactions of living systems. An abundant fluid solvent also assures that radiosynthetic pathways will be available to the living systems while providing shielding from the deleterious effects of high-energy radiations. The boiling and freezing points of the solvent under the pressure conditions of the planetary atmosphere set, approximately, the temperature limits for life in that environment. The high cosmic abundances and hydrogen bonding properties of water and ammonia make these two substances the most likely polar liquids to be retained by cool planets of intermediate size as biological solvents. Hot planets and small planets will generally not be able to retain atmospheres or large bodies of the liquids capable of serving as biological solvents.

Large but finite molecules are necessary to living systems for the retention and transmission of information and partial isolation from the environment. These giant molecules must be composed of abundant atoms which have the ability to form strong covalent bonds which are stable in polar solutions. On cool planets of intermediate size, the cosmic abundances of the elements, with hydrogen and helium considerably reduced in proportion, can be taken as an approximation to the environmental abundances of the elements. On large cool planets, which can retain hydrogen, the actual cosmic abundances of hydrogen and helium must also be considered. Of the more common elements, only carbon, hydrogen, nitrogen, oxygen and sulfur have the desired bonding properties for the skeletal construction of biomacromolecules. These desirable features can be traced to their high nuclear charge/radius ratios and, with the exception of sulfur, lack of vacant, valence-shell orbitals. Even though biomacromolecules are restricted predominantly to these elements, there is considerable room for variation in the molecular structures employed since radiosynthetic and chemosynthetic pathways to the macromolecules will be strongly dependent upon planetary physical and chemical conditions: chemical composition, atmospheric pressure, planetary size, etc. The chemical activities of these macromolecules are expected to arise from the secondary valence effects of nonbonding and π electrons of the constituent atoms and possibly from the occasional inclusion of less abundant elements. Phase equilibria (e.g., solvent extraction) and the employment of reactive trace elements may also be involved and it is therefore difficult to generalize about the nature of the reactivities of the macromolecules.

Living systems must be capable of producing their own energy for the sustenance of life processes. This is accomplished through chemical reactions involving chemical species whose chemical potentials are above the mean free energy of the environment. These species are synthesized from common environmental substances through the intervention of some extra-environmental source of energy. Cosmic and stellar radiations are most useful in this regard. Because these "fuel" molecules must be readily available to the living systems, they must also be composed of the more common elements and must not be so reactive that they are consumed in rapid nonbiological reactions. The "fuel" molecules must therefore be kinetically "stable" in the environment. This is most effectively accomplished when the useful energy of these molecules is stored in metastable covalent bonds. The in vivo reactions of the fuel molecules are accelerated by the employment of biological catalysts, which are chemically structured to transmit the biologically useful energy to specific life processes.

Those catalysts which promote oxidation-reduction reactions should have a delocalized π-electron system so that carbon and nitrogen are essential elements in their structures. Those catalysts which promote acid-base reactions must contain electron acceptor and/or electron donor groups. No limiting generalizations can be made about these molecules.

In view of the chemical attributes and great abundances of carbon, hydrogen, oxygen, nitrogen and sulfur, it is difficult, if not impossible, to conceive of living systems which are not composed predominantly of these elements. It is, therefore, reasonably safe to rule out the possibility of biochemistries based upon other elements than those comprising the bulk of terrestrial organisms. This, however, does not imply that extraterrestrial life forms must employ the same chemical structures found in terrestrial organisms. It would not be difficult to think of life forms employing ammonia as a solvent in place of water or using sulfur to a greater extent than it is used by earthly life forms. Furthermore, different solvent, pressure, composition and gravitational conditions on another planet might lead to synthetic and thermodynamic conditions favoring organic molecules and biosynthetic routes totally different from our purines, pyrimidines, sugars and amino acids as the building blocks of life. Ultraviolet and nuclear magnetic resonance spectroscopies may yield some very interesting results indeed, when the search for extraterrestrial life is begun.

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Attachment
Appendix

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APPENDIX

CHEMICAL STRUCTURE AND REACTIVITY (Ref. 7, 8)

The behaviors and properties of chemical compounds are predominantly due to the electronic configurations of the molecules which comprise these substances. Molecular properties are, in turn, dependent upon the electronic structures of the atoms of which they are composed and the natures of the interactions between these electrons. Quantum mechanics has been extremely useful in developing a qualitative picture of atomic, molecular and intermolecular electronic interactions. In this section the nature of electronic interactions in atoms, molecules and molecular complexes will be described briefly and will be used to account for the states of chemical combination of atoms and the structures and modes of reaction of molecules and molecular complexes.

A. The Electronic Structure of Atoms

Quantum mechanics has given us a qualitative model of atomic electronic structure in which a positively charged nucleus is associated with extranuclear electrons which move, very roughly, in orbits about the nucleus. The number of extranuclear electrons is equal to the number of nuclear protons in a neutral atom. The sizes and energies of the orbits are related to the principal quantum number $n(n=1,2,3,4.....)$. The greater the value of n, the greater is the mean radius and the energy of the orbit. The orbits are substructured into orbitals which have directional characteristics and determine the number of electrons which can occupy a given orbit. Each orbital can accommodate a maximum of two electrons. The smallest orbits, $n=1$ and $n=2$, each contain n^2 orbitals so that the $n=1$ orbit can contain a maximum of two electrons and the $n=2$ orbit can contain a maximum of eight electrons. For higher orbits, in many electron atoms, the picture is more complicated, due to the inability of atomic quantum mechanics to deal quantitatively with interelectronic repulsions. In constructing a model of many electron atoms, electrons are assigned to orbitals in orbits of lowest n until these orbits are filled. The orbits of next higher n are then occupied until all of the electrons are assigned to the orbits and orbitals giving the configuration of lowest energy. Thus, the atom with six nuclear protons and six extranuclear electrons contains two electrons in the $n=1$ orbit and four electrons in the $n=2$ orbit.

The orbitals comprising the incompletely filled, highest occupied orbit of an atom may be doubly occupied, and therefore filled completely, singly occupied and therefore half-filled, or completely empty. The chemical reactivity of atoms stems from the tendency of nature to fill all states (orbitals) thermally accessible to the system. This can be accomplished in several ways. First, a number of atoms having unpaired electrons can share their unpaired electrons, thereby mutually filling their partially occupied orbitals. The sharing of electrons between atoms results in attractive interaction between the atoms and is said to result in the formation of a covalent bond. The orbitals which are completed by the formation of a covalent bond do not retain their original characteristics. The simultaneous occupation of the two atomic orbitals by one electron pair results in an occupied molecular orbital. The number of unpaired electrons that an atom shares in this way is called its covalence. If two non-identical atoms share an electron pair, the pair will spend most of its time nearer one atom than the other. The covalent bond is then said to be polar. The tendency of an atom to polarize a covalent bond by attracting the electron pair is called its electronegativity. Correspondingly, the inability of an atom to hold an electron pair close to it is called electropositivity. Electronegativity is an electrostatic phenomenon and increases with increasing nuclear charge and decreases even faster with increasing atomic radius. The opposite is true for electropositivity. If an extremely electronegative element and an extremely electropositive element form a covalent bond, the bonded electron pair may be so strongly polarized that it resides in an orbital on the more electronegative element which is reminiscent of a pure atomic orbital. In this case the electropositive member of the bond is essentially stripped of the bonding electron. The almost complete transfer of an electron from one atom to another results in the formation of charged atoms or ions, and the largely electrostatic interaction holding ions together is said to be an ionic bond.

Second, those atoms which have completely vacant orbitals within partially filled orbits can accept pairs of electrons into these orbitals from atoms which have paired electrons in atomic orbitals. The originally unshared pair is then shared between two atoms, forming a bond and filling orbitals on both atoms. The bond thus formed is called a dative bond or coordinate covalent bond. The number of atoms attached to a given atom in this way is called its coordination number. Coordinate covalent bonding is not often observed in neutral single atoms which are not already engaged in covalent or ionic bonding. Rather, it is a property of atoms whose conventional covalences have already been satisfied. Consequently, it may be regarded as a secondary type of bonding.

Reactions in which a single electron is transferred from one atom to another are called oxidation-reduction reactions. The electron donor is said to be a reducing agent and is oxidized in the reaction. The electron acceptor is called an oxidizing agent and is reduced in the reaction. Reactions in which an electron pair is transferred from one atom to another are called acid-base reactions. The electron pair donor is called a Lewis base while the electron pair acceptor is called a Lewis acid. Coordinate covalent bonding is an example of Lewis acid-base interaction. Ionic bonding represents the result of the oxidation and reduction of atoms. Most chemical reactions can be classified as either acid-base or oxidation-reduction reactions.

All atoms having the same number of electrons in their highest occupied orbit have <u>similar</u> electronic configurations in these orbits and therefore show similarities in the compositions and electronic structures of the molecules they form, regardless of the value of n for the highest occupied orbit. This represents a statement of the Periodic Law which was proposed by Mendeleev in the nineteenth century when he observed a periodic recurrence of chemical properties of the elements as a function of atomic weight. Actually the periodicity is a function of atomic number (nuclear proton number). Thus all univalent elements combine with one atom of any other univalent element and divalent elements combine with two atoms of univalent elements, regardless of the identity of the atoms. The Periodic Law cannot be regarded as a reliable means of predicting all of the chemical properties of one atom from the knowledge of the chemical properties of an electronically similar atom (periodic congeners). This is due to the availability of greater numbers of orbitals in orbits of higher n and the differences in the electrostatic properties of atoms (electronegativity, etc.) of different nuclear charges, inner orbit electron populations, and atomic radii. These factors profoundly influence the details of atomic electronic structure, coordination number, bond type, bond strength and ease of oxidation or reduction of atoms engaged in bonding. The unreliability of the periodic law is of great importance to the present work.

B. The Electronic Structure of Molecules

The chemical and physical properties of matter are related to the types of bonds holding molecular atoms together in the molecule, as well as the spatial arrangements of these bonds. These factors are in turn determined by the ways in which atomic electronic orbitals combine to form molecular electronic orbitals and the ways in which these "molecular orbitals" are occupied by electrons.

Molecular orbitals are constructed by the overlapping of atomic valence orbitals. Each molecular orbital can accommodate two spin paired electrons, in accordance with the Pauli exclusion principle. The occupied molecular orbitals constitute the chemical bonds which hold the molecule together. Atomic valence shell electrons which do not participate in bonding are called non-bonding electrons and reside in orbitals which are localized on atoms but which, due to interactions with bonding electrons, do not exhibit themselves as true atomic orbitals. Inner shell atomic electrons, however, are not strongly perturbed by valence shell effects and behave as if they were in essentially "pure" atomic orbitals. The disposition of all valence shell electrons, bonding and non-bonding, about a given atom in a molecule, determines the bonding geometry of that atom. The equilibrium geometry of such an atom derives from the electronic configuration of least electrostatic repulsion compatible with the spatial characteristics of the available orbitals.

Chemical bonds are classified according to the way in which the atomic orbitals overlap and the distribution of electronic charge in the bond. Bonds which form as a result of collinear overlap of atomic orbitals and whose electronic charge is concentrated along the line joining the bonded atoms are called σ-bonds. Bonds which form as a result of overlap of atomic orbitals at right angles to the line of normal σ-bonding and whose electronic charge is concentrated above and below the line of normal σ-bonding are called π-bonds. Both conventional covalent and coordinate covalent bonding demonstrate σ- and π-bond formation. Ionically bonded compounds, on the other hand, demonstrate very little in the way of molecular orbital properties. The associative interactions in these compounds are primarily electrostatic. Consequently, rather than forming discrete molecules whose sizes are limited largely by the Pauli exclusion principle, ionic compounds tend to form infinite crystalline lattices.

For the sake of clarity, we shall at this point define as <u>molecules</u> those polyatomic aggregates whose bonding is the result of the sharing of unpaired atomic valence electrons. Molecules are therefore held together by conventional covalent bonds. Those species which are formed as the result of coordinate covalent bonding between molecules, by electrostatic attractions between molecules or by other charge transfer interactions between discrete molecules will hereafter be referred to as <u>molecular complexes</u>.

The atoms comprising the molecules with which this work is concerned exhibit covalences from one to six. If each bonding electron is shared with a different atom and all valence shell electrons are employed in bonding, the bonding geometry about the atom in question is linear, trigonal planar, tetrahedral, trigonal bipyrimidal or octahedral for atoms with two, three, four, five or six covalent bonding electrons, respectively. If two electrons in the valence shell of an atom are paired in a non-bonding orbital and each bonding electron is shared with a different atom, the bonding geometry (including the non-bonding pair) is linear, trigonal planar, tetrahedral or tetragonal pyramidal for atoms with three, four, five or six valence shell electrons, respectively. If two non-bonding pairs are present, a situation which can occur only with elements having six valence shell electrons, the geometry of the bonds and non-bonding pairs is tetrahedral. In all of the above cases, only σ-bonds are present. The sharing of two unpaired electrons of one atom with two of another atom results in the formation of one σ-bond and one π-bond. The stablest π-bonds all have planar geometry about the bonding area, but exceptions are known in which "strained" bent π-bonds are formed. In general, no atom may be engaged in more than two π-bonds.

A special case of π-bonding occurs when several atoms in the same molecule, relatively near each other, are engaged in π-bonding. Because the π-electron density is concentrated above and below the bonded atoms rather than between them, electrons in different π-bonds can undergo a super-exchange interaction. This is called "electron delocalization," and imparts great stability to the participating π-bonds, which are normally much weaker than σ-bonds.

The relevance of molecular electronic structure and molecular geometry to the behavior of matter can be illustrated by the following example. Water is a molecule composed of one atom of oxygen and two of hydrogen. The free oxygen atom has six electrons in its valence shell. Four of these form two non-bonding pairs, while two are unpaired. Hydrogen only has one electron. The water molecule is thus tetrahedral about the oxygen atom. The two O-H σ-bonds are about 105° apart. Because oxygen is more electronegative than hydrogen, the bond electrons reside closer to the oxygen than to the hydrogen atoms. Consequently, the oxygen atom carries a partial negative charge, while the hydrogen atoms carry partial positive charges. The asymmetry of the water molecule, coupled with the separation of charge in that molecule, results in the dipolar nature of H_2O. Among large numbers of water molecules, there are dipole-dipole attractions resulting in some ordering of the system at low enough thermal energies. As a result of these attractions, water is a liquid at much higher temperatures than methane which is of comparable molecular weight but is non-polar. Hence, the great importance of electronic structure and molecular geometry to the behavior of matter.

The attraction of water dipoles for one another results in what might be called a molecular complex. Here the intermolecular forces are electrostatic. Another type of molecular complex formation which results from chemical forces is coordinate covalent bonding. In this case non-bonding electrons from atoms already covalently bonded in molecules are donated into vacant orbitals on atoms in other molecules. Both σ type and π type bonds can be formed in this way, depending upon the relative orientations of donor and acceptor orbitals. As in the case of covalent bond formation, the geometries of coordination complexes are determined mainly by the configurations of minimum valence shell electron pair repulsions.

A third type of molecular complex formation is known. In this interaction, a non-bonding or π-bonded electron pair is donated into vacant high-energy π-orbitals of the acceptor molecule. The complexes thus formed are called charge transfer complexes and are considerably weaker than the other two types of molecular complexes.

C. Chemical Reactivity

The interactions between atoms to form molecules and crystals are the consequence of the tendency of matter to achieve the lowest state of potential energy compatible with the environment. In a similar manner, molecules will react to form the most stable species compatible with the environment. The conditions extant in the environment are extremely important in determining the pathways by which atoms and molecules react and the stabilities of the products of reaction. Equally important, however, is the elemental composition of the reactants and their electronic structures. The present section will deal with the important reactions of molecules and the effects of molecular structure and environment upon reactivity.

Chemical reactions may be divided into three broad classes: free radical reactions, acid-base reactions and oxidation-reduction reactions. Free radical reactions are processes involving the formation and subsequent reactions of species containing one or more unpaired electrons. Free radicals may be single atoms or molecular fragments. These species are produced by the decomposition of highly vibrationally or electronically excited molecules and are common reactive species only under high radiation fluxes or at high temperatures. The principal modes of reactivity of free radicals are atom or electron abstraction from normal molecules and radical recombination by electron spin pairing. While free radical reactions are probably not important to living systems as we know them in their normal functioning, they probably played an important role in the formation of the precursors to the molecules of life.

Acid-base reactions are of two types. The formation of coordination complexes by the donation of non-bonding electron pairs of a donor species to the vacant low energy orbitals of an acceptor species is called Lewis acid-base reaction. Sometimes π-bonded electron pairs can serve as the donated electrons. The electron donor in this case is called a Lewis base, while the electron acceptor is called a Lewis acid. The second type of acid-base reaction is due to the transfer of hydrogen ions from one species to another. This is called a Bronsted acid-base reaction and the hydrogen ion donor is called a Bronsted acid while the hydrogen ion acceptor is called a Bronsted base. Bronsted bases are always Lewis bases but Bronsted acids are not necessarily Lewis acids. The converses of both statements are also true.

The dissolution of a polar or ionic substance in a polar solvent always occurs as an acid-base reaction. The solvent dipoles orient themselves about the solute and the energy released by the ensuing acid-base reaction provides the driving force to overcome solute-solute attractions and disperse the solute into solution. All substitution reactions occurring in polar solutions are the result of acids or bases reacting with other acids or bases to form the most stable distribution of products under the conditions of the environment.

Oxidation-reduction reactions are reactions in which one reactant transfers one or more electrons completely over to another reactant. This is usually done in the direction of completing an electron pair on one atom or eliminating an unpaired electron on another. The electron donor is called a reducing agent and is said to be oxidized in the reaction while the electron acceptor is called an oxidizing agent and is said to be reduced in the reaction. Oxidation-reduction reactions between molecules in solution are thought to proceed by two possible mechanisms. Where the reacting molecules have extensively delocalized π-bonds, the electron transfer is believed to occur via the lowest vacant π-molecular orbitals. In the cases where no such π-system is available, reactants of similar molecular dimensions are thought to undergo oxidation-reduction by a tunnelling process.

As a general rule, the reaction of a molecule with a more electropositive species leaves that molecule in a reduced condition, while the reaction of a molecule with a more electronegative species leaves it in an oxidized condition.