Early Planetary Environments and the Origin of Life

1. Early Planetary Environments

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The Earth accreted from planetesimals 4.6 Ga[1] ago. The first few hundred million years were unfavourable for any kind of organic synthesis. Available evidences indicate that the time window for the origin of life on Earth is between 4.1 and 3.8 Ga ago. This period coincides with the late heavy bombardment of the inner Solar System by comets and asteroids and is too short for a complex system as life to have evolved from prebiotic chemistry. It is, therefore, speculated that at least some of the precursor organic compounds were impact-delivered to the early Earth by comets. These extraterrestrial bodies also supplied much of the Earth's volatiles.

Introduction

Life is amazingly beautiful, but ponder deep and you will realise how unique, mysterious and bewildering it is. To a rational scientist like the Nobel laureate Christian de Duve, life is just a cosmic imperative. It represents the result of 15 Ga of chemical evolution of the universe commencing from the Big Bang. Life is so complex that it defies proper definition and detailed understanding. According to Jerald Joyce (1994) life is a *"self-sustained chemical system capable of Darwinian evolution"*, meaning a chemical system that can reproduce, undergo material change over a historical lineage, and capable of genetic variation and evolution. Another definition compares life to a (bioinformation processing) computer in which the operating system is: DNA (deoxyribonucleic acid) to RNA (ribonucleic acid) to proteins which means that life is a complex information processing chemical machinery that is controlled by DNA, which directs

[1] (1 Ga=10^9 yr)

Box 1. Proteins

Proteins, like nucleic acids, are large molecules or biopolymers found in all life with amino acids as the monomer units. Linkage of several amino acids by peptide bonds (the bond between an amino, NH_2, group and a carboxyl, COOH, group of the amino acid) assembles them into peptides (containing upto 15 amino acids), polypeptides (upto 100 amino acids) and proteins (>100 amino acids). A gene (a certain nucleotide segment of the nucleic acid chain) codes for a particular protein. In fact, a gene consists of several nucleotide triplets, each triplet coding for a particular amino acid to be assembled into a protein. There are hundreds of thousands of genes in living organisms coding for as many number of proteins. The human body, for instance, synthesizes between 35,000 to 40,000 proteins. Deciphering the amino acid sequences in protein is called amino acid sequencing or protein sequencing. Proteins are responsible for vital life processes like growth, aging, reproduction, digestion and various physical traits of an organism. Enzymes, hormones and antibodies so essential for life are all proteins. There are structural proteins, regulatory proteins and enzymatic proteins depending on their function. The study of their structure and functions is the fast developing field of proteomics.

the synthesis of proteins (*Box* 1) via RNA. All living beings are made up of chemical elements; but it is not known when and how the non-living chemical compounds evolved into living molecules.

Life is very complex too. All living beings, both plants and animals, are composed of basic biological building blocks called cells, which are housed within a cell wall and differentiated into the cytoplasm and nucleus. The prokaryotic cells, however, do not have nuclei and the genome (*Box* 2) occurs within the cytoplasm itself. Within the nucleus there are chromosomes that hold genetic information in their nucleic acids, information required for the replication and biochemical functions of the cell. Further, there are proteins in the nucleus that occur combined with nucleic acids to form nucleoprotein. Besides, the nucleus also has a rich pool of nucleotides (nucleotides are the monomers, polymerization of which produces the nucleic acids) required for the synthesis of new strands of nucleic acids as nucleic acid helixes unwind and replicate just prior to cell division. Outside the nucleus, that is within the cytoplasm there are several functional units called organelles. Some of the organelles are ribosomes (the protein factories in the cell),

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Box 2. Genome and genome sequencing

Genome or genetic material is the nucleic acid (RNA/DNA) that holds heritable instructions in all living organisms for protein synthesis. Viruses, which are strictly speaking non-living organisms because they cannot self-replicate, have either RNA or DNA as the genome. Nucleic acids are polymers formed by the linear assembly of nucleotide monomers, the nucleotide triplets of which code for a particular amino acid to be assembled to form a protein. Since the four nucleotides (adenine, thymine, guanine and cytosine in DNA, shortened as ATGC; uracil replaces thymine in RNA) are repeated in a totally random manner in nucleic acids, it is absolutely essential to know each nucleotide in the chain in order to identify the triplet that codes for an amino acid. The procedure of analyzing and mapping the nucleotide sequences in the nucleic acid is called genome sequencing or genome mapping. A revolutionary technology called polymerase chain reaction (PCR) has made genome sequencing amazingly fast. This procedure enables small segments of nucleic acids to be amplified to produce sufficiently large quantities of the genetic material for processing and sequencing.

mitochondria (the powerhouse of the cells where the energy yielding chemical adenosine triphosphate, ATP, is synthesized and stored) and chloroplasts (which are responsible for the synthesis of carbohydrates in plant cells). Thus a living being is not merely a collection of hundreds of thousands of chemical molecules but a well-organised functional entity. The human body is estimated to have 10^{13} cells with information content of each cell being equivalent to 10^{12} bits. Further, the smallest DNA molecule has 1.5 million nucleotides and in the case of human DNA there are roughly 3.2 billion nucleotides. The complexity of human genome can be understood when we consider that if the entire coiled strands of human DNA are unwound and stretched from end to end, they would cover the distance from the Earth to the Sun and back.

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The Antiquity of Life

We have no evidence of life beyond the Earth and the Earth is the only planet known to have fostered the origin and evolution of life in the Solar System. Life on the Earth is pretty old. While there is no indication of life in the Hadean (4.6-3.8 Ga), existence of early Archaean microfossils and stromatolites is well documented now. The oldest unambiguous fossils are from the

3.465 Ga old Apex Chert of western Australia [1]. These are cellular filamentous structures, resembling modern cyanobacteria. Besides, isotopic pugmarks in the form of $\delta^{13}C$ of carbon in sediments from Greenland indicate biological carbon fixation as early as 3.85 Ga ago [2], though this evidence remains controversial (Myers and Crowley, 2000). Thus there is fossil evidence for the existence of life roughly 1.1 Ga after the accretion of the Earth, while carbon isotopic evidence shows emergence of photosynthetic life 750 Ma after accretion. These signs of biological activity confirm the great antiquity of life on Earth. The preceding period was very inhospitable because of repeated bombardments by colliding asteroids and comets. The blanket of dust clouds that filled the atmosphere during these impacts elevated surface temperatures to ~1700°C and pressures to 100s of bars that could have favoured evolution of only extremophiles (*Box* 3) like thermophilic prokaryotes similar to the extant bacteria. As CO_2-rich atmosphere evolved other prokaryotes like methanogens came into being. Photosynthesizing cyanobacteria (blue-green algae) evolved around 3.5 Ga ago. With the appearance of cyanobacteria that performed oxygenic photosynthesis, O_2 level in the atmosphere gradually increased. This paved the way for the diversification of life beginning with late Vendian (600-544 Ma). Unequivocal fossil evidence for prolific early life dates back to roughly 590 Ma in the form of Ediacaran fauna, though the earliest Ediacaran fauna evolved perhaps as early as 1 Ga ago. Ediacarans were metazoan prokaryotes that needed oxygen not only for respiration but also to synthesize the structural protein called collagen present in all metazoans. It is, therefore, unlikely that large-scale diversification of Ediacaran metazoans took place as early as 1 Ga ago. Their evolution in all likelihood was roughly parallel to the growth of atmospheric O_2.

Box 3. Extremophiles

Our entire perception of life is changing with the discovery of life in extreme environments (hence called extremophiles). Microbial life is now known to flourish in environments varying from the frigid, sub-zero temperatures of the sub-glacial lakes and dry valleys of Antarctica to the boiling point of water in the deep crust. Many of these organisms are unbelievably resilient; they go into hibernation when conditions become harsh and return to life when environments become normal. Extremophiles are very primitive organisms that form a class by themselves and include thermophiles, psychrophiles, acidophiles, alkalophiles, barophiles, xerophiles, halophiles and so on. The identification of life in extreme environments has made the search for life beyond Earth more tantalizing.

Early Planetary Environments

Carbon isotopic evidence points to the emergence of life on Earth roughly 4 Ga ago. From the origin-of-life point of view we are thus interested in the chemical nature of the atmosphere and

Was the early atmosphere reducing?

oceans at this time of Earth history. According to the Oparin–Urey model the primary atmosphere was composed of CH_4, NH_3 and H_2. Such an atmosphere would be highly reducing and a reducing atmosphere is favoured for the prebiotic synthesis of organic compounds, as it would facilitate rapid organic synthesis. But there is doubt today whether this was the composition of the primitive atmosphere when prebiotic synthesis began.

Ammonia is produced in the atmosphere today (by the reduction of NO_2^- and NO_3^- generated by atmospheric reactions driven by electrical discharges) and this would perhaps have been its important source in the prebiotic atmosphere too. Experimental data demonstrate that this is not a feasible process of NH_3 generation in the primordial atmosphere because NH_3 is thermally and photochemically unstable that would soon dissociate in the absence of an ozone shield. So nitrogen would have been present in the early atmosphere as elemental N_2 rather than as NH_3. However, experimental studies of Brandes and others (1998) show that N_2 can be reduced to NH_3 by mineral-catalyzed reactions at temperatures of 300-800°C and at pressures of 0.1-0.4 Gpa (Gpa means giga pascal; 1 Gpa=10^4 bars). The H_2 required for this reaction could be supplied by the action of water vapour on metallic or reduced iron of the early Earth. In the absence of molecular O_2, iron is believed to have been present in the primitive Earth in metallic or reduced state.

$$3Fe + N_2 + 3H_2O = 2\ NH_3 + 3FeO$$

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Minerals like pyrite and pyrrhotite present in crustal and mantle rocks can catalyze this reaction. Such environments are atypical of the surface but characterize crustal and oceanic hydrothermal systems, and therefore mantle/crustal N_2 could have been reduced to NH_3 that streamed out into the oceans through hydrothermal vents. The NH_3 in such environments could subsequently have been converted into nitrogenous organic compounds enroute to nucleotides and eventually to RNA. The experiments of Brandes and others thus point the finger to the ocean floor hydrothermal systems as the cradle for early life.

Box 4. Meteorites

Meteorites are extraterrestrial objects, originating from the asteroidal belt (between the orbits of Mars and Jupiter), which reach the Earth undestroyed. They are believed to be remnants of planetesimals, providing valuable information about the composition of the Solar System. They range in composition from almost metal to entirely silicates. Meteorites are broadly of three types: Stony meteorites (chondrites and achondrites; contain roughly 10% and 1% metal, respectively), Stony-irons (contain ~50% metals), Irons (>90% metal) and Tektites (composed entirely of glassy material). The metals in meteorites are chiefly Fe and Ni. The silicates that compose meteorites are pyroxenes, olivine and plagioclase feldspars. Besides, sulphide phases are also common. Meteorites have formation ages of 4.55 Ga. Occurrence of stones, stony-irons and irons as the principal meteorite types is indicative of an origin by fragmentation of a planetary body that had fractionated into a metal core and silicate mantle. Among the chondrites, the carbonaceous chondrites are the most carbon-rich and are very interesting from the origin-of-life point of view. They are also the most primitive, closest in composition to the Sun.

According to current planetary formation models, the Earth is considered to have formed by the accretion of planetesimals. Accretion of planets from planetesimals results in impact-degassing of the accreting bodies because of the extreme heat of collision. Although we are not quite sure of the chemical nature of the source materials from which the Earth accreted we can estimate their composition by analogy with the composition of meteorites (*Box* 4) because meteorites are considered to be residual planetesimals that never accreted to form a planet. Most of the chondritic meteorites are relatively dry bodies, but the carbonaceous chondrites contain upto 20% water by weight besides carbon. About 10% of the source material of the Earth-forming planetesimals had carbonaceous-chondrite-like materials, in which case the average water mass that was delivered to the Earth would be 10-100 times the mass of the present ocean. Similarly the average carbon content of the source materials could be 200-300 times as large as its present crustal abundance. 90% of the Earth-forming planetesimals are believed to have been devolatilised during accretion, resulting in an impact-induced proto-atmosphere that surrounded the proto-Earth. This proto-atmosphere was composed chiefly of H_2O and CO/CO_2 (and hence called steam atmosphere), which finally condensed to form the proto-ocean at the end of accretion.

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Atmospheric CO_2 controlled the early climate on the earth.

These components of the steam atmosphere are greenhouse gases that would have elevated surface temperatures to the melting points of silicates, eventually producing a magma ocean on the Earth's surface. CO is unstable in the presence of water vapour that would have converted it to CO_2. Thus the primordial atmosphere soon evolved into a CO_2-atmosphere. The dense CO_2 on the early Earth produced atmospheric partial pressures of 100-1000 bars for millions of years. The CO_2-atmosphere would also have mitigated the low-temperature effect of the faint young Sun (see [3]). CO_2 partial pressures could be lowered only by the extraction of CO_2 during weathering cycles, which removed it by reaction with cations supplied by continental and ocean floor weathering to deposit marine carbonates. Since continents were very limited in extent in the Hadean and early Archaean Earth, the atmospheric CO_2 and, therefore, surficial temperatures would not have lowered much until about 2 Ga. By that time the volume of continental crust had reached present levels of growth. Since then the CO_2 has been withdrawn from the atmosphere in depositing oceanic carbonate, thereby reducing its concentration in the atmosphere and consequently the surface temperature. The atmospheric CO_2 and the geochemical carbon cycle thus controlled the Earth's early climate. No organisms except thermophilic microbes could have withstood these extreme environments. Until recently it was considered that NH_3 and CH_4 are basic requirements for the initiation of biosynthesis on the primitive Earth. The current understanding is that such an atmosphere, if at all existed, was a very transient one and would soon have given way to a CO_2-atmosphere. If so could a CO_2-atmosphere facilitate biogenesis on the early Earth?

The answer is in the affirmative as confirmed by the experimental results of Chen and Bahnemann (2000). These authors demonstrated the synthesis of organic acids, aldehydes and alcohols of prebiotic relevance from CO_2 heated up in the presence of magnetite rock to 350°C at several tens of bars of pressure. Such environments are again typical of hydrothermal settings of the sea floor thus supporting the hypothesis of the origin of life in vent habitats.

Current evidences favour a mildly oxidizing prebiotic atmosphere.

The nature of the early atmosphere is of paramount importance in our understanding of the origin of life. If the prebiotic atmosphere were highly reducing with CH_4 and NH_3 as the chief components it would have fostered rapid biogenesis. But this seems to be too early a period for prebiotic organic synthesis because of the highly inhospitable conditions. It is not clearly understood whether the early atmosphere was highly reducing, mildly reducing or non-reducing. But certainly there was little free O_2 until the advent of photosynthesizing green plants. The evolution of the less reducing CO_2-atmosphere would not have facilitated Miller type (see [3]) of organic synthesis. Current evidences favour a mildly oxidizing prebiotic atmosphere, with compounds containing O_2, and nitrogen as elemental N_2 and carbon as CO or CO_2. Further, if the formation of the Earth's core were a slow process, much of carbon would have exhaled as CH_4 rather than as CO_2 (because metallic iron would have reacted with H_2O liberating H_2 that would convert carbon to CH_4). But if the core formation were a rapid early event the bulk of carbon would have escaped as CO_2, giving the atmosphere an intermediate oxidation state. Newsom and Sims (1991) arrived at the conclusion that core formation was essentially complete by 4.4 Ga ago, almost immediately after the formation of the Earth and so the early atmosphere was not that reducing.

The volume of the oceans during the prebiotic period is very significant because it is generally held that life originated in the oceans from a primeval organic soup. If the oceans were as voluminous 4 Ga ago as is now recognized, it would have diluted the organic soup. Though the proto-ocean was born by the condensation of water vapour from the proto-atmosphere, the impact events that followed the initial accretion would have been catastrophic leaving little of the primordial atmosphere and ocean. There is consensus of opinion today that the Moon formed by a glancing impact of a Mars-sized body on the Earth shortly after accretion. Such an extreme impact would have

Where did the water in our oceans come from?

eroded away all of any ocean and atmosphere because of the extreme heat of impact.

There is another reason to consider that the water of the oceans did not come from the beginning. The thermal history of the solar nebula is such that planetesimals near 1 AU (AU, the Astronomical Unit, is the mean distance from the Sun to the Earth, roughly 150 million kilometers) from the heliocentre were over 700°C that would eliminate any water other than vapour. The relatively dry ordinary chondrites formed at temperatures of ~240°C near 2 AU, while the carbonaceous chondrites, condensed at beyond 2.6 AU had formation temperatures of about 180°C. The giant planets and comets in which water occurs as ice are located beyond 5 AU. Since the Earth accreted from planetesimals at about 1AU the initial accumulation of the Earth was primarily from dry planetesimals.

Where else then was the source of the ocean water? Obviously comets. After the accretion of the inner planets and the Moon a rain of impactors fell on them. Estimates show that if 10% of these impactors were comets enough water would have accumulated to form the present oceans. The amount of terrestrial water from this rain of water is estimated to be an order of magnitude greater than that of the present ocean, 85% of which would have come from the vicinity of Jupiter and the rest from beyond. The present deficiency of oceanic volume is attributed to loss due to massive impacts. The noble gas (Ar, Xe and Kr) isotopic ratios also point to the arrival of water from comets. These ratios in comets are such that they could not have been the exclusive source of noble gases to the atmosphere. These ratios on the Earth and Mars are indicative of arrival from both internal and external sources. Owen (1997) observed that ice condensed at different temperatures trap noble gases in different ratios and identified the external source with ice condensed in the region of formation of Uranus and Neptune. The timing of these events is important for the consideration of the habitat for the origin of life. Delseme (1996) arrived at a time of 40 Ma for 90% of Earth accumulation and 70 Ma for the orbital diffusion of the comets from the zone of Jupiter. This implies that the ocean would have accumulated for the most part 4.45 Ga ago. The continued smaller rain of impactors would have been from the zone of Uranus and Neptune or from the Kuiper belt, or Oort cloud that is a huge repository of comets.

Water in other objects in the solar system.

Thus all the inner planets accumulated from dry planetesimals. They then acquired a thin veneer of liquid water plus atmosphere from comets. Analysis of comet Halley (from the Oort cloud) shows that it is composed of 23% rock, 41% water ice and 36% CHON (carbon, hydrogen, oxygen and nitrogen). The Moon lost this water in the low gravity while Venus lost it to UV dissociation during a runaway greenhouse warming. Mars has water mostly as permafrost. Recent exploration of Mars confirms that it did have surface water in its early history.

Impact Frustration

The early history of the planets of the inner Solar System is replete with heavy planetesimal and comet impacts, after their accretion, from about 4.6 Ga to 3.5 Ga. Impact data on the Moon confirm that the size of the craters and, therefore, the impact energy decreased exponentially with time. Since the Earth has higher gravitational power and larger surface area it would have received larger-sized and higher frequency of impactors than the Moon. The giant impact basins on the Moon such as the Aetken basin (~2200 km diameter) and Imbrium basin (1160 km diameter) correspond to impacting bodies of diameter 50-150 km. Statistical estimates show that the Earth would have been struck by about 17 giant impactors larger than those which created the largest lunar craters. Besides, extrapolation of lunar impact data suggests that the Earth was struck by $>10^4$ objects as large as comet Halley (~10 km diameter). According to Christopher Chyba (1990) many of these bodies that hit the Earth caused impact-erosion of the atmosphere. Chyba estimated that the Earth could easily have lost a contemporary atmosphere's worth of gases in this way. Obviously some of the early giant impacts had ocean-vaporising effects while some of the later

Meteoric impacts were frequent when the earth was young.

ones had photic-zone-vaporising effects. The immense quantities of dust and vapour thrown into the atmosphere would have caused unprecedented greenhouse effect (Sleep and Zahnel, 1998). Such impacts would also have effectively sterilized the Earth to depths of hundreds of metres. Fossil record and carbon isotopic data confirm that life on the Earth originated during the fag end of impact episode [5]. Evidently life would have become completely annihilated unless it had evolved into well-protected niches at depths. If the origins of life were still going on at the time of these impacts, there would have been several impact-frustrations for the origins of life (Maher and Stevensen, 1988) and it would have reappeared many times during the waning phase of impacts; and once the bombardment episodes greatly reduced in intensity (by about 3.8 Ga) life established itself.

If the Earth had witnessed cometary and asteroidal impacts in such profusion where are their vestiges? They were obviously destroyed by subsequent metamorphic and tectonic overprints. However, the late impact events that were synchronous with the deposition of the earliest sediment on the Earth such as those of Isua and Akilia. in Greenland (3.85 Ga, Nutman and others, 1997) must have left their marks in these sediments in the form of enhancement of platinum group of elements (PGE), [6]. Analysis of these sediments has so far not indicated any abnormal enrichment of PGE that could be attributed to extraterrestrial supply. Arrhenius and Lepland (2000), therefore, postulate that the late lunar bombardment was not at Solar-System-wide process but was largely limited to the lunar orbit, reflecting collision of the receding Moon with a series of small, marginal satellites of the Earth, which had comparatively little effect on it.

Extraterrestrial source of organic molecules on the Earth?

Exogenous Origins of Life

Since the time window for the origin of life on Earth was obviously very short many experts have pondered over an extraneous source for the precursor organics. Christopher Chyba and

Carl Sagan have considered three sources of organics to the early Earth: delivery by extraterrestrial objects, organic synthesis driven by impact shocks and organic synthesis by other energy sources like UV light or electrical discharges. Fred Hoyle and Chandra Wickramasinghe, in their theory of 'panspermia' proposed that life was dispersed throughout the universe by impacting comets. Though this theory looks outlandish, it is certain that some of the less catastrophic impactors delivered volatiles and organic compounds to the Earth for the origin of life. David Deming (1999) postulated that the Earth might have been subjected to high influx of extraterrestrially sourced volatiles (CHON and H_2O) derived mainly from comets. Though the influx rates were obviously of a greater magnitude during primordial times, the supply has not completely abated even today. Nevertheless, the delivery of intact organic molecules to the early Earth is more problematic. With the discovery of organic compounds in comet Halley (Jassberger and Kissel, 1991) the theory of cometary delivery of organic molecules to the Earth has attracted renewed attention. Comets may be as much as 25% organics by mass while carbonaceous meteorites and C-type asteroids are several percent organics. However, the problem is not in identifying a source but in envisaging a mechanism for the safe transport of organic compounds to the Earth. The Earth's present atmosphere cannot decelerate impactors of even 100 m diameters for their organic molecules to survive atmospheric entry and eventual impact. In a dense (~10-100 bar CO_2) primitive atmosphere small comets could have been decelerated sufficiently for their organic constituents to have reached the Earth intact. The discovery of unheated interiors in a meteorite that fell in Canada in 1965 suggests that within such unheated interiors organic compounds could still reside undestroyed. The detection of abundant extraterrestrial fullerene with trapped He at the 2 Ga-old impact crater at Sudbury, Ontario lends further credence to the view that complex organic compounds could survive terrestrial impacts. However, the most convincing evidence for exogenous delivery of organic molecules comes from the discovery of two extraterrestrial amino

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acids (α aminoisobutyric acid and racemic isovaline) in the Cretaceous-Tertiary boundary at Stevns Klint, Denmark. These organic compounds are rare in terrestrial biosphere but common in carbonaceous meteorites. These observations pose the distinct possibility of impact-delivery of organics from extraneous sources.

Can extraterrestrial organic molecules survive the impact?

Interplanetary Dust Particle (IDPs)

IDPs originating from disintegrating comets and colliding asteroids might have been another important source of organic molecules to the primitive Earth. IDPs typically contain ~10% by weight of organic compounds and those below 100 microns in size could sufficiently be decelerated by the Earth's dense early atmosphere and might have delivered their organics to the Earth almost undestroyed. Edward Anders (1989) estimated the flux of IDPs to the Earth and according to him the Earth is currently accumulating ~3×10^5 kg/year of intact IDP organics. However, the organics in IDPs have not yet been properly characterized, which is a difficult task in view of their extremely small size and amount. Laser microprobe techniques have recently demonstrated the presence of polycyclic aromatic hydrocarbons (PAHs) in IDPs, but PAHs are not known to play any significant role in contemporary biochemistry.

Having discussed the early Earth environments and the possible sources of primitive organic molecules let us consider what could have been the first living molecule with which life began and how did this molecule emerge from non-living chemistry. We shall discuss these aspects in the next part of this article.

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