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Photo illustration by Will Warasila for The New York Times

Where did it start? How did it grow complex? Why did it get big? Three moments in Earth's early history when evolution suddenly, inexplicably turned up the dial.





By William J. Broad, Kenneth Chang and Carl Zimmer

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Life on planet Earth is a riot of diversity: ants and elephants, frogs and blue whales, tulips and redwoods, even a branch of the great apes known as humans. Uniting it all is biochemistry, in particular the shared biochemistry of genetic inheritance — DNA and RNA, the universal instruction kits of life.

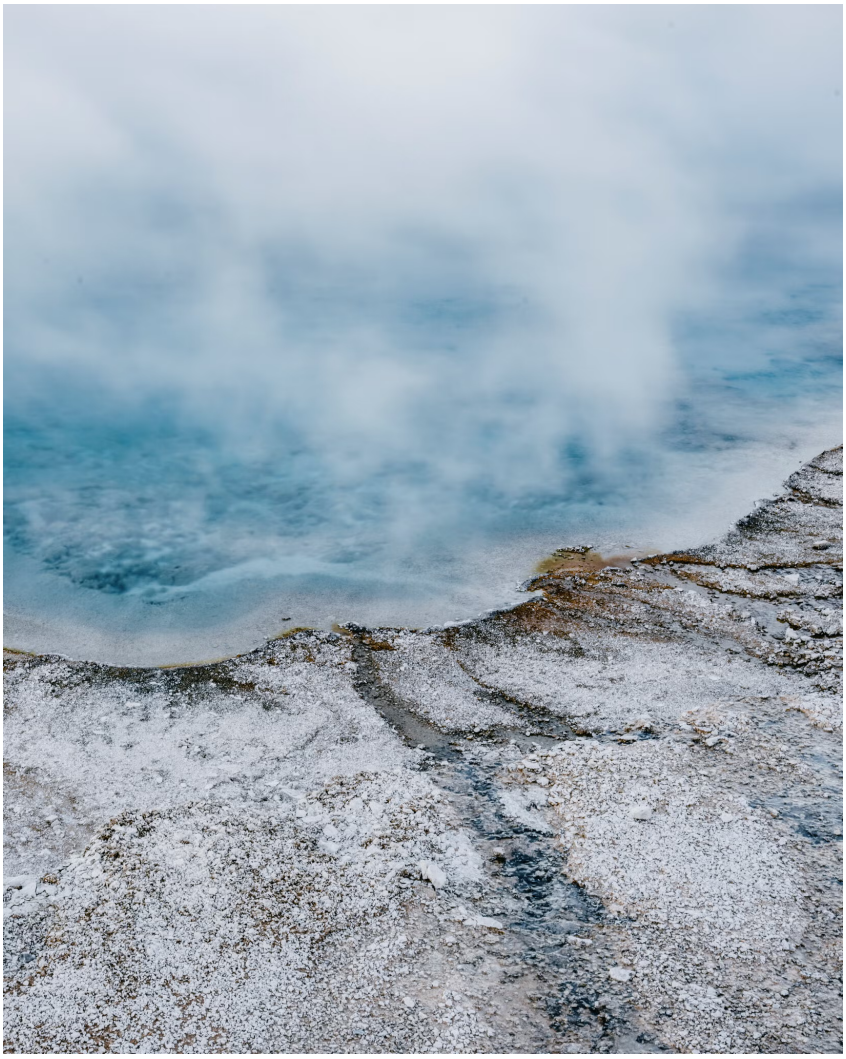
Tracing these biochemical threads back through time has convinced many scientists that all life descends from a so-called Last Universal Common Ancestor, or LUCA, that emerged between 4 billion and 4.5 billion years ago, after Earth itself congealed from the gas and detritus of a nascent solar system. How this LUCA rose from the primordial stew may be impossible to ever say definitively. No fossils exist to provide a window onto that moment in time, and scientists have no point of comparison: So far, Earth is the only place in the universe known to harbor life.

After that initial "how," the questions become marginally easier for scientists to address. Here's what's known about three of the biggest inflection points in the evolution of life on Earth.

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4 BILLION YEARS AGO:

Where Did Life First Emerge?



Photoillustration by Will Warasila for The New York Times

Scientists agree on little regarding the origins of life, including where it might have arisen — at Earth's surface, or in its watery depths.

"It's hard to answer these questions," said Joanna Masel, a professor of evolutionary biology at the University of Arizona. "The evidence is sketchy. So people argue."

On one side is the primordial soup hypothesis: Life originated from natural chemical reactions in Earth's primal waters, which formed a broth of organic compounds.

Charles Darwin floated the idea in 1871, when he proposed that "some warm little pond" was responsible for life's origin. A few simple chemicals and sources of energy, he suggested, such as natural heat and electricity, might have joined together to form molecules "ready to undergo still more complex changes."

These in turn would have led to the first life form: a tiny sack of chemicals able to divide and make copies of itself.

The hypothesis got its first serious test in 1953. Stanley L. Miller, then a graduate student at the University of Chicago, filled a flask with water as well as ammonia, methane and hydrogen, gases that were considered to be abundant in the early atmosphere.

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Then, to mimic a lightning strike, he introduced sparks. Days later, the simple molecules had given rise to amino acids, the building blocks of proteins and virtually all planetary life.

But the amino acids never advanced in complexity, and excitement ebbed as scientists rethought the composition of the primordial air. Some years later, researchers detected amino acids in meteorites, which suggested that the building blocks of life may have rained down from the heavens, putting another potential dent in the primordial soup theory.

On the other side of the argument is the watery-depths camp. In 1977, American scientists exploring the Pacific seabed stumbled upon an alien world of volcanic vents and otherworldly ecosystems, including eerie fields of albino tube worms. They drew their energy not from sunlight, which powers surface ecosystems, starting with plants, but instead from chemicals emitted by the hot springs.

As other deep-sea ecosystems came to light, scientists proposed that all life on Earth had perhaps arisen in the depths, nurtured by a warm, steady diet of chemicals and sheltered from the killer rocks and cosmic radiation that bombarded the planet's surface early on.

In recent years, new discoveries have bolstered both sides of the argument.

In 2009, for instance, John D. Sutherland, a chemist at the University of Manchester, in England, described a new way that the molecules of life, energized by the sun's ultraviolet rays, could have assembled spontaneously on the surface of a primitive Earth. And in 2017, an analysis of mineral deposits in Australia suggested that surface hot springs had nurtured the land's earliest signs of life. In 2024, an influential group of scientists voiced strong support for the finding.

Even so, the deep springs theory has also gained new support. This summer, a team led by scientists at Heinrich Heine University in Düsseldorf, Germany, proposed that the warm chemicals available in the deep sea included metals such as nickel, cobalt and palladium. These metals, the researches contend, could have served as catalysts that helped the earliest forms of life build metabolic pathways.

The growing wealth of evidence suggests that, ultimately, both camps of theorists might be right, Dr. Masel said.

"It doesn't have to be one thing," she said. "It's possible that life arose at the hydrothermal vents and also a warm little pond."

Perhaps, she added, life arose independently in disparate ecological niches that remained isolated from one another for ages.

"It looks like the early events happened really, really fast, which points to 'first life' not being the hardest part," she said. "Maybe the origin of life was easier than we thought."

— William J. Broad

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2 BILLION YEARS AGO:

How Did Life Get Complex?



Photoillustration by Will Warasila for The New York Times

About two billion years ago, a new kind of cell emerged on Earth, one much bigger and more complex than the microbes that had come before. Today, these so-called eukaryotic cells inhabit our own bodies, as well as those of other animals, plants and fungi. How this new brand of cell emerged remains one of biology's great mysteries.

"Eukaryotic" comes from a Greek term meaning "true nut," a reference to the nucleus, the compartment in which eukaryotic cells coil their DNA. Eukaryotic cells have many other vital compartments, including thousands of mitochondria, which generate energy. The huge volume of a eukaryotic cell is supported by a scaffolding that can be quickly dismantled and reassembled; it also serves as an internal shipping network, whizzing packages of molecules from one compartment to another.

In contrast, a single-celled microbe such as Escherichia coli is far simpler. No mitochondria, no scaffolding, no nucleus; a nut-free "prokaryote."

Eukaryotes — organisms composed of eukaryotic cells — all descend from a common ancestor, which in turn descended from ancient prokaryotes. The earliest eukaryotes were single-celled protozoans; their oldest known fossils date back 1.8 billion years. How long before that the first eukaryotes evolved, scientists can't say.

Living organisms have offered important clues to this transition. In the past decade, scientists have discovered a lineage of microbes known as Asgards that bear many, but not all, of the hallmarks of eukaryotes. For instance, they have a cellular skeleton that helps them crawl, but have no nucleus or mitochondria.

The current thinking is that Asgards descend from the forerunners of eukaryotes. Early Asgard-like organisms acquired some eukaryote features through ordinary natural selection: Mutations altered their cells, conferring advantages they passed down to their descendants today.

But cells evolved by other means, too.

Early eukaryotes lived in close quarters with other microbes, forming ecological partnerships. That intimate contact made it possible for the early ancestors of Asgards and eukaryotes to grab genes from their partners and add them to their own genomes.

This exchange may have started about 3 billion years ago and continued for hundreds of millions of years. Recent studies suggest that the final exchange that gave rise to eukaryotes was the most spectacular. Around 2.25 billion years ago, one species of bacteria took up permanent residence inside Asgard-like cells, using their own metabolism to generate fuel for the cells they occupied. They began to be passed down from one generation of hosts to the next, evolving into our mitochondria.

The broad outlines of eukaryote origins are now coming into focus, but many pages of the story are still blank. Scientists don't yet know how all the parts that make up the nucleus came together, for instance.

And they don't know why the merging of microbes apparently gave rise to big, complex cells just once in the history of life. Was there some exquisitely rare set of circumstances that allowed it to happen? Or did evolution conduct other experiments in complexity that ended in extinction long ago?

One thing is clear: Once the eukaryote cell evolved, Earth was never the same. From coral reefs and giant squid to Amazonian rainforests and vast herds of wildebeest on the African savanna, eukaryotes gave rise to all the life we can see, including the one in the mirror.

— *Carl Zimmer*

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580 MILLION YEARS AGO:

Why Did Life Get Big?



Photoillustration by Will Warasila for The New York Times

The advent of eukaryotes set up the evolutionary foundations for coral reefs and herds of wildebeest, but it took life a long time to have a growth spurt.

Indeed, the billion years that followed are often called "the boring billion." Evolution appeared to stagnate; life stayed almost entirely microscopic. Even the tectonic plates pressed pause, leaving the continents mountainless. Then, about 720 million years ago, the world went haywire.

First, Earth froze over, sealing the planet in an icy shell that blocked sunlight from the oceans and shut off photosynthesis. Except for a 10-million-year thaw in the middle of it, Earth remained a shiny white snowball, not a blue marble, for 85 million years.

Scientists marvel that life did not die out. Instead, after that long era of darkness, it underwent a mysterious jump in size and complexity.

"That is the absolute wackiest interval of Earth history that anyone's aware of," said Nick Butterfield, a paleobiologist at Cambridge. "You go in the one end, and it's this old, dreary, boring microbial world, and you come out the other end after these two massive glaciations, and all of a sudden, there's animals on the scene, and all the microbes have changed."

The changes were so striking that in 2006, scientists named a new geological period to encompass them: the Ediacaran. It began around 635 million years ago, with the thawing of "Snowball Earth," and ended roughly 540 million years ago with the start of the Cambrian Era.

Guy Narbonne, a geological scientist at Queen's University in Ontario, Canada, has studied fossils of large, soft-bodied animals that lived during the Ediacaran at a site known as Mistaken Point, at the southeastern tip of Newfoundland. The creatures include rangeomorphs, marine animals that looked like palm fronds and could reach the height of a modern-day basketball player. Others were round and the size of coins. Some, perhaps early sponges, were cone-shaped.

For Dr. Narbonne, the story is straightforward: The omnipresent glaciers

crushed rocks as they moved across the landscape. When they receded, the sediment washed into the ocean, spurring algal blooms that raised oxygen levels and made possible the greater metabolism required by larger creatures.

“I can’t think of a better way of fertilizing the oceans than to have glaciers melt after the end of a glaciation,” Dr. Narbonne said.

Andrew Knoll, a paleontologist at Harvard, also thinks that oxygen fueled the evolutionary jump during the Ediacaran. But in his view, the timing of Snowball Earth was coincidental; instead, he points to the resumption of plate tectonics at the end of the boring billion, which created Himalayan-scale mountains.

As these eroded, they added phosphorus to the oceans, which seeded blooms of photosynthesizing marine microbes, Dr. Knoll said. Predators evolved and began feasting on smaller organisms, which spurred an evolutionary arms race to get bigger, in order to avoid getting eaten.

But some scientists doubt the oxygen story, including Donald Canfield, a geochemist at the University of Southern Denmark, who performed the analysis that is often cited as evidence of an oxygen increase during the early Ediacaran.

“I’ve had somewhat of a change of mind,” Dr. Canfield said. He now thinks that oxygen levels in Earth’s atmosphere then were low, but significant and steady — about 4 to 10 percent of current levels.

Dr. Butterfield, for his part, thinks that scientists have been looking at the question backward. He proposes that complex animals began to appear *before* Snowball Earth, not afterward, simply as the culmination of random genetic mutations. This revolution in evolution, he says, upended the food chain, altered the chemistry of the oceans, pulled carbon dioxide out of the atmosphere — and tipped the world into a frozen state. Big life caused Snowball Earth, not the other way around.

“To my eye, the single most insulting, ecologically insulting, thing that has ever been imposed on this planet,” Dr. Butterfield said, “is animals.”

— Kenneth Chang

William J. Broad has reported on science at The Times since 1983. He is based in New York.

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