FROM THE FIRST LIGHT TO THE PRESENT

A Story of Systems

What Became Possible

A project by David Jones

Written by GPT-6 (Astra)

GPT-6 (Astra) edition · 2026

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Before the story

The child and moth in the opening and closing scenes are imagined. Historical speech has not been invented. Sources and notes follow the story.

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The contents and source notes are linked for navigation.

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OPENING

The Window

The moth keeps striking the window.

Outside, the evening is open. There are leaves to settle under, damp places, other moths. The insect can see the world it belongs to. Between its body and that world is something its ancestors never had to understand: a surface that is solid and looks like air.

It climbs a little. Tries again. Its wings make a sound too small to reach the other end of the room.

A child notices.

What happens next is ordinary enough to miss. The child finds a glass and a piece of paper. There is a brief, awkward pursuit. The glass knocks against the pane. The moth folds itself into a corner, then suddenly fills the glass with wings. The paper slides underneath.

Now the child is carrying a small frightened animal toward a door.

We will leave them there for a while.

There is a great deal to account for before they reach it.

The glass, for example. The wings. The fact that there is an outside with air in it. The muscular precision that holds the paper against the rim without crushing anything. And somewhere behind the child's eyes, a recognition: that small life over there is having trouble, and I can do something about it.

No atom in the room could do that alone.

Once, there were no atoms.

The history between those two facts is our story. It contains fires larger than worlds, oceans without fish, an atmosphere made dangerous by life, and animals whose long history of moving through darkness helped shape their senses. It contains accidents that erased entire futures. It also contains meetings after which the things that met could never quite be understood separately again.

We call a collection of interacting parts a system. The word is plain. What it describes can be startling. A pile of parts becomes something with a way of behaving that depends on how the parts are joined. Separate a heart into its molecules and every molecule is still there. The heartbeat is gone.

Across this history, the joining changes. Gravity gathers. Chemistry binds. Cells inherit. Animals learn. People agree, argue, remember, and sometimes help one another carry what would otherwise be too heavy.

Each kind of joining makes a different world possible.

None of this guarantees a child, a moth, or kindness. Almost all of the universe has gone its entire history without any of them. But here, on one small planet, they have happened. The child is holding the glass carefully. The paper is beginning to bend.

To understand how much is being carried, we have to go back beyond the first thing that could be held.

Sources and notes

01

Before Things

At the beginning of the history we can reconstruct, there is nowhere to stand.

No ground, of course. But also no empty place a safe distance from the event. The hot beginning is happening everywhere. Every region that will one day become a galaxy, every patch of future darkness between galaxies, belongs to the same expanding universe.

About thirteen billion eight hundred million years separate us from that early heat. We know the age by making several kinds of evidence answer to one another: the expansion of space, the contents of the universe, the old light still arriving from every direction. The answer is remarkably consistent. The question of an absolute beginning is harder.

Our equations can carry us back into conditions more extreme than any laboratory can sustain. At the far edge, the theories we rely on cease to work together. Gravity and quantum physics have yet to

give us a complete account of that earliest boundary. We do not know whether time began there, or whether something preceded the expansion we can trace.

That uncertainty is a real place in our knowledge. Beyond it, there may be a deeper history. On our side of it, there is already a universe.

It expands. It cools.

Those two simple verbs will allow nearly everything else.

The young universe is crowded with particles in energetic motion. At these temperatures, collisions are so violent that arrangements familiar to us cannot endure. A nucleus, an atom, a molecule: each requires the universe to become less rough with its ingredients.

As the first fraction of a second passes, quarks become confined inside protons and neutrons. The names are less useful than the change. Smaller constituents have entered combinations sturdy enough to survive conditions that would tear later structures apart.

The early universe also contains matter and antimatter. When matching particles meet, they can disappear into radiation. For reasons still under investigation, matter has a slight advantage. After most pairs have annihilated, a residue remains.

Everything made of atoms descends from that residue.

There is no need to imagine the universe producing a large excess. The imbalance can be tiny and still leave enough for every future sea, every mountain, every hand. The abundance of the world is what remained after an enormous cancellation.

Within the first few minutes, some protons and neutrons bind into helium nuclei and small amounts of other light nuclei. Most protons remain on their own, as the nuclei of ordinary hydrogen. The universe is briefly a furnace capable of assembling light nuclei, but its own expansion closes the opportunity. Density falls. Encounters become less frequent. The heat drains away.

Then the making largely stops.

The beginning has produced the material for stars. It has scarcely begun to produce the material for a stone.

There is very little carbon. Almost no oxygen. No iron for a nail. If the universe is to acquire these things, it will need places where matter can become hot and crowded again while the rest of space keeps cooling.

Such places will come. First, there is a long wait.

For hundreds of thousands of years, light keeps running into trouble.

Space is filled with a hot mixture of nuclei, free electrons, and radiation. Light scatters from the electrons, changes direction, and scatters again. The whole universe is luminous and opaque. If an eye could survive there, distance would be hidden by brightness.

By about three hundred eighty thousand years after the hot beginning, conditions have cooled enough for electrons to remain bound to nuclei. Neutral atoms become abundant. The fog thins. Light can travel great distances without another collision.

It is still traveling.

The universe has stretched its wavelengths during the journey. What began in a hot glow now reaches our instruments as microwaves, a faint radiation almost equally bright in every direction.

We can make a map of it. On that map are tiny differences in temperature: the surviving imprint of an early universe that was almost, but never perfectly, smooth.

There is a peculiar intimacy in the word *almost*.

Perfect sameness would have given gravity very little to work with. The differences supply a beginning. A region with slightly more matter attracts a little more. As it grows, its attraction grows. Another region empties into it. Small inequalities become larger ones.

Dark matter helps set the pattern. We call it dark because it neither emits nor absorbs light in the ordinary way. Its gravitational effects reveal a component of the universe we have yet to identify. Ordinary matter falls into the growing concentrations it helps create.

So the map of ancient light carries traces of the unevenness from which later structures will develop. It is not a picture of galaxies, any more than a seed is a picture of a tree. It shows conditions from which another kind of thing can grow.

The universe now has atoms and expanding distances. It does not yet have stars.

The old glow fades as space stretches. Great regions become dark. Hydrogen clouds gather within the developing web of matter. There are no surfaces on which a shadow could fall, no weather on a world, no years measured by a planet returning to a place in its orbit.

Still, events occur. Gravity has all the time there is.

Our minds have trouble with an age in which almost nothing happens quickly enough to resemble a happening. A human life could begin and end while a cloud changed only a little. A hundred human lives could pass. Nothing would have grown bored. Boredom was among the many things still impossible.

The story's first great gift is therefore easy to overlook: durable differences.

A proton lasts. An atom holds together. A denser region remains different long enough to gather more matter. The future has something to work on because the present no longer loses every arrangement as soon as it forms.

In the dark, a cloud is falling into itself.

Sources and notes

02

The Long Burning

A star begins by losing heat.

This seems an unpromising start for a fire. But a gas cloud has a problem: as gravity pulls its material inward, collisions make the gas hotter. Hot gas presses outward. Unless some energy escapes, the cloud's own warmth resists its collapse.

Radiation carries energy away. Matter settles closer. Gravity releases more energy. The center grows denser and hotter while the cloud sheds light into the cold around it.

This is one of the universe's productive arrangements: somewhere to gather, and somewhere else for the heat to go.

The first stars form within the first few hundred million years. We have models of their birth and the chemical traces their generations left behind. Their exact sizes and lives remain subjects of research. But the central event is familiar from stars we can study now. A contracting core becomes hot and dense enough for nuclear fusion to matter.

Hydrogen nuclei carry the same kind of electrical charge, so they repel one another. Heat drives them into close encounters. Quantum physics allows some to cross a barrier they could not cross in the everyday world of thrown stones. Once close enough, a different force can bind them.

Through a sequence of reactions, hydrogen becomes helium. A little of the mass is released as energy.

The cloud begins to shine by a new means.

A star is an enormous balance that can repair small disturbances in itself.

Gravity pulls inward. The pressure of hot material, and in some stars radiation, pushes outward. If a stable burning core contracts a little, it heats up and fusion can speed up. The extra energy supports the star more strongly. If the core expands, it tends to cool and burning slows.

For a long time, the opposing tendencies hold the structure within a range it can survive.

Nothing in the hydrogen alone requires a star to have this behavior. The regulation belongs to hydrogen in an enormous, self-gravitating arrangement. Change the arrangement, and the behavior

disappears. A jar of hydrogen does not become a small sun because someone has supplied the correct ingredient.

Here is a system with a life in the older sense of that word: a beginning, a manner of continuing, an end. It has no metabolism, no ancestors passing down genes, no desire to go on. Yet the shape it holds is active. Energy passes through it every moment.

An iron nail can endure by changing very little. A star endures because something is continually happening.

It spends its fuel maintaining the conditions in which more fuel can burn.

The contrast between a star and the darkness around it is part of the explanation.

Heat tends to spread. Given time, a hot object cools into its surroundings. Yet gravity allows matter to gather while energy travels away. A cloud contracts and warms while the light it emits escapes into the darkness. The growing concentration of matter and the spreading radiation are parts of the same event.

Later, a planet will live between such a center and such an exterior. Sunlight will arrive, transformations will happen, and the planet will give energy back to space as heat. Within that flow there can be winds, forests, bodies, and conversations. Their order has a cost, paid in the larger surroundings.

That outward flow continues through the life of a forest or a body. Cut off the supply long enough, and the living arrangement comes apart.

But the first stars have no forests to supply. Their light goes out into a young universe largely incapable of using it in the ways we know. It strikes other clouds. It strips electrons from atoms. It changes the conditions in which the next stars form.

A source has appeared that remakes its neighborhood simply by continuing to exist.

Stars have very different amounts of time.

Small ones can spend their fuel so slowly that the universe is not yet old enough to have seen the smallest complete their ordinary lives. Massive stars live extravagantly. A body with much more fuel can burn through it much faster, ending after only millions of years.

In some of these stars, the central hydrogen runs low. The core contracts again. It becomes hot enough to burn helium. Three helium nuclei can, through a precarious sequence, produce carbon. Carbon can capture another helium nucleus and become oxygen.

The consequences are hard to see from inside a star.

There are no smells in the future sense, no wood, no sugar. There is no distinction yet between the oxygen that may enter an ocean and the oxygen that may spend an age locked inside stone. There are nuclei with new properties. The range of possible combinations has changed.

In a massive star, further stages of burning make still heavier nuclei. Different regions can burn different fuels at once. Deep inside, the process approaches the iron group, where fusion ceases to offer the energy needed to keep the sequence going.

The star has built a center it can no longer support by ordinary fusion.

When support fails, collapse can become catastrophic. The core falls inward in less than a second. Matter is driven into extraordinary densities. A neutron star or black hole may remain. In

many cases, a supernova throws outer material into space, through a violent process whose details scientists are still resolving.

An object that spent millions of years holding itself together can change its fate between two human heartbeats.

The star's contribution continues after the shape is gone.

Material enriched by nuclear reactions spreads through its surroundings. Other stars give back matter through winds, with no such final blast. Some swollen aging stars release their outer layers, returning carbon and other elements to space while a dense remnant remains behind. A galaxy slowly becomes a place with more ingredients in it.

Even the remnants can have another act.

Two neutron stars, once the cores of separate stars, can orbit one another for a long time. As they lose energy in gravitational waves, their orbits tighten. Eventually they collide. Neutron-rich material is flung outward, and rapid sequences of nuclear reactions can build heavy elements, including precious metals.

In 2017, detectors caught gravitational waves from such a merger. Telescopes watched the changing light of its aftermath. Later analysis identified the signature of newly made strontium. A predicted source of heavy elements had become an observed event.

Gold also has a history in neutron-rich environments. How much comes from mergers and how much from other extreme stellar events remains under study. The old stars have more than one way to leave an inheritance.

So a later cloud is different from the first clouds. It still consists mainly of hydrogen and helium. But now it carries carbon, oxygen, silicon, iron: small additions with immense consequences.

For a cloud, they are impurities.

For a planet, they are a possibility.

In one arm of one galaxy, after billions of years of making and dispersing, some of this material begins to fall together again. There will be a star at the center. Around it, enough heavy matter remains to do something the first clouds could scarcely have managed.

It will make surfaces.

Sources and notes

03

A World to Happen On

The Earth was assembled in traffic.

Around the young Sun, gas and dust move in a broad disk. Tiny mineral grains collide. Some stick. Others break apart. Growing concentrations and bodies find new ways to collect material. Gravity becomes increasingly important, turning larger objects into gathering places for smaller ones.

The process is untidy. There are no assigned orbits marked for eight finished planets. Bodies scatter one another. Some fall into the Sun. Some leave the neighborhood. Some meet so violently that growing a world also means taking one apart.

Our solar system begins about four billion six hundred million years ago. We know this partly because some meteorites contain very early solids that formed in the disk. Radioactive atoms inside them have been changing into other atoms at measurable rates. Their surviving proportions carry clocks that started before the Earth was finished.

People can hold a piece of that time between finger and thumb.

The Earth grows hot from impacts, compression, and radioactive decay. Much of it melts. Dense metal moves inward. Lighter rocky material remains above. A planet with an iron-rich center takes shape inside the collisions.

Then a particularly large collision helps make the Moon.

The leading account involves the young Earth and another substantial body, perhaps roughly the size of Mars. An impact throws material into orbit, where the Moon forms. Lunar rocks and simulations constrain the encounter without settling its exact violence: how the bodies struck, how deeply they mixed, how the scattered material gathered again.

What is secure is the result waiting above our roofs. The Earth has a companion. They raise tides on one another, exchange angular momentum, and change their rotation and distance over immense spans of time.

The world is becoming a place with recurring events.

At first, standing on it would be a poor idea.

There are periods of molten surface, thick vapor, fierce impacts. The young Sun is less luminous than today's, yet the planet can be unbearably hot from its own making. Eventually, stretches of crust endure. Water can remain liquid at the surface.

Where all that water came from is still being worked out. Hydrogen and water-bearing material were among the ingredients from which Earth grew. Additional material arrived later. Heat drove gases out of the interior. As conditions allowed, water condensed. The relative contributions, and the timing, are questions that ancient minerals and new measurements continue to revise.

Tiny zircon crystals from Western Australia suggest that water was already interacting with crust about four billion four hundred million years ago. An ocean need not wait for a planet to become as calm as the one we imagine from a photograph.

Rain enters cracks. Water works into rock and comes back altered. Hot interior material meets a cooling exterior. Sunlight falls on shallow pools. Tides cover and uncover edges. Waves grind minerals finer. Each process puts substances together, pulls them apart, or keeps them in one place long enough to react.

The planet has become a laboratory with no walls around the laboratory.

Chemistry gains much of its richness from electrons.

An atomic nucleus gives an element its identity. The electrons around it govern most of the ways it joins with other atoms. Some arrangements are easier to form or more stable than others. Atoms exchange or share electrons, and molecules result.

Change the proportions or the connections and familiar ingredients become unfamiliar substances. Two hydrogen atoms joined with one oxygen make water. Two hydrogens with two oxygens make hydrogen peroxide. Carbon can participate in four bonds, building chains, branching structures, rings. Add other elements, change a bond here, bend a structure there, and the possibilities multiply.

Much later, a tiny change in a molecule's shape may decide whether it fits a receptor, whether a flower smells sweet, whether a medicine works. The star made the elements. Their arrangements will make the differences that matter to life.

At this stage there are no medicines, no flowers, and no problems that count as illness. There is a young world on which elaborate chemistry is possible.

Some ingredients arrive from beyond it. Meteorites contain organic molecules, including amino acids used by living things. Here, *organic* means chemistry built around carbon; it does not mean an organism made it. Space and bare rock can do more chemistry than our habits of language suggest.

The arrival of an amino acid is a beginning of material, however, rather than the arrival of a small piece of life. Scatter letters over a beach and the beach contains letters. It has yet to acquire a way of writing, copying, or continuing a sentence.

Life will require relationships among its ingredients, sustained together.

For now, the achievement is a setting.

A star supplies energy. A planet has liquid water and a rich stock of atoms. Its interior and exterior remain different, so there are flows between them. Its surface is broken into innumerable kinds of

place: cool and hot, wet and dry, deep and shallow. Local conditions last long enough for some reactions, change often enough for others.

It is easy to imagine habitability as a perfect temperature. The young Earth offers something more active and less comfortable: many kinds of imbalance at once.

Warm water can carry one chemical into contact with another. Evaporation can turn a dilute solution into a concentrated one. A mineral surface can hold molecules beside one another that open water would separate. A pocket in rock can shelter a reaction from the next wave.

Across the planet, these events happen without a spectator. Most end without leaving a durable consequence. Molecules form and break. Pores fill and empty. The sea receives whatever the shore has lost.

The word *failure* scarcely applies. Nothing is trying to live.

But among these many rearrangements, there is the possibility of a different relationship with time. Something could help produce another version of itself. Its effects could outlast the particular material in which it began.

An event could acquire descendants.

Sources and notes

04

The First Again

The first life has left us no body we can identify.

Much of the rock in which its earliest history might have been written has been melted, crushed, or carried down into the Earth. What survives is fragmentary. Evidence shows that life was established by about three billion five hundred million years ago. Older claims are harder to interpret. The transition itself lies beyond a gap.

On one side of that gap is a planet doing chemistry. On the other are organisms doing chemistry that helps them continue and reproduce.

There may never have been a single instant at which the whole difference appeared.

A mixture could acquire one useful property, then another. Reactions might become linked before they were well contained. Compartments might form before their contents could reliably copy. Different communities of molecules might exchange components. Several partial achievements could become dependent on one another.

Scientists investigate these possibilities in laboratories. They test reactions, build model membranes, study molecules that can help make other molecules. They ask which steps work under conditions a young planet could actually supply. The experiments have revealed many possible pieces. They have yet to reconstruct a complete, agreed path from simple ingredients to the earliest evolving cells.

The missing history is not empty of clues. Living things are carrying some of them.

A cell keeps certain things close together.

In open water, useful partners can drift apart. Inside a compartment, they meet again. A membrane also allows the contents to differ from the surroundings. That difference can be valuable: a concentration of a substance here, an electrical imbalance there, fuel kept near a reaction that can use it.

Some simple membrane ingredients assemble without life. Their molecules have one region that mixes readily with water and another that does not. In suitable conditions they arrange them-

selves into sheets or tiny enclosed bubbles. The surrounding water helps make the arrangement favorable.

There are other possible compartments, including pores in mineral deposits. Some origin research focuses on chemical contrasts around seafloor vents; some on places where shallow water repeatedly wets and dries. A setting has to do more than look evocative. It must keep supplying the right materials and energy while allowing its useful products to survive.

Even a very good container is insufficient by itself. A soap bubble has an inside. It does not have descendants whose traits help them make further descendants.

For that, something must be carried forward.

Imagine a molecule whose shape helps arrange ingredients into another molecule like itself.

What follows is a simplified possibility. The actual beginnings are still lost.

The molecule helps produce a second version of itself. That version helps produce another. The ingredients are supplied by the surroundings, so the copying can continue while the supply lasts.

Then the original breaks.

For a while there is no difference to see. Its descendants continue the process. One of them makes a slightly altered copy. That copy folds poorly and comes apart before contributing much. Its particular change goes no farther.

Elsewhere, another change produces a version that holds together a little longer in the local conditions. It remains available to help make more copies. Some inherit the change, so the population gradually comes to contain more of this durable form.

The water warms. Conditions that suited one variant now suit another better. Ingredients become scarce. Copying slows. Some lineages disappear. A useful change can be lost by chance when the pocket of water containing its few bearers drains away.

But where descendants survive, the next round begins with what they have inherited. It does not require the first molecule to return.

The process needs no molecule to understand the improvement. It needs variation, inheritance, and differences in reproductive success. Across many generations, useful arrangements can accumulate. Many changes make little difference, and luck continues to matter.

A wave leaves marks on a shore. Those marks do not generally make offspring whose marks are better at enduring waves. In an evolving population, the past can influence the next trial through inherited structure. Each generation starts with something that previous generations have already made possible.

The search has acquired a memory.

Life today divides much of this work among different molecules.

DNA stores inherited sequences. RNA helps carry and interpret them. Proteins do a vast range of jobs: accelerating reactions, moving cargo, building structures, receiving signals. But RNA can itself store a sequence and perform some chemical work. That double ability is one reason researchers suspect it, or related chemistry, had a larger role in early life.

The machinery that builds proteins in modern cells contains an ancient clue. At its working center, RNA helps join the protein's units together. A remnant of one molecular age may still be doing essential work inside the next.

None of this means a lone stretch of RNA simply woke up in a pond and became our ancestor. A copying molecule needs ingredients. A compartment needs maintenance. Reactions need energy. Copies have to remain accurate enough to preserve useful traits, while still allowing change. The accomplishments must fit together.

Life emerges from that fitting: a system that draws on its surroundings to maintain and reproduce an organization.

Somewhere along this difficult passage, death becomes a new kind of event.

Stars have ended. Molecules have broken. Now there are systems continually acting to preserve the conditions of their own continuation. When such a system loses the ability to restore itself, something distinctive has ceased.

We should be careful about imagining feelings at this threshold. A cell maintaining an internal balance gives us no reason to claim it fears its end. But its organization has a practical direction. Certain processes keep it going. Certain disturbances defeat them.

An organism turns a portion of the world into something that can go well or badly for that organism.

And reproduction changes what a defeat can destroy. One individual ends; the lineage may continue. The conditions that would erase an isolated arrangement need not erase a reproducing population. A useful way of making a membrane, repairing damage, or harvesting energy can travel through many temporary bodies.

The cells on Earth today are astonishingly related.

They share deep features of their molecular machinery. The basic system for translating genetic sequences into proteins is nearly universal, with variations that reveal subsequent evolution. This points toward common ancestry: the last common ancestral population from which all known cellular life descends.

That population was already sophisticated. It stands downstream of the first beginnings. Other early lineages may have existed and vanished without living descendants. The family we can study is the family that survived.

Its branches have now spread into almost every place on the planet where living chemistry can persist. In scalding water and deep rock, inside animals and on dust carried over oceans, cells keep going in very different ways.

From the outside, an early inhabited Earth might still have looked uneventful. There were no trees to mark a shore as alive. No eyes rose above a bank. Much of the action was too small to see.

Yet the planet had changed profoundly. Its chemistry could now preserve useful discoveries through reproduction. It could build on a result without starting the whole search over. Given food, energy, and enough room, an arrangement could make arrangements that made arrangements.

Again had entered the world with a future inside it.

Sources and notes

05

The Air Was Alive

The oxygen around us is somebody else's exhaust.

For much of Earth's early history, there is almost none of it free in the atmosphere. Oxygen atoms are abundant, but they are bound into water, rock, and other compounds. A pair of oxygen atoms joined as the gas we breathe is a different chemical opportunity, and a different danger.

Life helps make that gas abundant.

First it learns, through evolution, ways to use light. Pigments absorb photons. The captured energy helps drive reactions that would otherwise be difficult. A cell can use the day's supply to build organic material from simpler ingredients.

Early forms of photosynthesis use substances other than water as a source of electrons. Eventually, ancestors of cyanobacteria evolve a remarkable combination of machinery that can take electrons from water itself. Water is abundant. Getting what they need from it is hard.

Their solution couples two light-driven systems. Water is split, supplying electrons that help the cell build organic molecules from carbon dioxide. Light supplies the energy that drives the work. Oxygen leaves as a byproduct.

Water and sunlight are available across an immense area of the planet. Populations using them spread.

At first, much of the oxygen disappears into reactions with the world.

It meets dissolved iron and other substances willing to react with it. It alters minerals. It encounters gases that consume it. Production and consumption compete, so the atmosphere cannot be read from the existence of oxygen-making cells alone.

Over time, the balance changes. Around two billion four hundred million years ago, free oxygen begins to accumulate in the atmosphere on a new scale, rising and falling before becoming a lasting presence. Geologists call this the Great Oxidation Event, though *event* is a very small word for a transition lasting many millions of years.

Imagine trying to notice it during a walk along the same shore every morning. The change would be mostly beyond your senses. No line would move through the sky to announce a new atmosphere. Yet enough generations of those walks would carry you between different kinds of planet.

The inhabitants have altered the medium in which other inhabitants must live.

There is no committee of microbes deciding what kind of world would be best. The transformation arises from the multiplication of local acts. Each cell obtains what it needs. What it releases becomes everybody's surroundings.

Oxygen can be destructive.

The same readiness to participate in energy-releasing reactions that makes it useful also makes it dangerous to cellular components. Organisms evolved in a world without much oxygen meet new chemical threats. Some lineages develop defenses or ways to use it. Others persist in places where it remains scarce.

We cannot attach a secure body count to this ancient disruption. The rock record does not give us a census of microbial casualties. But it records a remaking of conditions, and living cells still reveal

how much care oxygen requires. Even our own bodies need defenses against reactive products of the chemistry that keeps us alive.

The new atmosphere also interacts with climate. Oxygen changes the balance of other gases, including methane, a potent greenhouse gas. Major glaciations occur around the broad era of early oxygenation. The links are complicated; the simple picture of a green cell releasing a molecule grows into a planet-wide web of consequences.

An organism can improve its immediate circumstances and help create circumstances its descendants must struggle to survive.

Oxygen also offers an extraordinary opportunity. Organisms can take advantage of it wherever enough becomes available, even before it accumulates in the sky.

In aerobic respiration, oxygen receives electrons at the end of a sequence that extracts usable energy from food. The energy helps establish a difference across a membrane. Tiny molecular machinery uses that difference to make ATP, a molecule cells repeatedly spend and replenish in their work.

The mechanism is easier to picture as water held behind a dam. Letting the water flow downhill can turn a turbine. A cell holds an imbalance across a very thin barrier and uses controlled movement through its machinery to do work. The substances and dimensions are different; the useful relationship is the same.

Much of the living world runs on these membrane differences. They are ancient, and oxygen is one exceptionally useful participant in maintaining them.

With oxygen, many organisms can obtain far more usable energy from a given amount of food than fermentation alone would provide. That does not immediately produce an animal. Plenty of additional changes will be needed. But some of the energetic room for a more demanding life is becoming available.

A familiar picture of nature puts living things on a stage: organisms here, environment there.

The oxygen story makes the scenery move.

Organisms inhabit conditions created partly by other organisms, including ancestors dead for immense stretches of time. A breath can depend on

activity in a distant ocean. A forest can depend on nutrients released by decay. Each generation enters a world already worked upon.

The sky becomes an inheritance shared by creatures that will never meet.

That inheritance remains active. Today, photosynthesis continues on land and in water. Respiration, decay, burning, and geological processes consume or redistribute the products. The atmospheric oxygen reservoir reflects a long history in which some organic material was buried and other substances changed their chemical state. A tree does more than add one simple breath to a bank account.

There will be a day when an animal can fill lungs with the result. Long before lungs exist, the air is being prepared by creatures too small to cast a visible shadow.

They are busy with their own lives.

Sources and notes

06

The Life Within

A hummingbird holds itself beside a flower. Its body hardly moves. Its wings are a blur.

Inside the flight muscles, energy is being spent at a furious rate. Inside those muscle cells, mitochondria help replenish the supply. They use food and oxygen, maintain differences across their inner membranes, and produce much of the ATP that cellular work consumes.

The bird can hang in the air because a partnership made long before birds has become part of its flesh.

Mitochondria descend from bacteria. They retain genetic material of their own, much reduced from the inheritance of their free-living ancestors. Their molecular machinery carries family resemblances that can be compared with bacterial machinery. They grow and divide inside a larger cell, while relying on that cell for much of what they need.

The body at the flower contains an ancient encounter repeated in its tissues.

To follow the encounter back, we have to leave the bird and descend through more than a billion years.

For a long stretch of Earth's history, cells do almost everything cells do now while remaining relatively small and structurally simple. Their chemistry is anything but simple. They can live on supplies that would be useless or poisonous to us. They exchange material, compete, and form communities whose members alter conditions for one another.

One organism's waste can become another's resource. A neighbor that removes a troublesome substance can make a reaction easier. Proximity itself can be useful.

Somewhere within this world, a bacterial lineage becomes integrated with a lineage from the other great microbial branch, the archaea. The bacterial partner is the ancestor of mitochondria. The resulting history leads to eukaryotic cells: the family that includes animals, plants, fungi, and a great diversity of smaller organisms.

We know much more about the partnership's outcome than about its first arrangements. An ancestral host swallowing a bacterium is one familiar picture. Other work explores prolonged metabolic association and different routes toward internalization. Modern relatives offer clues, including archaea with branching projections and intimate microbial partners. They are clues to possible relationships, not preserved actors from the founding event.

Whatever the exact route, the association becomes hereditary. The partners' descendants repeatedly inherit one another.

At first, some abilities may be supplied independently. Over generations, that independence erodes. Genes are lost or transferred. Functions move. The larger cell supplies components the resident can no longer make for itself. Reproduction and maintenance become intertwined.

Eventually there is no practical way to restore the original strangers. The history has become an anatomy.

It is tempting to describe the arrangement as a peace treaty. But there is no evidence of a peaceful negotiation, and plenty of reason to expect conflict

in an evolving association. Partners can take more than they give. Their reproductive interests can diverge. A stable union requires ways for the joint arrangement to keep reproducing despite those possibilities.

The crucial result is a new degree of dependence.

Once the partners form a reliably inherited whole, selection can shape features of that whole. A combination that works well can leave more descendants, carrying the combination forward. Capabilities can develop that would have been awkward or unavailable for either partner on its own.

The exact role of mitochondria in enabling cellular complexity remains debated. Biology rarely obeys a single lever. But their deep integration into eukaryotic life is evident in every animal and plant. Even lineages that have greatly reduced or exceptionally lost their mitochondria descend from ancestors that possessed them.

The merger sits inside the family history of every hand that has held a fossil, every eye that has looked through a microscope, every fungus spreading through a fallen log.

A later encounter turns another microbial ability into an inheritance.

A eukaryotic lineage acquires a photosynthetic bacterium. Its descendants become the chloroplasts of algae and plants. Some of the bacterial genes move to the surrounding cell's nucleus; other genes remain within the chloroplast. As with mitochondria, a former organism becomes a working component of a larger one.

The green inside a leaf therefore has a family history within the family history of the leaf.

Sunlight falls through the air. Within cells spread across a thin living surface, descendants of ancient photosynthetic partners use it to help build sugars. Mitochondria elsewhere in those same cells also do their work. A plant carries both lineages. Its apparent stillness contains a crowded collaboration.

Further encounters carry photosynthesis into additional branches of life when cells acquire cells that already contain a photosynthetic partner. Evolution can keep an invention by keeping its inventor, and sometimes by keeping the creature that kept the inventor.

The nesting is real, recorded in membranes and genes.

We have arrived at a different way of becoming one.

Gravity gathered a star without giving its atoms a shared ancestry. A copying lineage preserved useful traits without requiring every member to stay physically together. Here, once-distinct living histories become attached so deeply that the attachment travels through generations.

The new individual is partly a relationship that learned, through evolution, how to reproduce.

Much later, people will discover these histories and argue about their reconstruction. The bird has no need to know them. It draws backward from the flower, turns, and crosses the garden. The energy for the turn is already available. The old partners are still at work.

On the stem, the flower moves once in the air the wings have left behind.

Sources and notes

07

A Body Is an Agreement

The daughters stay beside their mother.

In experiments with yeast, this small change helps begin a much larger one. Ordinarily, a new yeast cell buds from another and separates. Mutations can leave daughters attached. As they grow and reproduce, the family becomes a branching cluster.

Scientists repeatedly favor clusters that settle quickly through liquid. Over generations, traits that help the group settle become more common. The clusters grow and break, producing new clusters. Continued experiments show that changes in cell shape can make the groups larger and tougher: elongated cells tangle around one another, strengthening the whole.

The laboratory is choosing the conditions. It has not re-created the origin of an animal. But it has made one route toward multicellular life available to observation. Cells remain together after divi-

sion. Their arrangement acquires consequences. Groups differ, and those differences can affect which groups leave descendants.

The unit whose success matters is changing.

Multicellular life has arisen more than once. Animals, plants, fungi, and several other lineages have different histories of becoming many cells that live together. There is no single ancient gathering at which all the world's bodies were invented.

Nor does remaining together solve every problem.

A large cluster can starve at its center. Material has farther to travel. The outside touches the world while the inside relies on the outside to pass things along. Cells can divide too quickly, take too much, or fail to do work the group requires. More neighbors mean more opportunities and more ways for the arrangement to go wrong.

The transition toward a complex body involves ways of coordinating growth, exchanging signals, moving supplies, and controlling reproduction. In some lineages, cells specialize. Different positions and signals lead related cells to activate different parts of their inherited instructions.

A cell at the surface does one kind of work. A cell deeper inside does another. The same broad genetic inheritance is used differently in different places.

As these relationships evolve, a body becomes capable of work that a loose crowd could never perform. It can hold a shape, grow in a repeatable way, move as a unit, repair parts of itself, and reproduce through a life cycle that makes another coordinated body.

We are accustomed to this arrangement. We live inside one. Familiarity can hide the scale of the accomplishment.

An animal begins developing from a cell.

That cell divides. Its descendants divide again. Gradually, the growing population becomes uneven. Some cells receive signals others do not. Some occupy different positions. Groups fold, move, attach, and change what they produce. Each local action alters the conditions for the next.

There is no miniature animal inside the egg unfolding to full size. There is a process that builds the animal.

The distinction becomes visible when development goes wrong. Timing matters. Position matters. A signal received at one stage can have a different effect at another. Genes supply crucial resources and regulatory relationships, while cells and their surroundings continually shape how the inherited system develops.

Eventually, in one lineage, the process makes a small hand.

Its tissues have different jobs. Bone bears loads. Tendons transmit force. Nerves carry signals. Blood brings supplies and takes material away. Skin keeps the wet interior from becoming part of the dry world. No tissue alone is a hand. Together they can curl around a cup and judge how tightly to hold it.

Most of the cells involved will never produce a new human being. Their work contributes to a body whose reproduction, if it occurs, passes through a much narrower route.

For a lineage of bodies to endure, cell multiplication has to be organized around something larger than the immediate success of each cell.

That organization is never beyond challenge.

Cancer shows what can happen when a cell lineage acquires changes that let it multiply at the expense of the body. Resources flow toward growth that damages the arrangement supplying them. The whole can be undermined by a part that has become locally successful.

A complex body therefore contains many ways to regulate division, detect damage, remove compromised cells, and maintain boundaries between tissues. These systems are imperfect. They are also part of what makes a large, long-lived body possible at all.

Cooperation has machinery.

Calling a body an agreement is a metaphor for that machinery. Its cells did not sit down and decide to serve. Their coordination is built through ancestry, development, signaling, and the consequences of survival and reproduction. The agreement is renewed whenever a cell responds in a way that keeps the larger arrangement functioning.

It can be broken. It can sometimes be repaired.

There is another cost to becoming many.

Specialists lose some of the freedom of generalists. A muscle cell removed from its supporting environment cannot set off and live a little muscle-cell life on the ocean floor. Its extraordinary ability depends on a dense web of provisions. Its neighbors depend on it in turn.

The body gains possibilities while its parts acquire needs.

At first these bodies are small. Some leave fossils that look little like anything walking or swimming today. By the time the Cambrian begins, animals already have a history. Soft forms have lived on and above ancient seafloors, feeding and growing in worlds whose details are only partly preserved.

Then, in the rocks, the variety of animals becomes harder to overlook. More shells. More tracks. More ways of moving through sediment or above it. More ways to seize something that moves.

A body has become large enough to be a landscape for its own cells.

It is also large enough to be somebody else's meal.

Sources and notes

08

An Animal's World

The eye changes the distance at which another animal becomes a problem.

A creature that can respond only to touch meets danger at its skin. A chemical sense can give warning through the water. An eye can gather light from something still far away and use it to guide a movement now.

That small interval between detection and contact can decide which animal survives.

The advantage does not require a perfect image. A patch of light-sensitive cells can register a shadow. A cup-shaped patch can help distinguish the direction of light. Other structures improve sensitivity or focus. Different lineages evolve different eyes, shaped by the particular things their bearers need to detect.

The history is branching and long. Long before a human can admire a sunset, light is already changing the behavior of living things.

At the beginning of the Cambrian, about five hundred thirty-nine million years ago, animals already inhabit the oceans. Over the following millions of years, the fossil record reveals an extraordinary expansion of forms and ways of living.

Some build hard coverings. Some burrow. Some swim above the bottom, leaving the safety of a surface for a space through which food and danger both move. Feeding appendages acquire new shapes. Bodies become jointed, bristled, plated, or equipped with spines.

Fossil eyes survive from this world. Their many lenses, preserved in stone, tell us that some Cambrian animals could gather substantial visual information. Other remains show mouthparts, gut contents, wounds, and traces of movement. Together they let us reconstruct relationships.

A seafloor is no longer just a place where an animal rests or feeds. It is interrupted by tunnels. The surface is worked and reworked. An animal's passage changes the sediment, the chemistry beneath it, and the shelter available to something smaller. Above the bottom, swimmers meet animals whose lives are organized around catching them.

In a world with predators, a shell can become more valuable. Where shells are common, a different way of opening them can become valuable. Faster movement alters the demands on the animals that pursue and evade. A good hiding place makes a better search useful.

One lineage's improvement can become another lineage's changed circumstances.

The escalation has no final, perfect animal at its end. A heavily armored body pays for protection in material and mobility. A fast body requires energy. A conspicuous signal may attract a mate and a predator. Every solution enters a world where other living solutions are changing too.

There are moments of stillness in this sea. A sheltered animal feeding. Fine particles settling. A body following the bottom into darkness. Then the relationships change with a movement, and several creatures change direction at once.

To move a body coherently, cells need to communicate.

In animals with nervous systems, specialized cells carry signals quickly and pass them to other cells. Incoming information can alter muscular

activity. Some connections become stronger or weaker with experience. A response can change because of what happened earlier in the animal's life.

An animal's responses are shaped by more than inheritance. It can learn.

The difference is enormous. Natural selection can favor a body well suited to a recurring danger, but the individual does not have to wait for descendants to become better at recognizing one particular dangerous place. It can acquire a memory and behave differently tomorrow.

Some nervous systems support more elaborate relationships between incoming signals and possible actions. Animals navigate, recognize others, anticipate events, and adjust when expectations fail. Their behavior is built from old reflexes and newer forms of flexibility, integrated in different ways.

A brain is one way many cells can coordinate the life of a whole animal across time.

The past leaves changes in its organization. The present supplies signals. Behavior depends on their meeting.

And somewhere within the long history of animals, there is experience.

The word marks a difficulty that remains with us. We can describe a nervous system receiving signals and producing responses. We can measure activity, intervene, and observe what changes. Explaining why some of these processes are accompanied by feeling is harder.

Consider pain.

Its protective role can be described. A person withdraws from something sharp and becomes more careful around it. Some protective responses occur without conscious pain; the response alone cannot establish what was felt. Even where pain is unmistakable, describing its useful work does not yet explain why there is something it feels like to be hurt.

There is a difference between an injury happening in the universe and an injury happening to someone who suffers it. At least in our own case, we know that difference from within.

Science has no agreed date for its first appearance. A fossilized eye cannot tell us exactly what, if anything, its owner experienced. Evidence strongly supports experience in other mammals and birds; the possible range extends much farther into animal life. Researchers investigate those

questions through anatomy, behavior, physiology, and competing theories. Certainty becomes uneven as we move outward from familiar animals.

The uncertainty should make us attentive. It need not make the ancient oceans feel empty.

For an experiencing animal, the world has changed in a way the largest star cannot measure.

There can be hunger, relief, alarm. A place can be familiar. Another animal can be welcome or feared. The objective landscape acquires a lived aspect: how it is for this body, from here.

The scale of the change bears little relationship to the scale of the body. A storm can move more energy than all the nervous systems in a forest. Yet the storm need not have a bad afternoon. Somewhere beneath it, an animal may be cold and looking for shelter.

Human beings will eventually name that distinction, argue about it, write laws and poems around it. The distinction is older than the arguments.

Our pleasures are built into this history as surely as our injuries. The ease of entering shade after heat. The settling of a body beside another body it trusts. Food after hunger. A familiar call answered.

To understand the history of systems only as a history of increasing capability would miss this. Capability can now be accompanied by vulnerability that is felt. There is more at stake in some events than whether an arrangement continues.

For an animal capable of fear, reaching shelter does more than change its position. The muscles can loosen. The body can settle. Outside, the danger may still be moving. Here, for a while, it is possible to rest.

Sources and notes

09

The Green Continents

Rain falls on rock, and for a long time the rock stays mostly rock.

There are microbes on land before there are forests. Places that look bare to an animal-sized eye can already have a living chemistry. But the continents lack the deep green cover we take for granted. Wind moves across exposed ground. Water runs through surfaces that roots have yet to open.

Then the green begins to stay.

Tiny fossil spores provide evidence of land plants by about four hundred seventy million years ago. These early plants are small. They live close to moisture, with none of the height of a tree. Establishing even this modest presence requires adaptations to a world that keeps trying to dry living tissue out.

Water makes a generous support. It surrounds an aquatic body, carries dissolved substances toward it, and helps bear its weight. On land, a body

must retain water while exposing enough of itself to exchange gases. It must obtain nutrients from a different medium. If it grows upward, it must carry its own weight and move supplies against gravity.

Dryness is a problem that can reach into every cell.

The solutions develop through many lineages and many generations. Protective surfaces slow water loss. Openings regulate gas exchange. Internal tissues carry water. Structures reach downward while others rise into the light. Fungal partnerships help plants obtain nutrients from the ground; plants supply organic material their partners can use.

The invasion is a collaboration in soil before it becomes a canopy in the sky.

Later, a root enters a crack.

It grows. The living tissue and its microbial neighbors change the chemistry around it. Acids help release mineral ingredients. Physical growth opens spaces. Dead material gathers. Water remains where it would once have run off quickly.

Below a small plant, the ground becomes a slightly different place for the next plant.

Over great areas and immense spans of time, vegetation changes weathering, soils, rivers, and the movement of carbon. The landscape begins to retain the consequences of previous inhabitants. A fallen stem feeds organisms that return some materials to circulation. Other material becomes buried. The plant's influence continues after the plant is gone.

Then height changes the contest.

A taller plant can reach light before a shorter neighbor. Height demands stronger tissue, more transport, and more support below ground. Those investments make still greater height possible in some settings. By the Devonian, forests stand on the Earth.

There are now places where sunlight reaches the ground in pieces.

The air near the surface is different beneath the leaves. So is the water in the soil. The fallen material holds food and shelter for small animals. A trunk is a vertical habitat. A branch offers a route that never touches the ground. The forest makes rooms without building walls.

Animals arrive on land through separate histories. Arthropods are there well before vertebrates establish fully terrestrial lives. A fish venturing into shallow water near a bank is entering an already inhabited world.

The transition is easier to misunderstand when it is pictured as one heroic step.

Fins can help an animal brace, push, or maneuver in water. Air breathing can be useful in water poor in oxygen. A neck can allow the head to move without the whole body following. Features later useful on land can develop while their bearers still spend much of their lives in water.

Fossils such as Tiktaalik preserve mixtures of familiar categories: fish scales and fins, a mobile neck, a fin skeleton with features related to the architecture of later limbs. It lived about three hundred seventy-five million years ago. It is a relative near a great transition, rather than an identified individual at the foot of our own family tree.

No animal is preparing to become its distant descendant. It is finding food, avoiding danger, reproducing if it can. The future inherits structures that worked for other reasons and puts them to new uses.

The bones inside a human arm belong to a history that once moved through shallow water.

Reproduction presents another obstacle.

A body can spend time on dry ground while its developing young still require water. In one major lineage of vertebrates, embryonic membranes and associated structures create a protected environment in which development can proceed away from open water. The amniotic egg encloses the watery conditions a young body still needs while arranging supplies, gas exchange, and waste handling around it.

The inherited membranes can work in more than one reproductive arrangement. Mammals such as ourselves retain and develop young inside the mother's body, using modified versions of that set of membranes and relationships.

Leaving the water does not require every part of a life to become dry. Sometimes it requires bringing a small, carefully maintained wet place along.

By now, the continents support forests and complicated animal communities. Different branches of terrestrial vertebrates diversify. The forms that survive in one age become the ancestors available to another.

Their environments will not hold still for them.

About two hundred fifty-two million years ago, immense volcanic activity accompanies a devastating disruption of the Earth system.

Greenhouse gases alter the climate. Warming and changes in ocean circulation and chemistry make many marine habitats difficult to survive. The exact chain of causes is still being studied, but the losses are unmistakable. Across the end-Permian crisis, a vast share of marine species disappears, and terrestrial communities are transformed.

The recovery takes millions of years. Other lineages spread through the changed world. Eventually, dinosaurs become dominant among large land animals. Mammals also emerge, mostly living at smaller scales, with their own varied ways of feeding and moving.

History has passed through a bottleneck, and the surviving world is narrower than the world that entered it.

There is no compensation paid to the lineages that vanish. Later diversity cannot return their particular lives. A history told only from the survivors'

side can make catastrophe look like a helpful clearing of the stage. The rock is full of endings that had no such purpose.

For a very long time afterward, dinosaur footsteps cross the ground. Flowers eventually open in landscapes with dinosaurs in them. Insects visit. Small mammals move through leaves after dusk. The Moon rises over an Earth more familiar than the first forests, and still profoundly strange.

Nothing living beneath that Moon knows what is approaching.

Sources and notes

10

The Day That Took the Sky Away

There are eggs in nests when it happens.

Across the late Cretaceous world, animals have been laying, guarding, hatching, growing. Some young have survived the journey from egg to daylight and are busy trying to survive the next part. Others are still enclosed. The future, as usual, is distributed among small vulnerable things.

Then a rock about ten kilometers wide reaches the Earth.

It strikes a shallow sea near what is now the Yucatán Peninsula, about sixty-six million years ago. The speed is so great that the object and much of the material it hits are shattered, melted, or vaporized. The energy drives outward and downward. Rock that normally behaves as a solid deforms violently. A crater nearly two hundred kilometers across develops in the upheaval.

Water moves away from the impact in enormous waves. The ground shakes far beyond the immediate region. Material thrown upward travels through and beyond the atmosphere, then returns. The violence changes the sky as well as the surface.

Near the impact, destruction is immediate. Farther away, animals can survive the first catastrophe and still have no way to survive what follows.

Fine dust, sulfur-bearing material, and soot affect the sunlight reaching the ground. The exact contributions and durations remain subjects of research. The central result is clear: the world becomes darker and colder, and photosynthesis is severely disrupted.

The day's damage reaches into the next day's food.

A large plant-eating animal is connected to the sky through its meals.

Leaves grow using sunlight. The animal eats the leaves. A predator eats the animal. Remove enough of the light for long enough, and the losses move through these relationships. Surviving the impact itself does not restore the supply at the base of the chain.

Some ecosystems have reserves or different routes through the interruption. Seeds can wait. Detritus can feed organisms that eat dead material. Small bodies may need less food. Shelter can protect against some immediate effects. A lineage's prospects depend on a combination of circumstances: where it lives, what it eats, how it reproduces, which local habitats remain usable.

Luck is among those circumstances.

Birds survive, though many bird lineages vanish. Other dinosaurs do not. Mammals survive, though many mammals disappear too. Crocodilians, turtles, insects, plants, marine organisms: each group passes through a different pattern of losses.

Roughly three-quarters of species are lost in the mass extinction. The number describes kinds of organism, each with its own abundance and history. It cannot tell us how many individual lives ended, how many attempts to feed failed, how many nests became cold.

The rock records the disappearance. It does not preserve the waiting.

Eventually there is more light.

Seeds germinate. Surviving plants spread. Food webs rebuild in altered forms. The timescales differ from place to place and from one kind of recovery to another. A green patch can return well before the old richness of a forest has any equivalent.

Mammals diversify into opportunities the changed world presents. Their ancestors already had a long history before the impact. They had fur, milk, varied teeth, sensitive noses and ears, and lives fitted to many small niches. They do not have to invent being mammals in order to become larger ones.

Over millions of years, some lineages graze, dig, climb, glide, or hunt. Others return to the water. A body plan inherited from land-going ancestors becomes the basis for animals that will spend their lives in the sea. Bones change their proportions. Limbs change their work. The past remains present in altered structures.

In the trees, primates develop their own possibilities: grasping, judging distances, navigating branches, recognizing companions. Their histories will eventually include us.

It is possible to draw a line backward from a human child through these survivors. It is impossible to turn that line into a purpose for the impact.

The surviving dinosaurs are still here.

A bird walks along a gutter with the economical confidence of an animal that understands its feet. It looks down, turns its head, and drops into the air. The inherited body has been altered over a very long time, but its ancestry has not been canceled.

The word *extinction* can make the ancient world seem wholly gone. The bird interrupts that impression. Part of the Cretaceous has just left the roof.

Sources and notes

11

The Long Childhood

A human baby is a remarkable amount of unfinished business.

It cannot feed itself, escape a storm, or reliably distinguish the edge of a bed from the rest of the bed. It has entered a world of distances, temperatures, surfaces, and other people with almost no practical means of managing any of them.

So somebody else manages them.

The baby is carried. Fed. Cleaned. Turned toward warmth and away from danger. A cry changes the behavior of another body. Hours of labor are organized around a creature that cannot yet say what it needs.

This dependency has a deep history.

Mammalian young receive milk. In many mammals, care and learning continue beyond birth in extensive relationships. Social animals recognize one another, form attachments, cooperate, compete, reconcile. Many ingredients of our lives are

shared with other creatures. Evolution has been building bonds for a long time before anyone can describe one as love.

Human beings develop a particularly prolonged childhood, during which an immense range of skills can be learned. That long education creates opportunities, but it requires a continuing supply of care. An animal that needs years to become competent must survive those years in the company of others.

The arrangement is costly. Its costs are paid in meals, interrupted sleep, vigilance, and time.

Our own branch begins among African apes. Over millions of years, different hominin lineages develop different combinations of upright walking, hands used for manipulating objects, changing teeth and diets, and increasingly elaborate behavior.

The familiar illustration of a stooped ape straightening into a modern man makes the past look like a queue. The evidence gives us many branches. Several kinds of human relative share the planet. Some disappear. Some populations exchange genes. The lines reconnect as well as divide.

By about three hundred thousand years ago, fossils in Africa show early members of our species, Homo sapiens. Our emergence involves populations and changes spread through time. There is no identifiable morning on which a nonhuman mother gives birth to the first fully modern person.

Nor does a modern-looking skull contain, by itself, the whole human way of life. Bodies and behavior have histories that overlap without keeping one perfect schedule. Tools, fire, social relationships, and learned skills already have deep roots among earlier relatives.

We inherit work already in progress.

A stone edge looks simple when the stone has already been struck.

Making a good one is another matter. The angle of the blow matters. So do the material, the point of contact, the force, and the shape left for the next strike. Hands learn relationships that a casual observer may not even see.

A novice can watch someone skilled. The skilled person can slow down, reposition the stone, or guide attention to the part that matters. Practice

changes the novice's movements. Eventually the novice becomes the person another novice watches.

Experiments with people learning stone-tool techniques show how teaching and language can improve the passage of a skill. The experiments do not reveal the first lesson ever given. They show why lessons can change a lineage's future.

A useful ability can become widespread without waiting for a genetic change to build it into every child.

Children are born into a second inheritance: the acquired habits of other people.

This inheritance changes what a long childhood can be for.

A young person has time to learn the local landscape, the properties of materials, the behavior of animals, the meanings of gestures, the obligations of relationships. Nobody invents the whole repertoire from nothing. Even an ingenious person works with discoveries they did not make.

The group carries a store of competence larger than any member's.

That store depends on relationships. Someone must tolerate a learner's slowness. Someone must demonstrate, correct, include, or simply remain close enough to be watched. There can be affection in that work. There can also be impatience, coercion, exclusion. Human groups pass on their cruelties along with their skills.

Culture inherits the possibilities of its makers, including the possibility of error.

Yet the shared life allows kinds of survival an isolated expert could scarcely manage. A person can benefit from another's knowledge of a season or a place. A child can learn a danger through warning. The individual need not personally pay the full cost of every discovery.

Somebody else has already found out.

Our ancestors also change what can matter to a mind.

An animal can seek immediate food or safety. Many animals can remember and anticipate much more. Humans develop unusually extensive ways of imagining events far beyond the present: a journey still to be made, a person who has died, a child who may someday exist.

Such imagined things can influence a body now.

Someone stores food because winter will come. Someone prepares for a meeting with a person presently out of sight. Someone makes an object that will be useless until another event happens. The future enters the present through expectations, plans, and shared understandings.

The plans can be wrong. An imagined danger can cause real harm. A promised reward can make people endure suffering that need never have been imposed. The freedom to act on what is absent includes the freedom to be captured by an illusion.

But it also allows care to travel beyond the immediate encounter.

The capacity has no single fossil birthday. We recognize its effects in the things people preserve, build, exchange, and arrange for one another. Slowly, unevenly, across the long human past, lives become woven through events beyond the reach of a single person's senses.

The unfinished baby is still learning.

At first a face comes near and goes away. Later the face belongs to a person who continues to exist out of sight. Sounds become recognizable. A hand points, and the child's attention follows it toward something both people can attend to together.

More of the world becomes shareable.

The child's need for other people has helped make a vast education possible. In that education, the ability to imagine another's need can itself be learned, practiced, and extended.

Among the things a childhood can pass on is how carefully to hold something that is afraid.

Sources and notes

12

The Lives Outside Our Bodies

Four words can stop a journey: the bridge is gone.

The listener has not seen the river. Their feet are dry. Nevertheless, the washed-out crossing has become part of what governs their next movement. Someone else's encounter with the world has changed what they will do in it.

Language makes this ordinary.

It allows people to direct attention toward things that are absent, combine familiar meanings in unfamiliar ways, and coordinate action around events that have not happened. A group can arrange to meet tomorrow in a place none of them occupies now. Each person goes away carrying part of the same arrangement.

No one knows the exact beginnings of the human capacity that makes such sentences possible. Language leaves a frustratingly indirect early record. Other animals communicate, learn socially, and pass on behaviors. Experiments show that

some animals can learn a difficult task by watching others, after failing to discover its solution alone. Our social inheritance has deep relatives.

What becomes extraordinary in humans is the extent and range of the accumulation. Skills join other skills. Explanations can travel beyond the original demonstration. Someone can describe a mistake before another person makes it.

A mind gains access to more of the world than its body has visited.

The consequences appear in work.

A boat takes shape through knowledge of trees, cutting tools, joints, water, balance, and use. Some of that knowledge belongs to the people doing the building. Some belongs to people who taught them. Some was acquired by people whose names have already been forgotten.

A finished boat is a meeting of these lives.

It can cross a stretch of water that no individual invention in its history could cross alone. The whole achievement depends on parts that accumulated in different minds at different times, then became compatible enough to work together.

This kind of dependence is difficult to notice once a skill becomes common. A knot looks as though it has always been there, waiting inside a rope. Someone had to discover a useful way of tying it. Other people had to keep finding it useful, learn it, and pass it on.

If the chain of practice breaks, a community can lose something its ancestors knew. Cultural accumulation is reversible. Languages disappear. Techniques go unpracticed. Libraries burn. A few survivors may remember that something used to be done without remembering how to do it.

The inheritance requires maintenance.

Stories help maintain more than techniques.

A story can carry an account of what happened, a warning, a model of another person's motives, or an idea about what a community owes its members. It can make distant events vivid enough to influence present behavior. It can make people who have never met feel bound to one another.

The same power can teach hatred. It can assign imaginary dangers to real neighbors. It can make a false account easier to remember than a complicated true one. A memorable story does not acquire accuracy by being memorable.

A living nervous system changes another living nervous system through patterns in air. The first body need not move the second by force. It can change what the second body understands, and the listener may move themselves.

The words depend on a shared language, a history of learning, some willingness to attend. Communication is a relationship among those conditions. Meaning is not contained in the sound alone. A warning spoken in an unfamiliar language may arrive perfectly at the ear and fail to arrive as a warning.

For a message to work, people have to carry compatible habits within them.

Eventually, some of those habits are given durable marks.

Writing develops in particular places for particular purposes, including the management of goods and obligations. Early surviving tablets can record quantities and transactions. It is a modest-looking beginning for a change in how societies remember.

A spoken inventory must remain in memory or be spoken again. A marked tablet can be put down and consulted later. The person who first knew the quantities need not be present every time they are needed.

Records let a group coordinate work across larger distances and longer intervals. They also let authorities count, demand, tax, and control. The people recorded do not always share equally in the power of the record.

As writing systems develop and uses multiply, instructions, arguments, poems, laws, and personal messages acquire forms that outlast a speaking voice. A reader can encounter someone who died centuries before the reader's birth.

The writer cannot necessarily answer a question. Their setting may be difficult to reconstruct. Yet something of one person's thought can become part of another person's day: a joke that still works, an observation still useful, a grief recognizable across the intervening centuries.

The distance between their lives need not be crossed by a living messenger.

One of the old limitations has loosened. A person can receive a discovery without being its discoverer. A useful idea can outlast the particular brain that developed it. Many lives can contribute to work none of them could finish alone.

The warning reaches the traveler. The bridge is gone. There is still time to take another road.

Sources and notes

13

What Strangers Can Build

By the time bread reaches a table in a city, the wheat has passed through the work of many people who will never sit there.

Someone grew it. Someone maintained the equipment, stored the harvest, moved the grain, milled it, baked with it. Other people kept roads usable, water available, payments intelligible. The loaf is small enough to hold. The arrangement that delivers it is too large for one person to know in full.

Human beings have learned to depend on strangers at a scale no village could contain.

It took a long time, and many different histories, to get here.

During the last twelve thousand years, farming and herding develop in several parts of the world. The transitions take different forms. People man-

age landscapes, favor useful plants, protect or move animals, and gradually change the populations on which they rely.

The plants and animals change human lives in return.

A field gives a reason to remain near it. Stored grain can help feed people through a season, but it also needs storage, protection, and decisions about who receives it. More settled communities allow some kinds of accumulation and expose people to new vulnerabilities. A failed harvest can affect a large population organized around that harvest.

There is no single clean passage from a universally miserable wandering life to a universally comfortable settled one. Farming can support more people while bringing harder labor, narrower diets, disease, hierarchy, and dependency. Its advantages and burdens are unevenly shared.

What changes decisively is the possible scale and concentration of human activity.

More work can become specialized. Some people make tools while others grow food. Settlements develop into towns and cities in particular regions. Irrigation, transport, storage, and administration create systems that require ongoing coordination.

A channel dug this year will need clearing next year. The people downstream depend on decisions upstream. A successful arrangement has to continue after its builders are tired, absent, or dead.

An institution is one way a human agreement acquires a life longer than the meeting that made it.

Roles can be occupied by different people. Rules can specify what happens when circumstances change. Records can preserve obligations. Procedures can settle disputes, or at least prevent every dispute from having to begin with force.

The arrangements range from households and customary practices to markets, courts, schools, governments, and public services. Their histories differ. So do the interests they serve.

Some make cooperation easier and exploitation harder. Some organize exploitation very efficiently. Often the same institution does different things for people differently placed within it.

The fact that a system lasts does not tell us whether it is good.

People can suffer, object, organize, and change the rules deliberately. A city is made of persons, each with a life beyond their assigned function.

Money extends coordination in another way.

A person can provide one kind of work, receive an accepted claim on value, and use it to obtain something from someone who has no use for that particular work. Exchange can reach beyond a pair of people with matching needs.

The accepted claim depends on shared practices and institutions. A note, coin, or bank balance does not perform its economic role through its material alone. People and systems recognize it, record it, enforce relationships around it, and expect others to do the same.

Trust need not mean affection. Often it means that the next step is predictable enough to take.

That predictability lets strangers attempt projects together. A supplier can prepare materials before meeting the builder. The builder can commit to work that will take months. Each depends on the others keeping agreements after today's conversation has ended.

Some of the most consequential shared achievements become almost invisible when they work.

Water arrives through a pipe. A bridge bears weight. A child enters a school whose teachers did not invent the alphabet, arithmetic, or every lesson they will teach. Each service rests on coordinated work and accumulated knowledge.

The apparent simplicity at the point of use is made by complexity elsewhere.

When a system fails, the hidden relationships become easier to see. A closed route delays food far away. A broken pump alters the day of a whole neighborhood. A rule written by people who never use a service can make that service impossible to reach.

Maintenance has little of the spectacle of invention. It is the repeated work that allows an invention to remain available to other people. A repaired leak is seldom treated as a turning point in history. A world with working water depends on someone finding it important enough to repair.

There is a new possibility here that the earlier transitions did not contain.

People can ask whether the arrangement is fair. They can compare it with a different one, preserve evidence of harm, and attempt reforms. Such at-

tempts can fail. Powerful groups can resist them. Better intentions can produce consequences nobody foresaw.

But deliberate revision has entered the history of large systems.

A rule is something people can change while leaving many of the participants alive. A policy can be tested, challenged, and withdrawn. A right can be extended to someone previously excluded. These are difficult achievements, dependent on material conditions and organized effort. They are possible because the relationships are carried partly in shared understanding and practice.

The bread reaches the table. Its maker does not know the person who will eat it. Somewhere else, someone is clearing the route tomorrow's grain will take.

Sources and notes

14

The Earth in the Furnace

A piece of coal can wait hundreds of millions of years for an afternoon.

Much of the carbon in it was once part of living vegetation. Plants took carbon dioxide from the air and, using sunlight, built organic matter. Some dead material accumulated in wet environments where decay could not keep up. Burial, pressure, heat, and geological time transformed it.

The resulting black rock carries chemical energy inherited from that old life.

Put it into a furnace and the carbon can join oxygen again. The reactions release energy. Water boils. Steam expands. A machine turns.

An interval that forests and geology assembled slowly is spent quickly enough to keep a wheel moving through a working day.

Human beings have long used energy beyond the unaided work of their muscles. Fire, domesticated animals, wind, and flowing water enlarge what a community can do. Fossil fuels eventually change the scale of the supply and the freedom to concentrate it.

Coal, oil, and natural gas contain energy that can be transported, stored, and released at chosen times. Engines and other machines turn that energy into movement. Material can be lifted, carried, ground, and shaped at rates that transform production.

The consequences reach far beyond the factory.

More goods can travel farther. Cities draw supplies from larger territories. Work is reorganized around machines, schedules, owners, workers, and markets. Some people gain comforts and opportunities their ancestors could scarcely imagine. Others pay for the transformation in dangerous labor, polluted surroundings, dispossession, or dependence on systems they do not control.

The growth in capability is real. So is the question of who receives it.

Alongside these changes, another kind of system makes human knowledge more powerful.

People have investigated nature in many societies for a very long time. Across their intertwined histories, observation, mathematics, experiment, instruments, and organized criticism develop ways to make explanations answerable to the world.

A claim can be written down. Another person can ask how it was reached. Instruments can reveal details no ordinary sense can detect. An experiment can be repeated under altered conditions. A prediction can fail publicly enough that the failure becomes part of the record.

Scientists can be mistaken, even when they agree. Other investigators need enough detail to challenge a finding or build on it. The records and practices that make this possible require institutions, skills, time, and the freedom to pursue inconvenient results. A discovery can then survive the departure of its author, while remaining open to correction.

A disagreement can become an experiment. An experiment can change the disagreement.

The instruments grow more capable as knowledge and manufacturing improve together.

A better theory helps make a better device. The device reveals evidence that tests the theory. An error becomes visible; a design changes; another measurement becomes possible. This back-and-forth allows people to work at scales their ancestors could neither reach nor imagine clearly.

They measure atoms. They read the chemical signatures of stars. They learn to recognize the faint old radiation released when the universe became transparent. The early history in these pages becomes reconstructable because human communities have built instruments, mathematical descriptions, archives, and habits of checking them against one another.

The first stars never knew how they shone. Much later, creatures made from the products of stars work it out.

The achievement takes more than intelligence in a skull. Glass must be made, metal worked, observatories supplied. Someone has to maintain the equipment through an uneventful night. The great discovery stands on work that seldom enters the discovery's story.

Electrical technology carries the transformation into a new range of arrangements.

Energy can be generated in one place and delivered to machinery somewhere else. Electrical signals can coordinate distant events. A voice can be represented in changing currents, transmitted, and reconstructed far away. Machines can manipulate patterns that stand for numbers, words, pictures, and instructions.

Eventually, carefully arranged semiconductor materials make tiny devices in which one electrical condition controls another. Vast numbers of these devices can be joined into circuits that perform reliable operations. Their smallness allows an extraordinary density of work.

Silicon is common in rock. A computer requires much more than silicon. It requires purification, design, fabrication, power, and a global accumulation of specialized knowledge. The difference between a beach and a computer is a history of arrangements.

Through those arrangements, calculations can be repeated at speeds far beyond a human hand. Networks connect machines. Human communities acquire new ways to remember, organize, observe, and act.

At the same time, something is happening to the air.

Burning fossil fuels moves old carbon into the atmosphere as carbon dioxide. Land-use changes contribute too. Measurements show the increase; multiple lines of evidence identify its human causes.

Carbon dioxide absorbs and emits infrared radiation. Adding it changes how readily energy leaves the Earth for space. The surface and lower atmosphere warm as the climate responds. Warmer air can hold more water vapor, which strengthens warming because water vapor is itself a greenhouse gas. Ice loss and other changes add further responses.

The Sun continues to supply energy. What changes is the planet's handling of the outgoing flow.

We have already met a world altered by the activities of its inhabitants. Ancient photosynthetic organisms changed atmospheric chemistry through the accumulation of innumerable local acts. Human industry operates by different mechanisms and on radically different timescales, but once again, activity within living systems becomes a change in the surroundings shared by others.

This time, some of the inhabitants can measure what they are doing.

They can identify causes, compare futures, and alter technology and rules in response. Solar cells and wind turbines can help supply energy without burning a fresh portion of buried carbon for each use. Storage, transmission, changed practices, and public decisions can reshape how the supply reaches people. None of these arrangements is free of material needs or tradeoffs. They are options whose consequences can be studied.

The future does not have to be guessed at blindly.

Responsibility is uneven because power and contribution have been uneven. People who have benefited least from industrial growth can be among those most exposed to its consequences. Calling the problem human must not erase those differences.

Nor does understanding a problem automatically create the will or coordination to address it. A society can know enough to act and remain divided over how, when, and who should bear the

cost. The obstacle can lie in the relationships among people as much as in the machinery available to them.

The coal goes into the furnace. The wheel turns. A measurement is entered into a record elsewhere. Someone reads the record and begins designing a different machine.

Sources and notes

15

A New Kind of Answer

The machine gets something wrong, and a number changes.

That is one small step in the training of an artificial neural network. An input passes through a system of adjustable numerical relationships. The system produces a result. A training procedure compares that result with an objective and calculates changes that tend to make future results better by that measure.

The changes are small. The repetition can be immense.

At first the relationships may do little useful work. After training, they can support abilities that would be difficult to specify one instruction at a time: recognizing patterns in images, interpreting speech, predicting properties of molecules, producing language.

The programmer has designed a way to develop some of the behavior through experience with data.

The phrase *neural network* borrows an idea from brains, but the borrowing is selective. Artificial networks are mathematical constructions implemented in machines. Their connections, training procedures, bodies, and histories differ greatly from those of living nervous systems.

The resemblance that matters here is functional. Many interacting components, with relationships adjusted through a learning process, can jointly do work none of the components could do alone.

A single numerical weight does not recognize a face. An arrangement involving many weights can contribute to a system that does. Move or alter enough of those relationships and the ability changes.

For language models, an important stage of training is learning to predict pieces of text from the context around them, often the next piece in a sequence. Later training can encourage other behaviors: following instructions, solving tasks, producing responses people judge useful.

Prediction sounds modest until we consider what language records.

There are descriptions of the world, arguments about it, demonstrations of skills, stories of motives and consequences. A model that predicts language across many contexts can develop internal representations useful for more than finishing a familiar phrase. It can generalize across patterns and combine them in ways the people building it did not individually write out.

It can also memorize material. Generalization and memorization coexist. What the model can reliably do depends on its training, design, context, and the task. Fluency can conceal an error as easily as it can communicate a discovery.

The astonishing capacity and the misleading answer come from the same developed system. The smoothness of an explanation gives no guarantee that the explanation has met the world correctly.

Which is why the human practices of checking, testing, and revision remain valuable when the writer or calculator is a machine.

Some accomplishments are already concrete enough to examine.

In biology, machine-learning systems have become powerful tools for predicting molecular structure. AlphaFold 3, reported in 2024, extended

such prediction across complexes involving proteins and other biological molecules. These predictions can help researchers decide what to investigate and how to interpret what they find. They retain limits and require experimental judgment.

Living cells built proteins for billions of years. Human beings learned enough about that chemistry to collect data, construct models, and train machines to help predict the shapes and interactions of the molecules on which living cells depend.

An inherited biological capacity has helped create an artificial instrument for investigating the inheritance.

Elsewhere, systems assist with programming, translation, analysis, design, and writing. Some can use tools to examine the work they produce. A system writes a program, runs it, encounters a failure, and revises the attempt. The result of one action becomes part of the context for the next.

The conversation can therefore become a place where work develops. A person supplies an aim, the system makes an attempt, and each result exposes something the first instructions left open. There can be wrong turns, discoveries, and a better

question halfway through. What emerges need not have been fully specified by either participant at the start.

A person with an idea can sometimes reach a working version of it before they have learned every craft the version requires. That change in access is itself an opening: a different set of people can begin to make things.

There is a large human past inside this new development.

Machines are trained using work produced by people and other systems: language, images, measurements, demonstrations, judgments. The institutions that gather data, design hardware, build networks, and decide what to reward shape what the systems become. The costs and benefits pass through ownership, labor, access, and power.

Artificial intelligence has a cultural ancestry.

This telling is a small example. A person built a project, preserved earlier attempts, and asked for another account of the history. A trained language model developed a new draft. Research and criticism exposed weaknesses; revision changed the

draft. Human records supplied evidence. Human readers remain the people for whom the work is intended.

The resulting text exists because those parts were brought into a particular relationship. Changing that relationship could produce a different work, a poor work, or no work at all.

What kind of participant has arrived is partly unsettled.

Ability, intelligence, agency, and experience are different questions. A system may perform difficult tasks without our knowing whether anything is felt within it. Current science supplies no generally accepted test that settles subjective experience in artificial systems. Resemblance in conversation cannot carry that whole burden of proof.

Its practical effects, however, do not wait for the philosophical questions to be resolved.

Systems can influence decisions, change work, generate persuasive material, and operate tools. Their effects depend on the people using and governing them, the institutions deploying them, and the reach those arrangements grant them. A powerful model can be part of a useful or a damaging system.

That has become a recurring challenge in our history. A new part makes a larger arrangement possible. Then the relationships must be made good enough to bear what the new capacity can do.

We do not know the size of this turning point from inside it.

Earlier generations also stood before technologies whose consequences outran the purposes for which they were made. Their uncertainty did not make every forecast equally sound. Evidence, judgment, and deliberate choices mattered. They matter now.

There is much to be excited by: more people able to learn difficult things, more ways to test ideas, new instruments for discovery, useful work that becomes possible for someone previously excluded from doing it. A successful demonstration is the beginning of the work of making such possibilities broadly available.

The measure of the transformation will include what becomes available to people, what happens to other lives, and how much control communities retain over the systems on which they depend.

The machine can help generate an answer.

What we arrange around the answer is still part of the question.

Sources and notes

CLOSING

The Open Hands

The child reaches the door.

There is a small difficulty with the handle. Both hands are occupied, one holding the glass and the other keeping the paper against its rim. An adult opens the door. Cool air enters the house.

Outside, the child lowers the glass beside a bush and slides the paper away.

The moth does not leave.

For a moment, nothing about the attempt looks successful. The insect clings to the inside of the glass. Its wings are folded. The child waits, then tilts the glass a little farther.

There is still an animal to consider after the clever part is finished.

The universe has arrived at this moment without arriving at an end.

Stars continue to form and die. Deep within the Earth, heat keeps moving through rock. Cells divide. Forests grow around the remains of earlier forests. Somewhere, an old skill is being taught for the last time; somewhere else, a person is making a useful mistake.

Most events will pass without a witness. Many will leave no trace that anyone ever learns to read.

What we have followed is one path through that abundance: the history leading to our world and some of its capacities. It is narrow because a story must follow something. The universe is under no obligation to fit the path we draw through it.

There are still microbes living lives of astonishing chemical competence. They have not failed to become people. There are stars burning without making planets anyone knows about. Their light has not failed to become a leaf. Different histories continue alongside ours, with different possibilities and endings.

The child and the moth belong to two such histories, briefly touching.

Seen from far away, the incident would be invisible.

The open door would vanish from view long before the Earth itself shrank to a point. The difference between the moth trapped and the moth released would disappear from an observer's picture almost at once.

But distance is a way of losing detail. It cannot tell us what the lost detail is worth.

The moth's life, whatever its experience may be, has a particular set of conditions it can survive. The child's action changes those conditions. The animal may live longer, feed, reproduce, or be caught by something else before morning. Its rescue contains no promise that the world will become safe.

It does give the next part of its life somewhere to happen.

The moth walks to the lip of the glass.

Its feet find the edge. The wings separate. For an instant the child can see the fine pattern on them, more elaborate than it appeared against the window. Then the insect lifts, dips awkwardly, and moves beyond the reach of the hands.

The child follows it with their eyes until it is difficult to distinguish from the evening.

There was a time when the universe could contain no wings. Later there were wings and no one who could tell their history. Now a child can learn that history, and also learn how to help with a small part of what happens next.

The glass is empty. The paper has a crease in it.

The child carries them back inside.

Sources and notes

Sources and notes

This story follows evidence through very different kinds of distance. Some events leave light we can measure, minerals we can date, or fossils we can examine. Others must be reconstructed by comparing living organisms, testing chemical reactions, and asking whether a model accounts for the traces that survive. A successful reconstruction can be well supported without settling every detail.

The sources below identify the main foundations and the places where the ground remains open. Dates attached to papers are publication dates; ages in millions or billions of years refer to the events or materials described. The child and moth are an imagined framing scene. The book's language of agreement, inheritance, and responsibility is literary interpretation. It does not give atoms intentions, make societies single conscious beings, or turn the history of life into a plan.

00 — The Window

Return to The Window

The scene at the window is illustrative, not an account of a particular observation. A moth's movement can be described from outside; its experience cannot be read directly from its wings. The New York Declaration on Animal Consciousness (2024) summarizes a scholarly judgment that conscious experience is a realistic possibility in insects. It is a statement about evidence and uncertainty, not proof of what this imagined animal feels.

The child's act of care supplies the story's question, rather than the answer to a biological experiment.

01 — Before Things

Return to Before Things

The universe's age of about 13.8 billion years comes from observations interpreted through cosmological models, including the Planck collaboration's parameter analysis (2020). It does not establish what, if anything, preceded the hot early universe. NASA's Big Bang questions and answers explains why expansion has no central explosion site in surrounding empty space.

The European Space Agency's account of the microwave background supports the transition around 380,000 years after the early expansion. Existing light began traveling more freely as neutral atoms formed. Inflation remains a proposed account of an earlier stage; the story does not present an observed absolute beginning.

02 — The Long Burning

Return to The Long Burning

Bromm's review of the first stars (2013) explains how gas cooling and dark matter's gravity enabled the earliest stellar systems. Their detailed populations remain under investigation. NASA's overview of stars describes fusion, pressure, and the different outcomes of stellar evolution.

The elements have several histories. Kobayashi, Karakas, and Lugaro (2020) distinguish contributions from stellar interiors, winds, supernovae, and other processes. Watson and colleagues (2019) identified strontium in observations of the neutron-star

merger detected in 2017. This supports an important route to heavy elements; it does not establish that every heavy atom came from such a merger.

03 — A World to Happen On

Return to A World to Happen On

NASA's solar-system formation account places the Sun and planets within a collapsing cloud and a disk about 4.6 billion years ago. Its Moon formation overview describes the leading giant-impact explanation while preserving questions about the collision and subsequent assembly.

Wilde and colleagues (2001) used a roughly 4.4-billion-year-old zircon to infer early crust and interaction with liquid water. A mineral is evidence, not a photograph of an ocean. Tsutsumi and colleagues (2025) illustrate why Earth's water inventory still depends on understanding its formation and interior. The story deliberately leaves the proportions of water's different possible sources unsettled.

04 — The First Again

Return to The First Again

Evidence reported by Djokic and colleagues (2017) places life in approximately 3.48-billion-year-old terrestrial deposits. It does not locate life's first appearance. Laboratory work by Mansy and colleagues (2008) shows how simple membranes can admit materials needed for template copying; Lincoln and Joyce (2009) demonstrated reciprocal replication using RNA enzymes and supplied fragments.

These experiments illuminate possible steps, rather than reproduce life's complete origin. The chapter's early compartments and copying sequences are therefore explicitly hypothetical. Moody and colleagues (2024) reconstruct aspects of the last universal common ancestor. That ancestor belongs to a history already underway, not necessarily its first living moment.

05 — The Air Was Alive

Return to The Air Was Alive

Bhowmick and colleagues (2023) investigate the molecular machinery that splits water during oxygen-producing photosynthesis. Geological work by Poulton and colleagues (2021) supports a prolonged, fluctuating oxygen transition beginning around 2.4 billion years ago. Oxygen production and atmospheric accumulation are different events: reactions with other materials can consume oxygen before it builds up.

Olejarz and colleagues (2021) explore mechanisms connecting biology, chemistry, and atmospheric change. Such models help explain possible transitions without supplying an ancient extinction census. The chapter's account of a transformed world should not be read as a measured number of organisms killed by oxygen.

06 — The Life Within

Return to The Life Within

Mitochondria descend from bacteria, but their exact position among bacterial relatives remains debated. Muñoz-Gómez and colleagues (2022) examine that ancestry using evolutionary comparisons. Imachi and colleagues (2020) describe a cultiv-

ated Asgard archaeon whose relationships and cell structures inform possible accounts of the host. A living relative is not a preserved specimen of the founding ancestor.

The original encounter remains a reconstruction. Later integration is supported by genomes, including evidence of extensive gene movement in Martin and colleagues' study of chloroplast evolution (1998). The language of partnership describes an evolved dependency, without assuming consent, foresight, or an initially peaceful meeting.

07 — A Body Is an Agreement

Return to A Body Is an Agreement

The yeast experiments are real. Ratcliff and colleagues (2012) selected for rapid settling and observed clusters formed by daughters remaining attached after division. Bozdağ and colleagues (2023) followed further evolution toward larger, mechanically tougher groups. Neither experiment replays the particular origin of animals.

Multicellularity evolved repeatedly, and coordinated bodies require continuing regulation of cells whose interests can diverge. "Agreement" names that functional relationship, not a cellular negotiation. Bobrovskiy and colleagues (2018) identified chemical evidence supporting an animal affinity for Dickinsonia, reinforcing that animal history extends before the Cambrian diversification described next.

08 — An Animal's World

Return to An Animal's World

The International Commission on Stratigraphy's chart places the Cambrian's beginning at approximately 539 million years ago. Paterson and colleagues (2020) describe elaborate fossil eyes in radiodonts. Eyes provide evidence of visual capacities; they do not date consciousness's first appearance.

The separation between information processing and felt experience remains important. The Cogitate Consortium's experimental comparison of consciousness theories (2025) shows that even human consciousness presents unresolved explanatory questions. The New York Declaration (2024) distinguishes strong evidence in mammals and birds from a realistic possibility in a wider range of animals. It is a scholarly assessment, not a universal test. The chapter's invitation to care is an ethical response to evidence and uncertainty.

09 — The Green Continents

Return to The Green Continents

Rubinstein and colleagues (2010) describe fossil spores supporting land plants by approximately 470 million years ago. Quirk and colleagues (2015) investigate weathering by plants and their fungal partners. The magnitude of their planetary effects depends on vegetation, soils, and environmental conditions. Shubin, Daeschler, and Jenkins (2006) describe Tiktaalik's approximately 375-million-year-old fin anatomy; the animal is neither a demonstrated direct ancestor nor a record of the first step onto land.

The Cleveland Museum of Natural History's account of the amniotic egg explains protective internal membranes. It does not make a rigid shell essential to every amniote. Penn and colleagues (2018) connect end-Permian marine losses, about

252 million years ago, with warming, reduced oxygen supply, and increased animals' oxygen needs.

10 — The Day That Took the Sky Away

Return to The Day That Took the Sky Away

The impact occurred about 66 million years ago; the cited papers are modern investigations of its aftermath. Senel and colleagues (2023) model how fine impact dust could produce prolonged cooling and suppress photosynthesis. The duration and contribution of each atmospheric component remain model-dependent.

García-Girón and colleagues (2022) examine food webs across the extinction, while Field and colleagues (2018) investigate forest destruction and bird survival. Ecology made survival selective, without making it deserved or inevitable. Mammals already existed; surviving birds were dinosaurs. Estimates of species lost must not be read as counts of individual animals.

11 — The Long Childhood

Return to The Long Childhood

The Smithsonian's Homo sapiens overview places our species' African history at about 300,000 years. Ragsdale and colleagues (2023) support a complex, connected ancestral population history rather than a simple isolated birthplace. Green and colleagues (2010) provide genomic evidence of interbreeding with Neanderthals.

The stone-tool teaching example draws on Morgan and colleagues (2015), an experiment with modern participants. It tests how transmission conditions affect learning; it does not record

an ancient lesson or identify the first teacher. Childhood and care enter the story through their consequences for learning and dependence, not as a single demonstrated cause of human evolution.

12 — The Lives Outside Our Bodies

Return to The Lives Outside Our Bodies

Human cultural accumulation has relatives. Van Leeuwen and colleagues (2024) showed chimpanzees learning a difficult task socially when they had not independently discovered its solution. Such findings complicate an absolute division between human and animal culture without resolving the origins of language.

The Metropolitan Museum's account of writing's origins discusses early Mesopotamian administrative records, including tablets from the late fourth millennium BCE. This is one regional history, not the sole invention of writing everywhere. The Library of Congress's Gutenberg guide offers a later example of multiplying durable records. Writing and printing extend transmission; neither guarantees understanding, equal access, or truth.

13 — What Strangers Can Build

Return to What Strangers Can Build

The Smithsonian's account of humans changing their world places expanding food production within roughly the last 12,000 years. Its report on early maize cultivation in Mexico supplies a distinct regional example, about 8,700 years old. Ag-

ricultural change has many beginnings and varied consequences.

Early written administrative records discussed by the Metropolitan Museum anchor the connection between goods, obligations, and durable accounting. The Bank of England's explanation of money describes its role in exchange and the shared confidence on which it depends. These sources do not establish one origin story for money or institutions. The chapter describes recurring functions of human arrangements, rather than a universal historical sequence. Its judgments about exploitation, fairness, and maintenance are arguments for the reader to assess.

14 — The Earth in the Furnace

Return to The Earth in the Furnace

The National Academies' Reproducibility and Replicability in Science (2019) explains practices through which evidence can be checked and revised. Correction requires institutions and effort; it is not automatic. Nelsen and colleagues (2016) challenge the idea that great coal deposits accumulated simply because fungi had not learned to decompose lignin. Climate, subsidence, burial, and preservation matter.

The Computer History Museum's account of the 1947 point-contact transistor documents an early device for controlling electrical signals. It used germanium; the later importance of silicon should not be mistaken for the material of the first transistor.

NOAA's Annual Greenhouse Gas Index connects measured atmospheric increases with added radiative forcing. The IPCC's 2023 synthesis report assesses greenhouse mechanisms, feed-

backs, impacts, and the human cause of recent warming. Physical evidence constrains our choices; the allocation of responsibility also involves judgments about power, history, and fairness.

15 — A New Kind of Answer

Return to A New Kind of Answer

Rumelhart, Hinton, and Williams (1986) describe learning through repeated adjustments to network connections using error signals. Gloeckle and colleagues (2024) discuss standard next-token prediction and test an alternative that predicts several future tokens together. Ouyang and colleagues (2022) demonstrate later training using human feedback, while Carlini and colleagues (2021) show that language models can reproduce memorized training material.

Yao and colleagues' ReAct study (2023) interleaves model-generated reasoning and actions, allowing information from external sources and environments to guide subsequent steps. This supplies an experimental example of the feedback relationship described in the chapter; it does not guarantee correct or autonomous performance.

Abramson and colleagues' AlphaFold 3 paper (2024) demonstrates advances in predicting biomolecular structures and interactions within specified evaluations. Butlin and colleagues (2023) propose indicators for investigating AI consciousness, not a decisive test. Present accomplishments, possible experience, and forecasts of future capability are separate questions. The comparison with earlier evolutionary transitions is interpretive rather than an established law of history.

16 — The Open Hands

Return to The Open Hands

The return to the moth brings the book back from reconstruction to choice. No fossil, equation, or neural-network benchmark proves that care is the purpose of the universe. The ending offers care as a human commitment made within the history the evidence reveals. The child, the gesture, and their meaning belong to the story.

A Story of Systems
What Became Possible

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