THE STORY OF CARBON

BY

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"Elementary…"
– *Sherlock Holmes*

Condensed from my blog *The Carbon Pilgrim*

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PART ONE

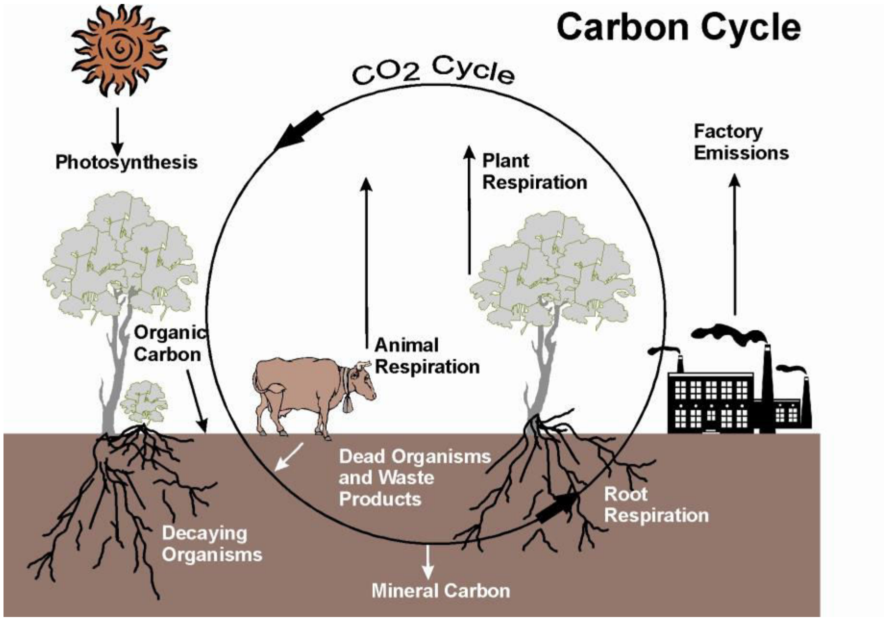
THE ESSENTIAL ELEMENT

The (boring) Carbon Cycle

Carbon is the most important element on Earth and the best way to begin explaining its significance is with the terribly important carbon cycle. The trouble is whenever I see the word ‘cycle’ my eyes start to glaze over. It doesn’t matter if it is the water, mineral, energy, nutrient, or some other cycle critical to our existence, for some reason my attention begins to wander the instant I see the word. I remember attending a conference years ago where a speaker displayed an image of the nitrogen cycle on a farm he was studying. It had something like sixty-four separate arrows flowing in every possible direction, including in circles. I took one look at the image and immediately put my pen down. No amount of note-taking was going to make sense of this cycle when I tried to explain it later.

Maybe it’s something we pick up as children. When my daughter did a homework assignment on the hydrological cycle for a science project both of us struggled to stay focused. It was good stuff – don’t get me wrong – and she enjoyed drawing clouds and rain and squiggly lines flowing upward from the ocean into the sky. When it came time to explain it all, however, the fun disappeared as fast as water on a hot sidewalk. Let’s be honest, ‘evapotranspiration’ is hard to *say* much less describe in simple terms. Making circles in the air with my finger was the best I could do.

The problem is there’s usually no *story* to go with these big ideas. Take this image of the carbon cycle produced by the Quivira Coalition for one of our publications:



As a depiction of the never-ending cycle by which carbon dioxide (CO_2) flows out of the atmosphere into the soil as carbon via photosynthesis and green plants and then back out again via decomposition and respiration, round and round, sustaining nearly *all life* on the planet, the image does a great job. I especially like the way it distinguishes nature from industry. The fossil-fuelled factory sits off to the side, outside the circle, pumping three hundred million year-old carbon, previously buried in the ground as coal, oil or natural gas, directly into the atmosphere as CO_2. No cycle there – just a straight line up.

I like this image of the carbon cycle, but *it's boring*. That's because it doesn't tell a story. What's up with the cow, for instance? What is it doing there? Does it belong to someone? Did a visitor leave a gate open someplace allowing the animal to wander in? And what about that factory? What's it *making*? Electricity? Cement? Artificial fertilizer? Is it Chinese? American? Brazilian? Does its owner hire undocumented workers? Is up to code? Has it been busted for improper disposal of byproducts?

I'm being facetious, sort of. Carbon is essential to life but it's also rather abstract which is one reason why we're having a hard time getting our minds around CO_2 pollution, carbon credits, soil organic matter, carbon sinks, carbon farming, even global warming. Carbon needs a story. Or rather, lots of stories. It isn't enough to wave our hands in the air and say "if we damage the carbon cycle all sorts of bad things will happen!" Instead, I look at this image and think "Will someone get that lost cow back into the pasture with its herd!" That's the rub – how do we get important concepts across without the eyes-glazed-over effect? It ain't easy. But it's important to try because the issues involved are increasingly critical. I'll see what I can do.

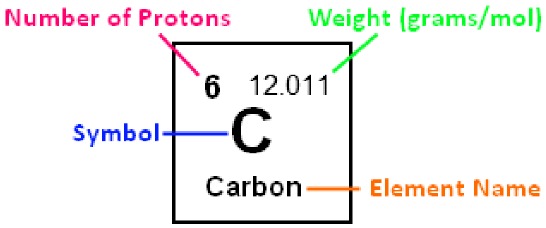
I'll start with a different version of the carbon cycle – on a family farm in Vermont:

Carbon Is Everywhere

Carbon is the graphite in our pencils, the diamond in our rings, the oil in our cars, the sugar in our coffee, the DNA in our cells, the air in our lungs, the food on our plates, the cement in our sidewalks, the steel in our skyscrapers, the charcoal in our grills, the fizz in our sodas, the foam in our fire extinguishers, the ink in our pens, the plastic in our toys, the bugs in our gardens, the wood in our chairs, the leather in our jackets, the electrodes in our batteries, the rubber in our tires, the coal in our power plants, the nano in our nanotechnology and the humus in our soils.

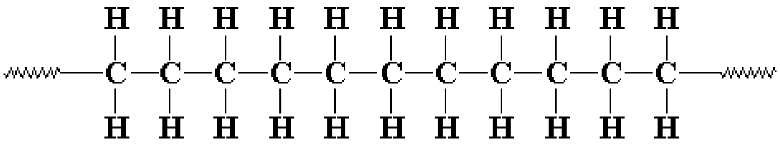
All carbon

Carbon is the fourth most abundant element in the universe, the fifteenth most abundant element on Earth, and the second most abundant in the human body after oxygen. Carbon is present in all known life forms. It can be found dissolved in all water bodies on the planet. It is abundant in the Sun, stars, comets, meteorites, and in the atmospheres of most planets (the atmosphere of Mars is 96% carbon dioxide). Carbon is Number Six on the Periodic Chart of the elements, between Boron and Nitrogen. It exists in many inorganic compounds (gases, rocks, liquids) and all organic ones.



Carbon is star dust. It first formed in the interiors of stars not long after the Big Bang and then scattered into space as dust as a result of supernova explosions. Over time, it coalesced into star systems such as ours, as well as planets, comets, and other heavenly bodies. Eventually, it coalesced into us. We are star dust.

Carbon is promiscuous. It forms more compounds than any other element with almost ten million compounds discovered to date – a tiny fraction of all theoretically possible. Carbon especially likes to bond with other small atoms, including other carbon atoms, and is capable of forming long chains of complex and stable compounds which is why it is found in so many different forms on Earth.



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Carbon is history. In antiquity, it was called “carbo” which is Latin for coal or charcoal. Carbon was well known to the earliest humans as soot and to the earliest civilizations as diamonds. The Romans made charcoal for cooking and the Amazonians made terra preta (biochar) for burying to improve their nutrient-poor soils. No one knew it was all the same element until 1694 when French chemist Antoine Lavoisier pooled his money to buy a diamond which he placed in a closed glass jar. He focused the sun’s rays on the diamond with a magnifying glass and saw the diamond burn and disappear. The jar was filled with carbon dioxide – just like what happened to charcoal in an earlier experiment. He called common element “carbone.” In 1779, scientist Carl Scheele did the same thing with graphite and carbon’s reputation took off.

Carbon is energy. Coal, oil, natural gas (methane), shale gas, tar sands, bitumen, and everything in between are all hydrocarbons, a highly stable and yet easily combustible bond between hydrogen and carbon. Refrigerants, lubricants, solvents, plastics, chemical feedstocks, and other types of petrochemicals are all hydrocarbons. The world made-by-humans would literally grind to a halt without carbon.

Carbon is life. It exists in every organic life form. Life is impossible without it. When combined with water it forms sugars, fats, alcohols, fats, and terpenes. When combined with nitrogen and sulfur it forms amino acids, antibiotics, and alkaloids. With the addition of phosphorus, it forms DNA and RNA – the essential codes of life – as well as ATP, the critical energy-transfer molecule found in all living cells. The carbon atom is the essential building block of life. Every part of your body is made up of chains of carbon atoms, which is why we are known as "carbon-based life forms."

Carbon is a miracle. Chemically, we're just a bunch of inert compounds. What breathes life into us? The answer is the relationship between the molecules of energy and nutrients fueled by carbon and water. Billions of years ago, Earth was just geology and chemistry – no biology. Then something happened to spark life, something mysterious. Between the geochemical origins of Earth and its eventual biological life is something scientists call a 'black box' – a figurative box they cannot peer into. Below the box are chemicals, above it DNA. The link is carbon, scientists agree, but how it happened precisely remains a mystery – one that I will come back to later.

Carbon is hope. Because where there's life, there's hope.

Slow Carbon

The carbon cycle never sleeps.

The carbon in the atmosphere, the oceans, the trees, the soils, us and everything else is constantly in motion, flowing in a giant circle from air to land and back to air again in an unending, closed loop. The Law of the Conservation of Matter says that in a closed system matter can neither be created or destroyed. It can only cycle and recycle. The Earth has been a closed system almost from its origin with only solar energy, an occasional electromagnetic pulse from the sun, and stray bits of asteroids and comets entering from space. What's here now has always been here, including carbon whose total amount is essentially the same as it was when Earth formed 4.5 billion years ago.

The ancient Greek philosophers understood all this intuitively, proclaiming that "nothing comes from nothing." Epicurus wrote "the totality of things was always as it is now, and always will be." Nothing can be created or destroyed. This observation was explained scientifically by none other than Monsieur Lavoisier who discovered that although matter may change its form or shape – a diamond into gas – its mass always remains the same.

So it is with carbon. And what carbon does is cycle, a process essential to life on Earth. It's a carefully regulated process so that the planet can maintain critical balances. Call it the Goldilocks Principle: not too much carbon, not too little, but just the right amount. For instance, without CO_2 and other greenhouse gases Earth would be a frozen ball of rock. With too many greenhouse gases, however, Earth would be like hothouse Venus. *Just right* means balancing between the two extremes, which helps to keep the planet's temperature relatively stable. It's like the thermostat in your house. If it gets too warm, the cycle works to cool things off and vice versa. Of course, the planet's thermostat gets overwhelmed at times, resulting periods of rapid warming or cooling (think Ice Ages).

Fortunately, the miraculous carbon cycles keeps working, scrubbing excess CO_2 out of the atmosphere or adding more if necessary.

Too little carbon

Too much carbon

Just right

Who does all this regulatory work? Two quick answers: green, growing plants and evolution. Photosynthesis is the process by which carbon is transferred from sky to soil. It's what makes the Goldilocks principle tick. Evolution is the process by which life changes over succeeding generations – what lives, what dies, which population expands, which one contracts. It keeps the Goldilocks principle ticking over time – long periods of time. The two work in concert. The quantity of carbon in the environment influences the course of evolution and vice versa. The greenhouse effects of an excessive build up of CO_2 in the atmosphere, for instance, will impact the fate of generations of living things. Carbon and evolution interact and adjust to each other, regulating and responding in a sophisticated dance. Carbon chooses the music, if you will, while evolution dictates the steps in a planet-wide choreography. It is a dance with a profound effect on audience members.

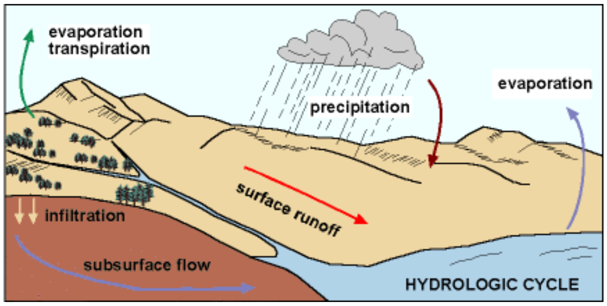
During the Carboniferous Period of Earth's history, which lasted from 350 to 300 million years ago, the music was turned up *very* loud. A potent combination of swampy terrain, warm temperatures, high humidity, and unprecedented levels of oxygen caused an explosion of life across the planet. Insects grew to huge sizes. Modern-looking fish evolved. Birds, reptiles and mammals began to lay eggs on solid ground for the first time in a fateful evolutionary leap. It was the vegetation, however, that really went wild. As the Period's name implies, massive amounts of carbon-bearing trees grew during this time, many of which toppled into swamps when they died becoming entombed in muck. Layer after layer of trees piled up, creating, three hundred million years later, the rich coal seams that we exploit today for our energy (for better or worse).

Then

Now

Carbon is not the only dance on the planet, of course. Our world is full of cycles – water, energy, nutrients, nitrogen, phosphorus, and many more – interacting with each other in complicated ways. Some cycles are short, like a song, while some are long like a symphony or a mass. Carbon has both. Its short, or fast, cycle revolves around green plants and photosynthesis – the process by which carbon is separated from oxygen, stored in roots and soils, and released back into the atmosphere via death and decomposition. Its long, or slow, cycle is geologic – what happens when carbon is released after being trapped or frozen in layers of rock for millions of years. In the case of the slow cycle, the symphony is *really long*. Carbon can take one to two hundred *million* years to rotate fully through rocks, soil, ocean, and atmosphere.

In the slow cycle, carbon in the atmosphere combines with water vapor to form carbonic acid (in a weak solution) that falls to the ground with rain events and begins to dissolve rocks – a process called chemical weathering. This process releases minerals, including potassium, sodium, calcium, and magnesium, all of which are carried by streams and rivers to the ocean. There, it provides the calcium carbonate necessary for shell-making creatures, such as corals and plankton, to grow – a key to life underwater. When these organisms die they fall to the sea floor where they become, over time, carbonate rocks, such as limestone. Then, after more time (a lot more) carbon is returned to the atmosphere via volcanic activity. Ejecta flies upward into the air in the form of ash, lava or other material. Volcanism also releases trapped carbon dioxide – and the cycle starts all over. Round and round, very slowly.



Fast Carbon

It is the fast carbon cycle – photosynthesis – where the real music can be heard.

The process by which atmospheric CO_2 gets converted into soil carbon has been going on for at least a billion years and all it requires is sunlight, green plants, water, nutrients, and soil microbes. It's an equation: healthy soil + healthy carbon cycle = beautiful music. One of the first researchers to recognize the significance of this equation for its climate implications was Dr. Christine Jones, an independent soil scientist in Australia. According to her, there are four basic steps to the CO_2 / soil carbon dance:

- *Photosynthesis*: This is the process by which energy in sunlight is transformed into biochemical energy in the form of a simple sugar called glucose via green plants – which use CO_2 from the air and water from the soil, releasing oxygen as a by-product. The chemical reaction looks like this: $CO_2 + H_2O + energy = CH_2O + O_2$

- *Resynthesis*: Through a complex sequence of chemical reactions, glucose is resynthesized into a wide variety of carbon compounds, including carbohydrates (such as cellulose and starch), proteins, organic acids, waxes, and oils (including hydrocarbons), all of which serve as 'fuel' for life on Earth.

- *Exudation*: Carbon created by photosynthesis can be exuded directly into soil by plant roots to nurture microbes and other organisms. This process is essential to the creation of soil from the lifeless mineral soil produced by the weathering of rocks over time. The amount of increase in organic carbon is governed by the volume of plant roots per unit of soil and their rate of growth. More active green leaves mean more roots, which mean more carbon exuded.

- *Humification*: or the creation of humus – a chemically stable type of organic matter composed of large, complex molecules made up of carbon, nitrogen, minerals, and soil particles. Visually, humus is the dark, rich layer of topsoil that people generally associate with stable wetlands, healthy rangelands, and productive farmland. Once carbon is stored as humus it has a high resistance to decomposition, and therefore can remain intact and stable for hundreds or thousands of years.

Lots of humus

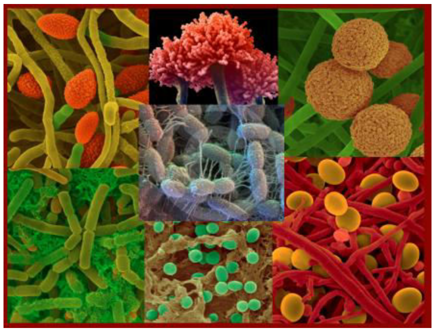
Not so much

A lack of humus often means the carbon exuded from plant roots will simply oxidize and recycle back to the atmosphere as CO_2. Additionally, humus-rich soils can be disturbed by human activity, such as plowing which exposes the stored carbon to air, facilitating its release. In each case, oxygen combines with sugar to release water, carbon dioxide, and energy. The chemical reaction looks like this: $CH_2O + O_2 = CO_2 + H_2O$ + energy.

The key to creating humus is a class of microbes called mycorrhizal fungi, which get their energy in liquid form as soluble carbon directly from actively growing plant roots. In turn, these fungi facilitate the transport of essential nutrients, such as phosphorus, zinc and nitrogen, into plant roots in exchange for carbon. In this way, these mycorrhizal fungi help turn atmospheric carbon into humus, often quite deep in the soil profile. When mycorrhizal fungi are functioning properly, a great deal of the carbon that enters the leaves of plants can be channeled directly into soil as soluble carbon – which is why people get excited about the prospect of storing excess CO_2 in the soil as one remedy for global warming. Not only is it possible on a practical level, all it requires are the processes that create life – and creating life is something that the Earth does very, very well.

Mycorrhizal fungi

Perennial plant



Soil microbes

By the way, this complex interplay of carbon, microbes, nutrients, and water in the soil is nearly identical to what happens in the digestive gut of humans, livestock, and other animals. It is not a coincidence either. What goes on in the soil is the same as what goes on in our gut: creating the optimal conditions for life. The chemical, physical, and biological components of the human ecosystem also require regulation and balancing, often through slow-and-fast cycles of our own. We are star dust, after all, just like every other living organism on the planet. And just like a watershed or a population of animals or the microbial universe in the soil, the way this balance is expressed is by *health.*

And good health is what we all want.

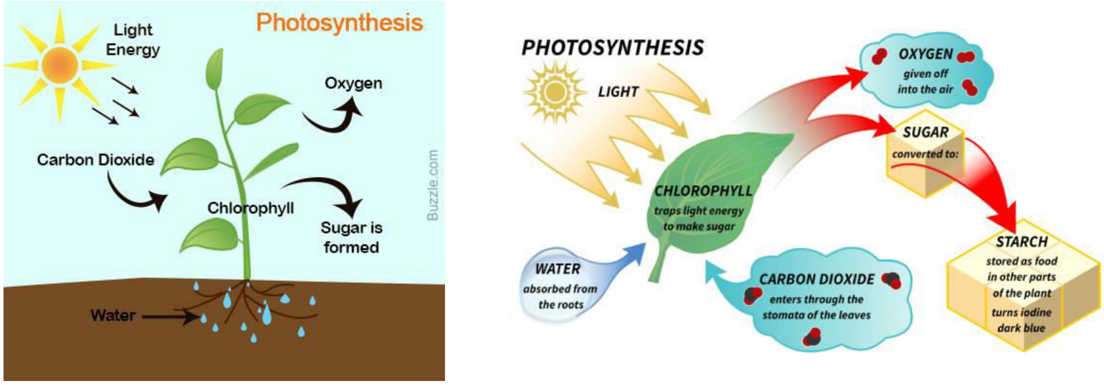
Three Molecules

Think of what happens below the soil surface as a type of biological engine. Plants convert sunlight and carbon dioxide into jet fuel (liquid carbon) which is then sent to the factory underground via an elaborate root system to nourish the microbes at work on the engine. The job of these micro-critters is to break down organic matter into smaller and smaller bits, “dig up” minerals from the soil to supply the engine, and facilitate deliveries of fresh water. To do this they need a steady supply of oxygen, which is provided by tiny air pockets in the soil. They also need a healthy work environment free from toxic chemicals, thuggish gangs of viruses, and cataclysmic events such as plowing. It’s also good to have large friends, such as earthworms, to help with the labor. And like all workers, the critters need to rest, eat a good diet, and pass gas – carbon dioxide in this case, which makes it way up to the surface and out into the atmosphere. If all the parts of the biological engine are healthy and working together efficiently then the bountiful end product is *humus* – good, rich, dark organic soil.

As the engine grows all of its parts grow with it. Plant roots get bigger and extend deeper into the soil sending larger amounts of jet fuel to the micro-workers who grow more numerous, excavate more minerals, store more carbon, and pass more gas. As the humus expands, all this work makes it “fluffier” (more porous with air pockets) which in turn holds more water. This encourages additional biological activity, which creates more humus, round and round. Life begetting more life, turning *dirt* into *soil*.

Dirt is *chemistry*: individual particles, minerals, and other elements, including nitrogen, calcium, phosphorus, and potassium. Soil is *biology*: bacteria, fungi, protozoa, nematodes, earthworms, reproduction, growth, life. Getting plants to grow in dirt is chiefly a matter of getting a chemical formula right and applying it mechanically according to a calculated prescription. Getting plants to grow in soil, by contrast, is a matter of getting the biology right. If the ground is devoid of micro-critters, for instance, you need to add them (via compost, say). Then step back to watch the engine come to life.

The key element in revving up the engine is carbon. To explain, let’s follow three carbon molecules from the air to three separate destinations. Imagine these molecules enjoying a carefree life as a gas, each accompanied by two oxygen molecules, as they joyride side-by-side through the air without a care in the world. Suddenly, all three smack into a green, leafy something and quickly pass from the bright light of the atmosphere into the dark, vascular world of a plant. Now their carefree existence turns into a wild toboggan ride of photosynthesis. The three molecules go through a series of transformative twists, turns, and drops as they travel through the plant, bathed in green, drenched in water, stripped of their oxygen buddies, and eventually picking up new molecular passengers, including hydrogen, nitrogen, and more carbon. At the end of their wild ride, the molecules are no longer part of a gas having become instead part of a sugary carbohydrate called *glucose*, a vital source of energy for the plant. At this point a new ride begins and our three carbon molecules are quickly sent in three separate directions.



Two depictions of photosynthesis at work

The first molecule concludes its journey in a leaf cell, where the glucose is converted by the plant into a kind of biological battery called *starch* which it stores for later use, such as winter when photosynthesis is turned off. Other uses of glucose by the plant include respiration, creating the sweetness in fruit, conversion into cellulose for cell-wall strengthening, forming fatty lipids for storage in seeds, and generating proteins, which are an important source of food for all living things. In this case, our carbon molecule rests quietly in its cell waiting to be summoned when the leaf is suddenly ripped from its host by a hungry herbivore. After a brief but tumultuous ride through grinding teeth, the molecule slides downward into a smelly stomach and eventually passes into the animal's digestive tract, where the starch is processed and the carbon absorbed into a cell of muscle tissue. A month later, the cycle is completed when the animal breaks a leg and dies in the wild. As it decomposes, the carbon molecule is exposed to the air where it picks up two oxygen atoms swinging by and together they rise upward to begin the joyride all over again.

The second carbon molecule shoots underground through the plant's stem and then slows to a crawl as it reaches the tip of a slender root. The plant intends to use the glucose to build new root mass so it can tap additional water and nutrients, but before it can the plant suddenly shudders as half of its leaves are wrenched away by the hungry herbivore. This causes the plant to send an emergency signal to its roots: *retreat!* To help recover its vigor and grow new leaves again, the plant must now use the glucose stored in its root cellar, ordering the supplies upward. It's not a crisis however (unless the hungry herbivore comes back around for a second bite) because by removing last year's dead material along with this year's green growth, the herbivore has freed up the plant to grow unimpeded. One of the plant's first responses is to slough off the tips of its roots to conserve energy. That means our second carbon molecule finds itself detached and isolated from the rest of the plant, lost and lonely in the soil – but not for long.

Soon, the decaying root tips attract the attention of a host of hungry microbes and other critters, including protozoa, nematodes, fungi, earthworms, arthropods, and a huge variety of bacteria (there are more microbes in a teaspoon of soil than humans on the planet). Bacteria go to work first. These are single-celled creatures with one goal in mind: eat! They are particularly ravenous for carbon and after they have digested a bunch of it they become attractive to predatory critters in the neighborhood. Soon, a feeding frenzy begins. Our particular carbon molecule disappears down the throat of a nematode, which is a type of tiny worm. There are approximately one million different species of nematodes on the planet, found in every type of ecosystem, accounting for 80 percent of *all creatures* in existence on Earth. That makes for a lot of eating and pooping going on below ground.

In this case, the nematode eventually excretes our molecule into the soil where it bonds with two sly oxygen molecules hanging out (smoking cigarettes) in the tiny air pockets between soil particles and becomes part of a carbon dioxide molecule once again. Eventually this new CO_2 molecule makes its way up to the soil surface and back into the atmosphere – a process scientists call *soil respiration* – to join zillions of their buddies for another wild ride. Round and round.

Meanwhile, our third carbon molecule has followed a similar path to the plant's roots, only to end up inside a fungus instead of a nematode – and not just any fungus, but one of the heroic mycorrhizal varieties. These are long, skinny filaments that live on the surface of plant roots with which they share a symbiotic relationship, trading essential nutrients and minerals back and forth (*mycorrhiza* is Greek for *fungus + root,* or "I'll scratch your carbon if you'll scratch mine"). The fungus-root mutualism reduces a plant's susceptibility to disease while and increasing its tolerance to adverse conditions, including prolonged drought spells or salty soils. Fungi in general are best known to humans as the source of mushrooms, yeasts, and the molds that make cheeses tasty, ruin houses in humid climates, and produce antibiotics. Like plants and animals, fungi form their own taxonomic kingdom. In fact, there are an estimated two to five million individual species of fungi on the planet, of which less than 5% have been formally classified by taxonomists. In the soil, fungi can be "good guys" or "bad guys" depending on your perspective (the "bad guys" cause a variety of diseases).

Our third carbon molecule ends up in a good guy called an arbuscular mycorrhizal fungus. After absorbing the bit of glucose containing our molecule from the plant root, the skinny arbuscular fungus next pushes the carbon into one of its *hyphae* – hair-like projections that extend as much as two inches into the soil in a never-ending search for nutrients. Then, in a process that is not completely understood by scientists the carbon molecule is extruded into the soil from the hyphae in a sticky protein called *glomalin* – one of nature's superglues.

Gomalin (the circles) on a root fiber

You can *feel* glomalin. It's what gives soil its tilth – the rich, smooth texture that tells experienced farmers and gardeners that they holding great soil in their hands. To create tilth, the soil engine needs both biology and chemistry working together and glomalin is the glue that binds them.

It's an extraordinary process, one which creates a world of possibilities!

PART TWO

OUR CARBONIFEROUS WORLD

Healing the Carbon Cycle with Cattle

In 2004, cattle ranchers Tom and Mimi Sidwell bought the 7,000-acre JX Ranch, south of Tucumcari, New Mexico, and set about doing what they know best: earning a profit by restoring the land to health and stewarding it sustainably.

As with many ranches in the arid Southwest, the JX had been hard used over the decades. Poor land and water management had caused the grass cover to diminish in quantity and quality, exposing soil to the erosive effects of wind, rain, and sunlight which also diminished the organic content of the soil significantly, especially its carbon. Eroded gullies had formed across the ranch, small at first but growing larger with each thundershower, cutting down through the soft soil, biting into the land deeper, eating away at its vitality. Water tables fell correspondingly, starving plants and animals alike of precious nutrients, forage, and energy.

Profits fell too for the ranch's previous owners. Many had followed a typical business plan: stretch the land's ecological capacity to the breaking point, add more cattle when the economic times turned tough, and pray for rain when dry times arrived, as they always did. The result was the same – a downward spiral as the ranch crossed ecological and economic thresholds. In the case of the JX, the water, nutrient, mineral, and energy cycles unraveled across the ranch causing the land to disassemble and eventually fall apart.

Enter the Sidwells. With thirty years of experience in healing land, they saw the deteriorated condition of the JX not as a liability but as an opportunity. They began by dividing the entire ranch into sixteen pastures, up from the original five, using solar-powered electric fencing. After installing a water system, Tom Sidwell picked cattle that could do well in dry country, grouped them into one herd and set about carefully rotating them through the pastures, never grazing a single pasture for more than seven-to-ten days in order to give the land plenty of recovery time. Next, he began clearing out the juniper and mesquite on the ranch with a bulldozer, which allowed native grasses to come back.

As grass returned – a result of the animals' hooves breaking up the capped topsoil allowing seed-to-soil contact – Sidwell lengthened the period of rest between pulses of cattle grazing in each pasture from sixty to 105 days across the whole ranch. More rest meant more grass, which meant Sidwell could graze more cattle to stimulate more grass production. In fact, Sidwell increased the overall livestock capacity of the JX by 25% in only six years, significantly improving the ranch's bottom line.

Tom Sidwell and restored grasslands on the JX Ranch

Another significant positive impact was on the carbon cycle. By growing grass on previously bare soil, by extending plant roots deeper, and by increasing plant size and vitality – all as a result of good stewardship – the Sidwells are storing more carbon in the ranch's soil than the previous owners had, thanks to photosynthesis. It's an ancient equation: more plants mean more green leaves, which mean more roots, which mean more carbon exuded, which means more CO_2 can be stored in the soil. In other words, if bare, degraded, or unstable land can be restored to a healthy condition with properly functioning carbon and other cycles, covered in green plants with deep roots, then the quantity of CO_2 that can be stored in the soil is potentially high.

There's another benefit to carbon-rich soil: it improves water infiltration and storage due to its sponge-like quality. Recent research indicates that one part carbon-rich soil can retain as much as four parts water. This has important consequences for the recharge of aquifers and base flows to rivers and streams which are the life bloods of towns and cities. It's also important to people who make their living off the land, as Tom and Mimi Sidwell can tell you. In 2010, they were pleased to discover that a spring near their house had come back to life. For years, it had flowed at a miserly rate of ¼ gallon-per-minute, but after clearing out the juniper trees above the spring and managing the cattle for increased grass cover, the well began to pump 1.5 gallons a minute 24 hours a day!

The water cycle has improved all over the ranch, a consequence of water infiltrating down into the soil because of the grass cover rather than sheeting off erosively as it had before. This is good news for microbes, insects, grasses, shrubs, trees, birds, herbivores, carnivores, cattle, and people.

What the Sidwells are doing on the JX is reassembling the carbon landscape. They have reconnected soil, water, plants, sunlight, food and profit in a way that is both healing and sustainable. They did it by reviving the carbon cycle as a life-giving element on their ranch and by returning to nature's principles of herbivory, ecological disturbance, soil formation, microbial action, and good food. In the process, they improved the resilience of the land and their business for whatever shock or surprise the future may have in store.

The Carbon Sheriff

On a visit to California, I spent a day with John Wick, a landowner and founding member of the Marin Carbon Project, located north of San Francisco. The principle goal of the project is to explore the value of soil carbon storage in rangelands as a way of providing ecological and agricultural benefits to rural communities while combating climate change. The idea came to Wick when he went to hear permaculture guru Darren Doherty speak about soil carbon – the stuff that makes life thrive underground. What he heard changed Wick's life. Like many people, Wick worries about the buildup of greenhouse gases in the atmosphere. This buildup began with the invention of the plow four thousand years ago (which depleted soil carbon stocks), expanded with the advent of fossil fuel combustion during the Industrial Revolution, and dramatically accelerated in recent decades.

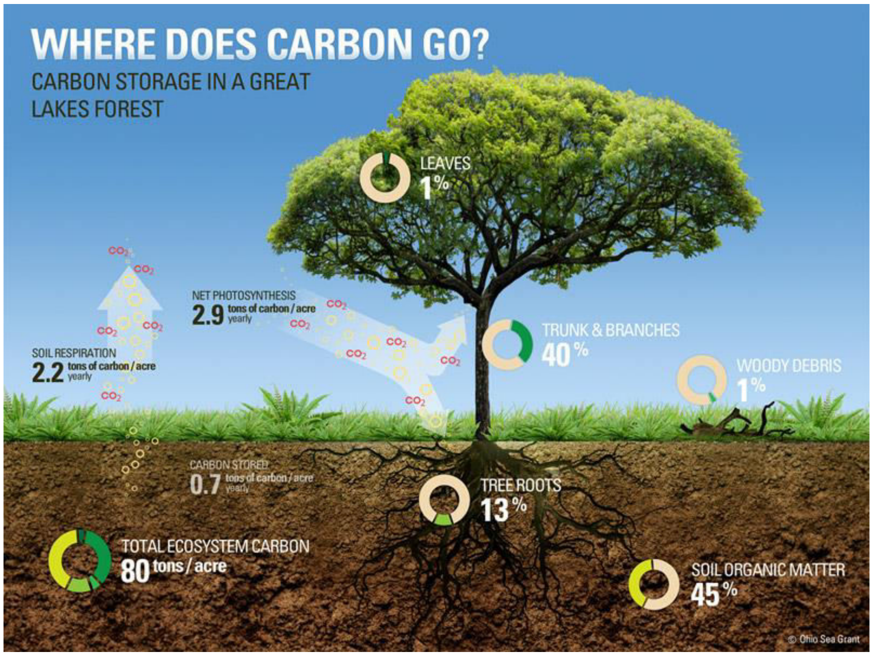
The main culprit is carbon dioxide, a colorless and odorless gas which has existed on Earth in small but varying quantities for billions of years. In many ways, carbon dioxide has been given a bad rap. It is, after all, an essential gas for the maintenance of life on the planet. As every schoolchild knows, all green plants require CO_2 to live. In other words, CO_2 is a *good* gas. But like any substance, it's only good in proper amounts. Scientists warn us that there is too much CO_2 in the atmosphere, creating a potentially toxic situation for life on Earth. Levels of CO_2 must come down, they insist, way down.

This is where Darren Doherty's talk comes in. He reported that a mere 2% increase in the organic content of the planet's soils, particularly in its grasslands, *could soak up all the excess carbon dioxide in the atmosphere within a decade.* Soils around the planet, Doherty continued, have been mismanaged for centuries resulting in the depletion of their original organic content and thus their capacity to soak up CO_2. But now, in a big irony, all these depleted soils were available to start absorbing all that troublesome atmospheric CO_2 again if we rebuilt their carbon through better land management.

Our mission, Doherty said, is to build topsoil and save the planet.

Wick was stunned. Could it be true? Could it be that simple? It's estimated that the original carbon content of the rich, dark prairies of the American Midwest before the Great Plow-up began in the mid-1800s was as high as 25%. Today, this total has fallen to around 4% in many places thanks to plowing and erosion. Doherty's idea to reverse this slide was highly intriguing, Wick thought. But soak up all the excess CO_2 in the atmosphere? That was crazy talk!

Or maybe it wasn't.



The wheels in Wicks' head were turning, so as soon as he returned home he began to read about the carbon cycle, learning that it wasn't a complete circle. A bunch of the carbon remained in the soil, having exited the plants roots in order to feed the microbial life there, where it stayed for decades if it wasn't disturbed. In other words, Doherty was right – at least in principle – excess CO_2 not only could be pulled out of the air by a natural process, it could be stored safely in the soil for long periods of time. It's called *sequestration*, which the dictionary defines as the process of "safekeeping, withdrawing, or seizing for the purposes of placing in custody." What if we became carbon sheriffs, Wick thought, seizing excess CO_2 and placing it into custody of soils for a lengthy jail term where it would feed plants and promote life.

Now Wick's wheels really began to turn. Three ideas leapt to mind after Doherty's talk: could farming and ranching actually play a significant, positive role in reducing excess CO_2? Could the practices that sequester CO_2 in the soil also improve land health and profits? Could this be the basis of a new carbon economy? Wick decided to find out and the Marin Carbon Project was born.

John Wick speaking to a group of Chinese scientists

"Now I think about carbon in everything I'm doing, and it's completely changed my life," said Wick in a radio interview. "This whole ecosystem down there, is alive. I mean up until this point it was just dirt to me, something I pushed around with my bulldozer."

"We can solve climate change right here on the ranch," he told me. "There's no doubt about it."

Grapes and Olives

I knew I had reached the Fetzer vineyard when I saw the sheep. Hundreds of sheep. Happily grazing. On my trip to California, I saw a lot of vineyards out the car window. Rows and rows of grape stumps. In no vineyard that I saw, however, from Santa Barbara to Santa

Rosa, did I see sheep. Only at Fetzer. That's because Fetzer is a different sort of wine company for a major label. While many wine makers have gone "green" in recent years, whatever that means, few have gone as far as Fetzer, especially on the carbon front. That's why I drove all the way to Ukiah to see for myself. The managerial job of the sheep? Eat the weeds and trim the grass between rows.

Sheep at a Fetzer vineyard

I had first heard about Fetzer's sustainability program at a conference on climate change and agriculture at UC Davis in 2011. Program Director Dr. Ann Thrupp told the large audience that Fetzer had implemented a variety of carbon-friendly practices, including composting leftover grape skins and stems which are then added to the soil to boost carbon stocks; planting cover crops between the vines in order to protect the soil from erosion; attracting beneficial insects with the type of cover crops they plant; and eliminating fossil-fuel based fertilizers (this is another reason why the sheep were there).

There was more: the grapes for its *Bonterra* brand are certified organic, biodynamic, and sustainable. Started in 1992, *Bonterra* has become the number one selling brand of wine made from organic grapes. Better still, unlike the wall-to-wall grape stumps that I had seen in other vineyards up and down the state, Fetzer is dedicated to conserving its oak woodlands and riparian areas. As much as 45% of its land is protected by the company as wild country.

This is important said Dr. Louise Jackson of UC Davis, who followed Thrupp's presentation, because mosaics of vineyards and wild land can store a lot of carbon. Jackson had conducted a comprehensive assessment of the carbon stocks across Fetzer's various land holdings, including its undeveloped woodlands, and determined that the ecosystem services being provided by Fetzer – voluntarily and unremunerated – were substantial. This has major policy implications for California because there is a lack of understanding about the benefits of carbon sequestration among policymakers, who are more focused on emissions. Changing this focus would encourage better farm stewardship and habitat conservation.

Earlier during my trip, I had visited with Dr. Jeffrey Creque, an agroecologist at the McEvoy Olive ranch, near Petaluma. Creque successfully implemented a comprehensive composting program on the property, but he also accomplished another important goal: doubling the carbon content of the soil from 2% (the level in 1997) to 4% – which is the estimated amount of carbon that existed in the soil prior to the arrival of European colonists.

To accomplish this ambitious goal, Creque and his co-workers embarked on a soil-building strategy that included applying lots of compost made from on-ranch olive mill waste, livestock manure and landscaping debris; employing no-till cultivation made possible by the maintenance of a permanent cover crop beneath the olive trees; seasonal rotational grazing of sheep through the orchard; and riparian area restoration to address downcutting gullies on the property.

Dozens of soil samples are taken every year from all over the ranch and sent to a laboratory for analysis. The trend over time has been clear: upward. In fact, after ten years the carbon content in all samples began hovering around 4%. This means that the olive ranch is sequestering more CO_2 than it did back in 1997. It’s also more productive and its soils are holding more water.

Creque didn’t want to stop there, however.

“There’s no reason to think that we can’t increase soil carbon in our agricultural systems to levels above those that would occur without management,” Creque told me. “Besides, there are no downsides to trying and lots of upsides, especially for agricultural productivity, sustainability and climate change mitigation. If we can manage our soils to store more carbon, we’ll also enable them to store more water, while reducing the volume of CO_2 in the atmosphere. That’s a big upside.”

Creque notes that millions of tons of organic waste – food, grass clippings, branches, manures – go into landfills every year across the nation where they produce a lot of methane, a potent greenhouse gas. Let’s compost them instead, he said, and then spread the compost across farms and rangelands where it could provide multiple benefits to the landowner and the public. Of course, there’s a financial and carbon cost to hauling this material around, but it could be offset by increased ecological productivity and potential carbon credits, not to mention benefits to the Earth's climate system.

Sounded like a low-cost, nature-based solution to a big problem!

Carbon Country

While visiting northeast Wyoming, I decided to do some carbon tourism. The famous Power River Basin is home to one of the largest coal deposits in the world. The Basin produces over 400 million tons of coal a year, which is about 40% of all the coal burned in the nation's power stations and more than twice what second-place West Virginia mines. Recently, the U.S. Department of the Interior made more coal leases available on public land in the Basin, much to the consternation of many of us who are worried about climate change.

Coal seam in Powder River country

The word *coal* comes from the Old English *col* which means 'fossilized carbon' and the substance itself has been in use as a fuel source in England since the 13th century. Geologically, it's a brown or black sedimentary rock laid down in layers or seams usually as the result of plants becoming submerged in an oxygen-less medium (such as the bottom of a swamp). Subjected to intense heat and pressure over the eons, the carbon first becomes peat, then lignite, then subbituminous coal, then bituminous coal, then anthracite, a rock.

The Powder River Basin contains a lot of subbituminous coal which is highly prized because it is low in sulpher dioxide (SO_2), another pollutant. Production in the Basin exploded when regulations kicked in recently to limit the amount of SO_2 that could be released from Appalachian mines and power plants. However, mining the coal seams in the Basin requires the removal of a great deal of overburden – the rock lying between the coal and the surface. The cost of removing this overburden is high, which means coal dances back-and-forth across a fine economic line – cost effective vs. not cost effective. Right now, it's having a hard time competing with natural gas, which has glutted the energy market.

There's another price, of course: climate change. But don't tell that to Wyoming residents. They love their coal. And they have the pick-up trucks to prove it – many of which traveled well in excess of the speed limit on their way to work as I saw first-hand, scaring the beejesus out of animals trying to cross the road. Powder River mines have a life expectancy of only twenty years, so maybe the drivers felt a need to get to their jobs as fast as possible!

Actually, it's not a joke to the locals. According to a recent news story, power generation in America from coal is falling quickly. According to the U.S. Energy Information Administration, coal made up 36 % of U.S. electricity in the first quarter of 2012 – down from 44.6 % in the first quarter of 2011. This steep drop is primarily due to low natural gas prices and it is expected to continue into the foreseeable future. That's bad news for Wyoming-nites, I suppose, but good new for everyone else.

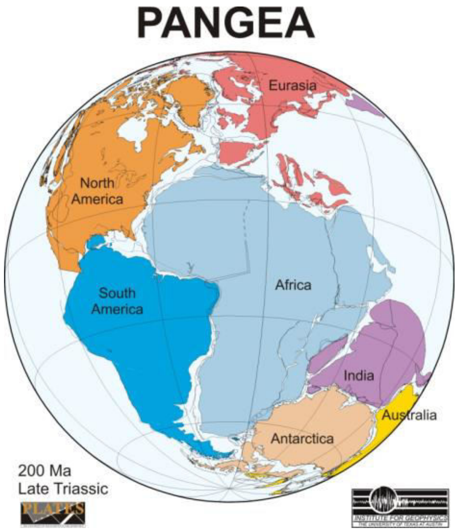
As far as carbon tourism goes, there wasn't much to see. I had expected something like a 'National Sacrifice Area' around Gillette – a veritable moonscape of gouged-out land and hulking infrastructure. Instead, what I mostly saw were coal trains, often 120 cars in length stretching a half-mile on the tracks. Each train carries 17,000 tons of coal at a time. I chased one as it left Gillette, paralleling Interstate 90, wanting to snare a photograph if I could. As I drove, another coal train passed going in the opposite direction – empty. I watched as the two trains sidled past one another, one full of climate-damaging carbon, the other returning for a refill. There was something oddly symbolic about seeing the two trains pass each other. We shouldn't burn coal; we know it's bad for the planet and us, but we do it anyway. It's an addiction that we can't quit.

It's not just Americans. Coal companies are increasingly looking to overseas markets for their unwanted coal, especially in Asia which has a rising appetite for the black stuff. According a news story, the export market to Asia jumped from 3.8 million tons in 2009 to 27.5 million tons in 2011. One of the Powder River Basin coal companies said its exports ballooned 42 % to almost 5 million tons of coal last year. This is doubly bad news. Instead of staying in the ground, where it belongs, the CO_2 from Powder River coal would still end up in the atmosphere. I say, the best place for this type of carbon is in the soil – leave it be.

The Age of Oxygen

Driving through the coal country of northeastern Wyoming set me to thinking: where did all that coal come from? The quick answer: it came from swamps, a long, long time ago. We don’t give swamps much credit today, other than as a source of alligators, but without ancient swamps the world would be a much different place.

Most of the world’s carbon that we know as coal and oil was formed between 360 and 300 million years ago, between the Devonian and Permian Periods in a time called the Carboniferous Period. The term was coined in 1822 by two geologists, William Conybeare and William Phillips, while studying England’s coal deposits. In North America, the Carboniferous is divided into the Mississippian and the Pennsylvanian sub-periods. It was a geologically active time as the Earth’s two massive continents, the southern Gondwana and the northern Laurasia, merged by the end of the Carboniferous into the mammoth Pangea supercontinent (I’ve often wondered why the Earth didn’t wobble like a lopsided spinning top with so much landmass accumulated in one place!).



At the start of the Carboniferous, huge ice sheets at the South Pole locked up large amounts of water as ice, dropping sea levels significantly which in turn led to big increases in tropical and swampy conditions across both continents. These conditions fostered the novel evolutionary development of bark-bearing trees, including the fiber lignin which when buried in the soil can linger relatively intact for thousands of years. The swampy conditions also encouraged ferns and other seedless plant life to grow to huge proportions.

Shallow, warm oceans repeatedly flooded the continents, covering fallen trees and plants in water that apparently lacked bacteria necessary for decomposition. With the flooding came sediments which covered and sealed the plant material. These layers, some of which were over thirty feet thick, eventually formed peat beds which eventually became coal. The Carboniferous was also a time of active mountain-building as the supercontinent Pangea came together. It was this process of geological uplift and submersion that generated the heat and pressure required to transform the peat beds into coal and oil.

All this plant life resulted in the oxygen composition of the atmosphere rising to 35% (compared to 21% today) which is why the Carboniferous is sometimes referred to as the Age of Oxygen. Not surprisingly, the carbon dioxide content of the atmosphere lowered correspondingly as plants ‘inhaled’ it in copious amounts. In fact, the CO_2 level during the Carboniferous became among the lowest in Earth’s history. This had two effects: the vast amounts of CO_2 that plants pulled from the air remain locked in their stalks after they fell into the swamps, which contributed to the carbon richness of the coal they were eventually transformed into; and the sinking amount of CO_2 in the atmosphere changed the planet’s climate, cooling it significantly. Scientists credit the Carboniferous with initiating the pattern of planetary warming and cooling – Ice Ages separated by warm periods – that continued until the end of Holocene (when we messed it up by burning all that coal and oil).

Another important biological milestone was the development of the amniotic egg (such as the modern chicken egg). A gradual drying of the climate on continents over the course of the Carboniferous encouraged reptiles to diversify and expand their territory at the expense of some types of amphibians. This resulted in adaptation of a hard-shelled egg. Scales too. In fact, it wouldn’t long (only another 100 million years) before ‘terrible lizards’ – dinosaurs – became a dominate species on the planet. Insects also grew well in the humid and high-oxygen conditions of the Carboniferous. One of the largest was an ancestor of the dragonfly, which had a wingspan of sixty to seventy-five centimeters. A giant millipede grew to be more than 1.5 meters long, and had thirty pairs of legs.

With the creation of the Pangea supercontinent, the Carboniferous Period drew to a close. Except, of course, it hasn’t. Every time you flip on a light or plug in an electronic gizmo, you step right back into the Carboniferous Period. As long as we continue to burn coal and oil, we’ll be revisiting the Age of Oxygen. We can thank swamps for that.

Carbon Copy

I thought I'd leave the Big Picture for a moment to concentrate on the more mundane components of our carboniferous world. I'll start a personal favorite – and one that will instantly date me: carbon paper.

Anyone remember it? It was a thin sheet of light-brown paper that you inserted between two sheets of paper, usually in a typewriter (remember those?). By pressing on the top sheet, called the 'original,' with a writing implement or striking it with key in the typewriter an exact copy could be imprinted on one or more sheets underneath. One side was coated with ink and bound with montan wax, which was derived from brown coal. Montan was a high gloss type of wax used in shoe and car polish, paints, and phonograph records.

The heyday of carbon paper occurred between the invention of the typewriter in 1868 and the development of the photocopying machine, which came into commercial use in 1959. Its principle purpose was to provide exact replicas – a carbon copy – of the original document for distribution to recipients, who were identified on the page by the letters 'cc.' This, of course, is the source of the 'cc' we use today in our email correspondence.

The first 'carbonate paper' was invented in England in 1806 in response to the introduction of the steel pen, which replaced the quill. In use for over one thousand years, the demise of the quill marked the end of what some historians call the 'Age of Handwriting.' The quality of the copies of this early carbonate paper, however, was not very good and the paper was not widely utilized. English courts, for example, refused to admit carbon copies as evidence in trials.

It wasn't until a promotional stunt for a grocery firm in Cincinnati, Ohio, in 1870 involving a hot air balloon that carbon paper took off. During an interview with the balloon pilot, Lebbeus Rogers, in the offices of the Associated Press, Rogers became very intrigued by the carbon paper being employed by the reporter. Quickly grasping its commercial potential, Rogers founded a company to produce carbonate paper and shortly made his first sale – to the U.S. War Department. It wasn't until an office-friendly version of typewriter hit the market a few years later, however, that carbon paper use zoomed.

The key ingredient in carbon paper is carbon black, which is created when a hydrocarbon, such as oil, is burnt to ashes (at 3000 degrees) in a special furnace, leaving a powdery residue. This residue was then mixed with water and spun in a centrifuge, which created almost pure carbon. It had many uses besides copying, including the manufacture of automobile tires and the 'blacking' of shoes. Charles Dickens worked in a 'blacking' factory as a boy – and lucky for us he didn't contract a life-shortening illness from it!

Lebbeus Rogers also developed the first carbon-coating machine to make the paper (it had been a hand-made process until then). He developed the first typewriter ribbons as well, which also employed carbon, and was the first to spool them onto reels and sell them in small boxes in stores.

Carbon paper had a serious limitation, however. While it was extremely useful in making copies of outgoing correspondence and documents, it was useless in doing the same for incoming mail. As the volume of business correspondence grew in the first half of the 20th century, this limitation became acute. It was solved by – you guessed it – the invention of the photocopier. Photocopy toner, by the way, used a lot of black carbon powder, often poured from a bottle into the machine (remember that too?).

Many of these inventions were still in use to one degree or another up through the 1980s until the Computer Revolution made them obsolete. I used carbon paper regularly in college and my graduating class was the last to use a typewriter, a fact that makes my children's eyes grow big. Mine too. But I'm not sentimental in the least. I don't miss for a second searching for typewriter ribbon in drawers or on the shelves of unfamiliar stores. And if you've ever used 'White Out' to correct mistakes made by a typewriter, you're probably not very nostalgic for the old days either.

Still, carbon paper is important because it was synonymous with business and domestic correspondence for nearly a century, demonstrating once again how dependent we are on this critical element.

When in Kansas

I am embarrassed to admit that I drove through the fabled Flint Hills of Kansas to a no-till workshop and barely noticed.

I flew to Wichita, rented a car, and drove to Emporia, ninety minutes to the northeast, cutting right across the state's famous grasslands. I did notice how dry everything looked, but that was about all. Arriving at the workshop, a colleague asked me what I thought of the Hills. I gulped. What hills? Did he mean the slight up-and-down motion I experienced on the highway, like a gently rolling ocean wave covered with grass? He did. Were those hills? *The Flint Hills?*

Chagrined, on the drive back to the airport two days later I paid more attention. Sure enough, I saw outcrops of limestone and the highway definitely made a rolling motion, dipping down between grassy swells. Hills! How had I missed them? I knew why: I was still in New Mexico mentally. Gentle hills like that would hardly merit a second look in the Land of Enchantment, especially with so many mountains around. But that was my fault. I was in Kansas. After all, the Flint Hills are pretty:

Historically, the shallow deposits of flinty limestone that make up the 82,000 square-miles of the Hills, mostly located in eastern Kansas, prevented the land from being plowed up. That's why it's such good ranchland today. Geologically, 250 million years ago the area lay at the bottom of a widespread sea where for millennia it collected the remains of countless dead sea creatures. Carbonically, the shells of these creatures are composed of calcium carbonate ($CaCO_3$), a mineralized version of carbon dioxide that makes its way into the oceans via rain and rivers where it eventually gets compressed into rock. This process is an essential part of the planet's carbon cycle. In fact, 80% of the planet's terrestrial carbon is locked up as limestone. As for the flint, they're quartz-like intrusions made mostly of silica – a whole different kettle of fish.

The Flint Hills are a remnant of the vast Tallgrass Prairie that once covered Kansas and other parts of the lower Midwest. Its rareness means it's the subject of keen interest by conservationists and ranchers alike. I knew that the Hills were a model of collaborative conservation and good stewardship, especially the constructive role fire plays in prairie landscapes. In fact, Flint Hills landowners were known for being ecological pyromaniacs. Signs along the highway warned drivers about fire and smoke – and to not call the police. It was just the way things were in this part of the country.

What wasn't normal was the drought. On the first day of the workshop, the thermometer hit 105 degrees. Throw in the incredible humidity and you had a recipe for a Midwestern sauna. It wasn't just the heat, however; it had stopped raining as well. The weather people called it a "flash drought" which meant it had happened in a hurry. All over the nation too. The previous Monday, the federal government announced that drought conditions covered more than 60% of the nation's counties and had reached a scale of severity not seen since 1956! The news across the Midwest was all about farmers plowing under or chopping up their corn and soybean crops, writing off the year as a complete failure.

The term 'Dust Bowl' was being tossed around too. Standing near a group of farmers during a break in the workshop, I overheard a young man talk about a wall of dust he had witnessed the previous week while driving. It was probably 500 feet high, he said. Seriously? This is Kansas, after all, not dry and dusty New Mexico. Supposedly, farming practices had improved considerably since the 1930s. But 500 feet! Was the drought that bad?

Of course, this was the point of the workshop. No-till farming means exactly what the name implies – no tilling. No plowing. No turning the soil over. No dirt blowing away. The key to no-till is *cover crops* – plants that keep the land covered with something green and growing at all times, even in winter. Conventional farming, in contrast, likes a lot of bare dirt between the crop plants. It likes a lot of till too. In fact, the idea of *not* plowing fields is roundly pooh-poohed by nearly all of Big Ag and large segments of Academia and the Government. No-till agriculture, especially organic, is way beyond Business-as-Usual, especially in a farm state like Kansas.

I won't go into the details here about the advantages of no-till except to say that it's a boon for life underground, which encourages increased carbon storage, which helps sequester atmospheric CO_2, which can mitigate climate change. Round and round.

One snapshot: during the on-farm portion of the workshop, we walked into a cover-cropped corn field with butterfly nets supplied by one of the instructors, a USDA entomologist. Under a blazing sun, we swept the ground fifty times with our net and returned (quickly) to the shade of a large tree where we examined what we had caught. There were bugs galore in our nets, especially spiders, which excited the entomologist. It proved, he said, how much *life* existed in this field. A comparative sweep of a conventional cornfield, drenched in fertilizer and pesticides and largely uncovered by green things for most of the year, would have some up mostly empty, he said. It was the difference between biology and chemistry, he continued. Which we did we prefer?

As I knew, the difference is carbon.

Colonial Carbon

While visiting Barcelona, my family and I rested for a moment on stone steps that led to a palace where Christopher Columbus was greeted by King Ferdinand and Queen Isabella upon his return from his historic voyage to the New World. It recalled an article I had read a year or so earlier about how Columbus was responsible for – of all things – an interval of global cooling! When we returned to the U.S., I looked the article up. As I suspected, the main actor was our old friend carbon.

As author Charles Mann eloquently explains in his book *1491: New Revelations of the Americas Before Columbus*, the New World was not a wilderness. Instead, it was a landscape full of people, perhaps as many as 100 million, all of them busy hunting, planting, raiding, building, laughing, singing. And all these millions of busy people had a profound impact on the land, including the clearing of large swaths of forests for intensive slash-and-burn agriculture, expanding cities and villages, and producing charcoal to improve nutritionally ‘thin’ soils, especially in the Amazon Basin. Estimates of how much forested land might have been cleared of trees are hard to determine but researchers are certain that it was high.

An example of slash-and-burn agriculture

Enter the Europeans and their diseases, including smallpox and diphtheria. As Mann painfully recounts, more than 90% of the indigenous population of the Americas died in the wake of the European conquest – died of disease, not warfare. This sudden change had a profound impact on the environment.

“Until Columbus,” wrote Mann, “Indians were a keystone species in most of the hemisphere. Annually burning undergrowth, clearing and replanting forests, building canals and raising fields, hunting bison and netting salmon, growing maize and manioc, Native Americans had been managing their environment for thousands of years…But all of these efforts required close, continual oversight. In the sixteenth century, epidemics removed the boss.”

With the boss gone, the trees grew back. That’s where carbon comes in. According to Stanford University geochemist Richard Nevle in an article published online last year in *ScienceNews*, the restoration of the forests after the massive die off of indigenous peoples of the Americas pulled billions of tons of carbon dioxide from the atmosphere, which in turn diminished the heat-trapping capacity of the atmosphere and cooled the climate for a while. In previously published research, Nevle and his colleagues reported that ice cores from Antarctica showed a drop in carbon dioxide levels by six to ten parts per million between 1525 and the early 1600s. Nevle thought he knew why.

"We have a massive reforestation event that's sequestering carbon …coincident with the European arrival," he wrote in the article.

Tying together many different lines of evidence, Nevle and his team estimated that this new growth could have soaked up between two billion and seventeen billion metric tons of carbon dioxide from the air. That was potentially enough to stoke Europe's so-called Little Ice Age, a long period of cooler temperatures that followed the Middle Ages. One line of evidence from the ice cores is the increasing presence of carbon-13 over these decades. Trees prefer carbon-12 (one neutron lighter), leaving the heavier version of carbon dioxide in the atmosphere.

"There's nothing else happening in the rest of the world at this time, in terms of human land use, that could explain this rapid carbon uptake," said Jed Kaplan, an earth systems scientist at the Federal Polytechnic School of Lausanne in Switzerland. Kaplan pointed out that while the evidence isn't conclusive, it does demonstrate that the New World epidemics highlight mankind's ability to influence the climate long before the start of the Industrial Revolution.

It also demonstrates the critical role that trees and other vegetation play in the planet's carbon cycle, as well as why so many people are working today on climate change mitigation and adaptation strategies that focus on forests. Protecting forests from destruction, especially in the tropics, is usually near the top of all the 'To Do' lists of scientists and conservationists. Professor Nevle's research added a punctuation point to their arguments!

Rereading the article and the extensive online comments it generated, I was reminded of just how raw the wound represented by Columbus remains in this country. Hero or Villain? When I was a kid, Christopher Columbus was portrayed as indisputably heroic. There was even a school-free federal holiday named after him. However, by the time of the 500th anniversary of his famous voyage into "the ocean blue" Columbus' reputation was in tatters, especially as Native Americans began to speak up, encapsulated in an emotional 1992 documentary called *Surviving Columbus*. Throw climate change into the mix, as Dr. Nevle has, and you have a volatile recipe for lots of strong feelings still today.

Did Columbus "cause" the Little Ice Age? Yes! No! Yes! No!

Hero or villain?

Lost in the raw emotions is a simple fact: we continue to underestimate the impact of human activity on the natural world. We did it when contemplating the world in 1491, and we're doing it today. Fortunately, with science's help we're getting a clearer picture of our impact, then and now. Hopefully, it'll help us clear our heads as well.

Whatever we decide to do ultimately, carbon will be there.

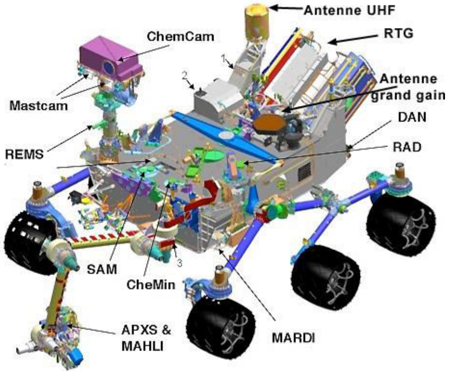
PART THREE

THE UNIVERSE AND ALL THAT

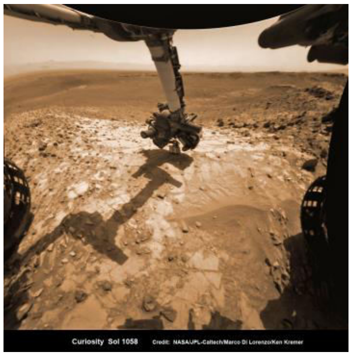
Carbon on Mars

On August 5th, 2012, NASA successfully landed a one-ton, $2.5 billion-dollar exploratory rover called *Curiosity* in Gale Crater on the planet Mars. It was a picture-perfect landing and a remarkable achievement given the huge size of the payload, the extreme distance, and the unprecedented technical challenges involved. It is a success rightly celebrated by NASA scientists and engineers, as well as space buffs the world over.

Like many, I followed the news eagerly but what caught my attention was one of the primary targets of the rover's scientific investigation…carbon! *Curiosity's* overall mission is not a new one: to discover if life ever existed on the Red Planet. This has been the objective of intense scientific and popular speculation for centuries, of course, including the famous Viking landings in the 1970s. But those inquiries "followed the water" as one observer put it this week. The mission of *Curiosity* is different – it intends to "follow the carbon."



Curiosity



Curiosity at work

According to NASA, this "mission of the decade" is looking for the building blocks of life as well as investigating how and why Mars turned from a wet and warm planet millions of years ago into the dry and cold place it is now. NASA chose Gale Crater specifically because it contains exposed layers of what appear to be water-borne sediments, particularly on the slopes of three-mile high Mt. Sharp (named for an astronomer). Mars is similar to Earth in key ways and researchers want to know if it once hosted the elements necessary for microbial life. In other words, did it have a carbon cycle at one point, even a rudimentary one?

To find out, *Curiosity* brought along the 'Sample Analysis Mars' or SAM. Its specialty is the detection of organic molecules without which life is not possible. Organic molecules are made of carbon and hydrogen atoms often called ‘hydrocarbons’ even though they can also include other elements, such as oxygen, nitrogen, sulfur, phosphorus, calcium, and iron. These atoms can join together in a huge variety of ways, usually in long chains which means millions of organic molecules potentially exist. SAM’s mission is to investigate whether any are present in Gale Crater or on Mt. Sharp.

SAM will be looking for isotopes in particular. Isotopes are versions of an element, carbon in this case, that are a little bit heavier because their nucleus contains more neutrons. For example, carbon-13 is an atom of carbon with an extra neutron which makes it a heavier version of the more common carbon-12. Occasionally, a carbon-13 will take the place of a carbon-12 atom in an organic molecule. This is important since life tends to favor the lighter isotopes because their chemical reactions require less energy. So, if a Martian soil sample has more light carbon relative to heavy carbon than would be found randomly, this might suggest that life existed there at one time.

Here’s why all of this is important (from NASA’s web site):

> *“Mars today is a desolate world of cold and windswept deserts, apparently without life of any kind, at least on the surface. But there is evidence of a wetter (and possibly warmer) past – features resembling dry riverbeds and minerals that form in the presence of water indicate that water once flowed through Martian sands. Since liquid water is required for all known forms of life, scientists wonder if life could have risen on Mars; and if it did, what became of it as the Martian environment became more hostile, drying up and losing its magnetic shield, the atmosphere growing thinner, and the climate changing and growing colder. Hopefully, SAM will provide the some answers.”*

It did! A few weeks later, scientists announced they had discovered the essential element for life in a scoop of Martian soil. The essential element is carbon, of course, and NASA found traces of it in the soil near where *Curiosity* made its landing in an area dubbed the ‘Rocknest.’

According to John Grotzinger, lead scientist for the mission, *Curiosity* ‘baked’ a soil sample in its microwave oven discovering that it contained water, sulfur, and chlorine-containing compounds, including chlorinated methane gas – a substance that contains carbon. It didn’t, however, find these elements in sufficient quantity or in the right combination to create life. Still, the presence of carbon compounds in the soil sample was a bit of a surprise to the scientists. That’s because scientists aren’t sure where the compounds originated.

“We don’t know if they are indigenous to Mars or not,” Grotzinger said. It’s possible that carbon molecules ‘hitched a ride’ from Earth as contaminants in the SAM on *Curiosity* despite careful precautions. It’s a situation similar to one that frustrated scientists during the Viking missions to Mars, when the two Viking rovers also scooped up Martian soil, heated it, and analyzed the gases that came off, detecting chlorinated methane. However, the Viking scientists eventually determined that the gas had been contaminated by solvents used to clean the rover before launch.

But *Curiosity* wasn’t cleaned with those solvents. And NASA performed its soil analyzing procedure four times with four different soil samples, only analyzing the fifth scoop when scientists felt confident that the threat of contamination was near zero. And voila! Chlorinated methane gas! Carbon on Mars!

According to Dr. Paul Mahaffy of NASA, what *Curiosity* detected were trace amounts of three of the simplest possible carbon-containing compounds: a carbon atom with one, two, or three chlorine atoms attached in place of hydrogen atoms. The heating, he said, may have decomposed a natural component of Martian soil which in turn could have broken down some form of carbon in the soil sample and chlorinated its carbon atoms. The next step will be to determine whether the carbon in the Martian soil was *abiotic* – a non-living chemical or physical process – possibly the result of the presence of carbonates such as the baking soda in your kitchen cupboard, or whether it was *biotic*, the result of a biological process such as the impact of a hydrocarbon-bearing asteroid that hit the planet, or the remains of a living microbe or other organism that died a long, long time ago.

Earth or Mars? ***(Mars!)***

However, just finding carbon doesn’t mean that you’ve found life. “If you have organic carbon and you don’t have any water, you don’t have a habitable environment,” said

Grotzinger. Even with carbon and water, life needs other chemicals, such as sulfur, oxygen, phosphorous and nitrogen, to form and evolve. “It tells us that we have a lead into a measurement of one of the important ingredients that adds to a habitable environment,” Grotzinger said. “We still have a lot of work to do to qualify and characterize what it is.”

Another condition for life is water, and once upon a time Mars had a lot of it.

In 2004, NASA’s rover *Opportunity* discovered evidence that eons ago Mars was once a wet planet, raising hopes that evidence of past life could be found today. In the same year, NASA’s *Mars Explorer* detected huge reserves of water ice at the planet’s South Pole, followed a year later by an announcement that water also existed at the North Pole. In 2006, NASA displayed images taken by the *Mars Global Surveyor* which suggested water had flowed on the surface of Mars fairly recently, though some scientists were skeptical, suggesting that sand or blowing dust could produce similar effects. In 2008, NASA’s *Phoenix* rover, which landed in Mars’ Arctic plain, confirmed the presence of frozen water below the surface when it exposed ice while digging into the soil. After four days, the water was gone – sublimated back into the atmosphere.

Evidence of water erosion on Mars

Today, scientists are very confident that Mars had abundant water very early in its history. Precipitation fell on the planet, creating rivers, lakes and possibly oceans, evidenced by the presence of large clay deposits. Life may have happened as a result of all this water (plus carbon in the soil) which is why NASA is still digging holes in the Martian soil. NASA would also like to understand in better detail what happened to Mars over the millennia. Nearly all of the water eventually disappeared; the atmosphere became composed mostly of carbon dioxide, temperatures plummeted, and life – if it ever existed – was extinguished. In other words, Mars experienced a profound change in its climate, likely the result of intense volcanic activity which may have released large amounts of carbon dioxide into the atmosphere. In this case, Mars went through a massive case of global cooling, not warming.

As they say, more research is needed.

By the way, in September NASA reported "clear evidence" of carbon dioxide *snow* at Mars' poles – the only known example of carbon dioxide snow falling anywhere in the solar system. Frozen carbon dioxide – known as 'dry ice' here on Earth – requires temperatures of about -193 Fahrenheit. NASA said the carbon dioxide snow reminds scientists that although some parts of Mars may look quite Earth-like, the Red Planet is a very, very different place.

Meteors and Comets

The news that NASA recently reconfirmed the existence of carbon atoms in Martian soil led me to wonder: where does carbon come from anyway?

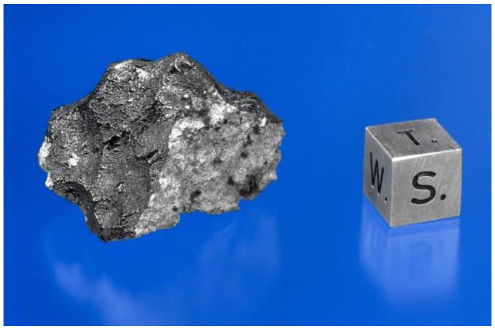
The bulk of Mars, like Earth, is composed of *rock*: i.e., a dense, central core of iron and nickel enveloped in a thick mantle of silicates (silicon + oxygen) with some potassium and phosphorus thrown in. Mars has proportionally more iron than Earth does, which is why early astronomers tagged it as the 'Red Planet' – from the oxidation of iron on its surface. Carbon is present on Mars chiefly as carbon dioxide (CO_2) which comprises 96% of its atmosphere. In 2003, tiny amounts of methane (CH_4) were detected for the first time by NASA creating a scientific mystery. Methane breaks down quickly under ultraviolet radiation from the Sun, so its presence suggests there is an active source on the Martian surface someplace. Where? Volcanoes have been ruled out for lack of geologic activity, as have living microorganisms, for obvious reasons. The methane source might non-biological carbon, called carbonates (such as limestone), but their role on Mars is still unclear.

Scientists do know, however, that carbon continues to arrive on the Red Planet via bombardment by meteorites, which often contain graphite, diamonds, and other carbon compounds. Mars, like Earth and our Moon, have been pummeled by meteorites over the millennia, sourced largely from the asteroid belt located between the Red Planet and Jupiter. This belt is likely the remnant of an ancient 'pre-planet' that never got its act together before being pulled apart by Jupiter's immense gravitational fluxes. In fact, seventy-five percent of all asteroids that have been studied so far by scientists are *carbonaceous* (i.e., they are rich in carbon) and chemically they match primordial materials formed during the early solar system, which makes these asteroids approximately four billion years old!

A word about words: *asteroids* are space-bound objects, some of which are big enough to be called 'planetoids' while *meteorites* are any rocky object that strikes the surface of a planet. When an *asteroid* of any size enters a planet's atmosphere it becomes a *meteor* and when it hits the surface it becomes a *meteorite*. Capiche?

Amazingly, bits of Mars have been discovered on Earth. In 2011, desert nomads watched a cluster of small meteorites fall to Earth near a town called Tissint in southern Morocco. Upon inspection, scientists discovered that the fragments were from Mars! Apparently, they were blasted off the Red Planet 700,000 years ago by a gigantic meteorite in what must have been a spectacular explosion. There are at least sixty other 'Martian meteorites' known to researchers and most appear to be from the same cataclysmic collision. The *Tissint* fragments excited scientists for two reasons: they were 'fresh' from the heavens, and therefore uncontaminated by Earth-bound chemicals; and they showed clear evidence of weathering by water – further proof that Mars was a wet place once-upon-a-time.

Artist conception of early Earth



The real thing – a Tissint fragment

This story illustrates the role meteorites may have played in the creation of life on Earth. In 2011, NASA announced there was a reasonable chance that meteorites brought source materials for DNA to our home. Scientists used advanced mass spectrometry instruments to scan eleven carbonaceous asteroids for *nucleobases* which are part of the building blocks for DNA and RNA. They discovered three that, while common to asteroids, were rare or absent on Earth. "Finding nucleobase compounds not typically found in Earth's biochemistry strongly supports an extraterrestrial origin," said Dr. Jim Cleaves, one of the NASA scientists.

The plot thickens!

Carbon is also transported through the solar system by comets, though impacts with planets are much less frequent than asteroids. For many years, scientists harbored doubts about the carbon content of comets, a view that changed dramatically in 2005 when NASA's *Deep Impact* probe scored a direct hit on comet *Tempel 1*, producing a plume of gas and dust far richer in carbon compounds than scientists expected. This spectacular discovery meant that comets could also have contributed the chemical raw materials that produced life on Earth so long ago.

Comets, sometimes called 'dirty snowballs,' are composed of rock, dust, water ice, and frozen gases, including methane, carbon dioxide, carbon monoxide and ammonia. As the *Tempel 1* experiment revealed they also contain a variety of organic compounds, including long-chain hydrocarbons and amino acids, the latter confirmed by NASA's *Stardust* mission in 2009. Comets wander periodically into the inner solar system from deep space and some scientists speculate they may have brought life-starting water and organic compounds to Earth and Mars. There are over 4000 known comets, though this number is likely only a fraction of the potential comet population. Some researchers speculate that the 'reservoir' of comet-like bodies in the outer Solar System may number one trillion. To us, the number of comets visible to the naked eye averages only one per year, and many of these are faint.

Comet Tempel 1

There are spectacular exceptions, however, including what scientists call the *Great Comets*, the most famous of which is Halley's Comet. Named for the British astronomer who correctly computed its periodicity – the comet makes an appearance every 75-76 years – the comet has been observed and recorded for over two thousand years. An appearance in 1066, just prior to the Battle of Hastings, was taken as a bad omen for the King of England (who was subsequently shot in the eye by a Norman arrow). In America, the writer Mark Twain was born in 1835 – the year Halley's Comet cruised across the sky. In his autobiography, written in 1909, Twain said, “I came in with Halley’s comet in 1835. It is coming again next year, and I expect to go out with it.” He did – Twain died in April, 1910.

It’s not just meteorites and comets, carbon can be found in abundance throughout the solar system. Our sun has a great deal of carbon and exhibits elements of a carbon fusion cycle in which carbon takes over from hydrogen as the main source of fusion energy. The atmosphere of Venus is 96% carbon dioxide, though unlike Mars, its surface temperature is boiling, not freezing. There appears to be a hydrocarbon ‘sea’ on Titan, the largest moon orbiting Saturn. All of the planets contain lots of carbon and if you toss in the asteroids and comets, not to mention the carbon cornucopia called Earth, then you have a strong sign that carbon is one of the ‘founding’ elements of our solar system.

We are carbon – carbon is us.

Deep Carbon

But where does carbon come from *originally*?

When the Earth got its act together four-and-a-half billion years ago, it had relatively little of the life-giving element lying around, scientists say. Carbon only arrived in useful quantities over the millennia as a result of a steady bombardment by comets and asteroids. But where did they get their carbon? And what about the sun and Jupiter, both of which are carbon-rich. Where did this life-giving element come from and how did it get here?

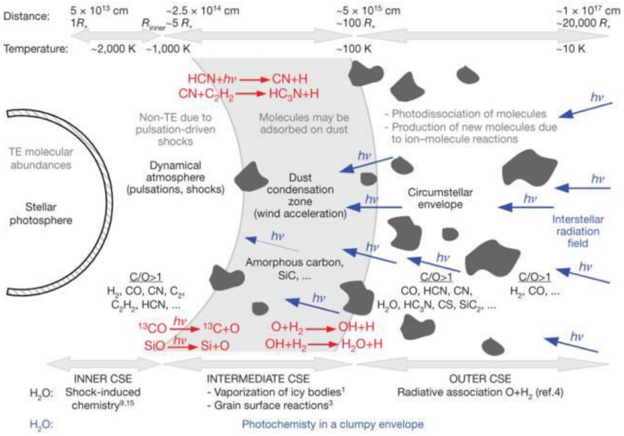
To answer these questions, we have to go back to the origin of the universe.

In the beginning, according to British scientist Stephen Hawking, there was no carbon. When the Big Bang created the universe approximately fourteen billion years ago, the explosion was so phenomenally hot that all matter existed solely as protons and neutrons. Then a minute after the Big Bang, when the temperature dropped to ‘only’ a billion degrees, some neutrons began to decay into hydrogen while others collided with protons, creating helium. These were the two original elements in the universe. Fast forward two billion years and vast gravitational forces have slowed the expanding universe down, causing large quantities of hydrogen and helium to coalesce into what eventually became galaxies and stars. Some of these stars were extremely hot and would have burned their hydrogen and helium into heavier elements, such as carbon, oxygen and iron – a process that can take only a few hundred million years. When these stars exploded as supernovas, as many eventually did, they ejected their heavy elements into space to create the raw material for the next generation of stars.

Recent research, in fact, now suggests that our home Sun came into existence as the result of a localized ‘Little Bang’ nine billion years after the Big One. Scientists believe that an exploding supernova created a dense cloud of gas and dust that eventually birthed the Sun and the solar system thanks again to the work of intense gravitational forces. It’s not likely, however, that the cloud contained much carbon due to the intense heat generated by the explosion. Carbon arrived later, likely when nearby Red Giant stars blew off their outer, carbon-rich atmospheres, before collapsing into White Dwarfs. This carbon traveled through space mostly as stardust, riding interstellar winds, before coalescing into comets, asteroids, and small planets. This stardust carbon found its way to Earth and eventually into us.

There are, by the way, *carbon stars*, which typically are older stars whose atmosphere contain more carbon than oxygen, often giving them a red appearance. In contrast, our Sun is an “ordinary” star, meaning it is richer in oxygen than carbon, which accounts for its yellowish color.

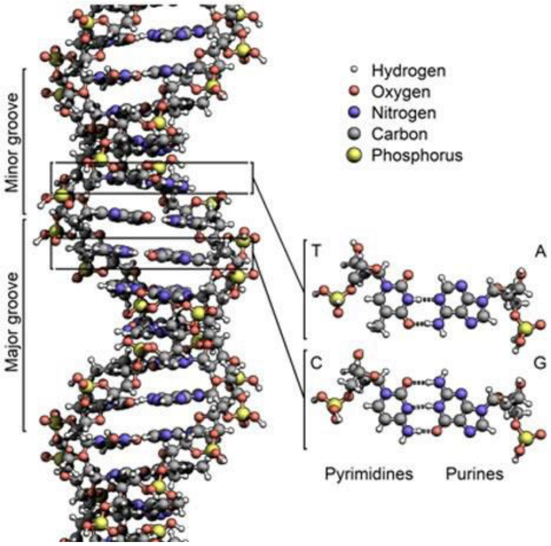
A Carbon Star



Its chemistry

Current thinking among scientists is that most of the carbon on the Earth’s surface arrived in a rain of comets early in its history, not long after the planet cooled. That’s because the early solar system was a chaotic place with all sorts of interstellar objects whizzing around. These early bombardments may have delivered virtually all the carbon and other organic material that we can see today on Earth. Some researchers believe that more than half of Earth’s carbon may have been brought in by one massive comet, demonstrating how a single event can change the entire history of a planet.

That's how carbon made it to Earth, but the really interesting question is how life actually began. In other words, how did chemistry (carbon, iron, silicon etc) become biology (DNA, RNA)? According to Stephen Hawking, we don't really know. Chemists say that the chances of a DNA molecule arising by random events from non-biological material are tiny. It's equally unlikely that a DNA molecule arrived via a comet, according to Hawking, because DNA can't survive for very long when exposed to so much radiation. We do know, thanks to fossil evidence, that life existed here about three and a half billion years ago, or only 500 million years after the Earth became cool enough for life to develop. This suggests that there's a chance of the spontaneous generation of life in suitable conditions. Maybe there was an early form of RNA which eventually built up to DNA. We can't say for certain, however, because scientists haven't yet been able to create life from non-living materials in the laboratory.



Carbon in DNA

That's been the conventional wisdom. However, scientists have recently reexamined the 'extraterrestrial origin' idea. In 2009, NASA announced that it had found glycine, one of the fundamental chemical building blocks of life, in a comet for the first time. The amino acid was detected in the dust of comet *Wild-2* in 2004 and returned to Earth by the *Stardust* probe in 2006. "The discovery of glycine in a comet supports the idea that the fundamental building blocks of life are prevalent in space," said Dr. Carl Pilcher, head of NASA's Astrobiology Institute, "and strengthens the argument that life in the Universe may be common rather than rare."

In 2008, organic compounds found in the *Murchison* meteorite suggested that RNA molecules were formed extraterrestrially. Ditto with a study published in 2011 that said DNA molecules found in meteorites indicated that they were formed in outer space. And recently, scientists announced that cosmic dust found throughout the universe contains complex organic compounds that could have been created by stars under much harsher conditions than what existed on Earth during its formative stages. As one of the scientists put it, these organics could have served as the basic ingredients for life. And lastly, in August 2012, astronomers reported the detection of a sugar molecule in a distant star system for the first time. This finding suggests that complex organic molecules may form in stellar systems prior to the formation of planets, eventually arriving on young planets early in their lives. Such as ours. Whatever happened, it's clear that the odds were incredibly long that life would gain a purchase on Earth. It did, luckily for us.

And carbon was key.

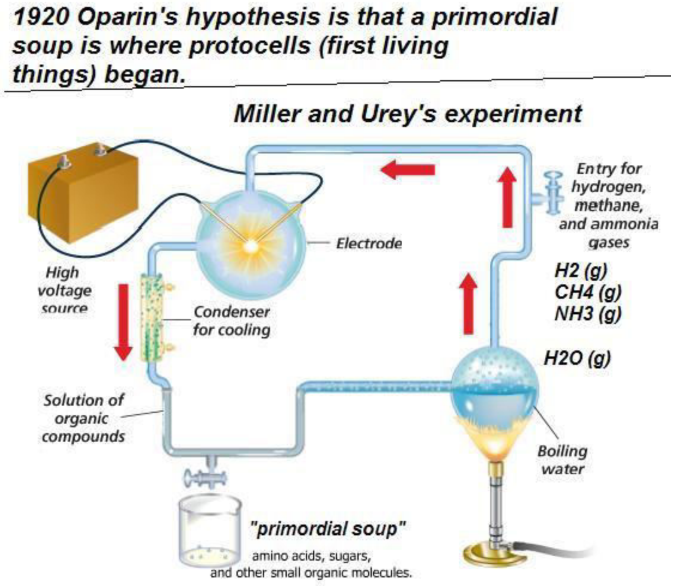
Primordial Soup

Before scientists discovered that comets and meteors carry the elemental building blocks of life – carbon-based amino acids – the best guess for the origin of life on Earth was the 'primordial soup' theory. Its progenitor was none other than Charles Darwin, who in an 1871 letter to his close friend and fellow scientist Joseph Hooker speculated that life may have begun in a "warm little pond, with all sorts of ammonia and phosphoric salts, lights, heat, electricity, etc. present, so that a protein compound was chemically formed ready to undergo still more complex changes."

Darwin's idea lay dormant until the 1920s when two researchers, Alexander Oparin and J.B. Haldane, working independently of one another, asserted that the Earth's original oceans were a vast "primeval soup" of non-organic molecules that bubbled and stewed for millennia, absorbing the energy of sunlight, until it "grew" organic molecules that could survive and reproduce on their own – as some bacteria molecules do today in hot springs and volcanic vents. Oparin argued it only had to happen once; life, once started, could take care of itself. The first living organism, they said, would be little more than a few chemical reactions encased in a thin membrane to keep them from being destroyed. These organisms would grow by absorbing organic molecules around them, grow, divide, and grow again.

Eventually, photosynthesis would arise and the oxygen it created would change the Earth’s atmosphere, making it amenable to further life. Haldane called this process *biopoiesis*, a name that didn’t catch on. However, his description of the oceans as a “hot dilute soup” did.

In 1952, this powerful metaphor received a significant jolt, literally. University of Chicago graduate student Stanley Miller and his professor, Harold Urey, decided to test the Oparin-Haldane hypothesis in what became one of the classic experiments of post-war science. Their goal was to recreate the prebiotic conditions of Earth’s early oceans and atmosphere in the laboratory to see if they could generate organic compounds from inorganic ones. Speculating that volcanic activity would have released methane, hydrogen, and ammonia into the Earth’s proto-atmosphere, they sealed these gasses in glass piping, constructed in a closed loop. On one end of the loop was a flask filled with water which was boiled to create water vapor; on the other side were two electrodes representing lightning. After sparking the vaporous mixture with the electrodes, the gasses were cooled and allowed to ‘stew’ for a few weeks before being analyzed.



What they discovered made headlines around the world and is still a foundation of most scientific inquires into the origin of life on Earth.

They discovered that as much as 10–15% of the carbon in the system (originally methane) had formed simple organic compounds and 2% had actually become amino acids – essential to life. In an interview at the time, Stanley Miller said: “Just turning on the spark in a basic pre-biotic experiment will yield 11 out of 20 amino acids." More remarkably, in 2007 scientists reanalyzed the sealed vials from the original experiment discovering that there over *twenty* different amino acids in the mixture. In this way, the experiment strongly supported the Oparin-Haldane "primordial soup" theory by showing that simple organic compounds could be formed from gases with the addition of energy. Lightning, their experiment suggested, had provided the original spark of life on Earth.

Recent research has challenged parts of their conclusion, however. Investigations into the actual composition of the Earth's atmosphere during its proto-development phase, called the *Hadean Period* (after the Greek god of the Underworld), reveal that its chemical composition was more complicated than Miller and Urey envisioned, including the presence of oxygen which would have hostile to the formation of organic compounds. While complicated, the picture emerging is one of an extremely turbulent, mostly liquid planet subjected to intense ultraviolet radiation, massive undersea volcanic eruptions, and frequent bombardment by rocky debris from outer space. These impacts would have kicked up large amounts of steam which eventually blanketed the entire planet with hot, smelly clouds. Rain – and lightning – could easily have followed. It is quite possible under this scenario that additional amino acids arrived on Earth hitched to meteorites and comets, tossed into the bubbling primordial soup like cosmic potatoes or carrots. Directions for Life: add carbon and let stew for a few hundred thousand years!

This raises a question: is life possible without carbon?

Yes, said a group of scientists in a report published by the National Research Council in 2007. They call it "weird life" – life with an alternate biochemistry than what's found on Earth. According to the report's authors, the fundamental requirements for life as we know it – water-based biosolvents + a carbon-based molecular system capable of evolution + the ability to exchange energy with the environment – are not the only ways to support the phenomena recognized as *life*.

"Our investigation made clear that life is possible in forms different than those on Earth," said lead author John Baross, professor of oceanography at the University of Washington. But we'll never recognize it, he continued, if we're only searching for Earth-like life in outer space.

"No discovery that we can make in our exploration of the solar system would have greater impact on our view of our position in the cosmos, or be more inspiring, than the discovery of an alien life form, even a primitive one," wrote the report's authors. "At the same time, it is clear that nothing would be more tragic in the American exploration of space than to encounter alien life without recognizing it."

The astronomer Carl Sagan once referred to this situation as "carbon chauvinism," arguing that life could alternatively be based on silicon or germanium. This may have been the inspiration for a famous *Star Trek* episode where Captain Kirk and company explore a planet dominated by aggressive and gooey silicon-based life forms called Horta – an encounter with which prompts a memorable mind-meld with Mr. Spock. The trouble with silicon, however, is its powerful attraction to oxygen. Life, as we define it, requires a respiratory process, which removes waste. In carbon-based life forms, the waste product is a gas, carbon dioxide, which is easily dispatched. The waste product of silicon, however, is sand – a solid. This means, according to biochemists, that it would be very difficult for silicon to provide a basis for viable life, even "weird" life.

What Is Life?

Imagine the origin of life on Earth four billion years ago as a kind of 'black box' floating in the air. Below the box, earliest Earth is all *chemistry*: rocks, gasses, liquids, and other physical (inorganic) elements. Above the box, *biology* has appeared in the form of rudimentary cellular (organic) life. The box blocks our view of what links the two, hiding an extraordinary mystery: how did life happen when no life existed previously? How does chemistry, in other words, produce biology? Scientists don't know the answer yet, but they are getting closer.

In Charles Darwin's day, the black box was huge; today it has shrunk dramatically, thanks to countless experiments and hundreds of researchers. While its contents are still a mystery, two theories have emerged about what happened inside the box all those years ago.

But let's take a step back first.

The basic unit of all life is the *cell*, the smallest unit on the planet classified as a living thing. Cells have the same essential parts: interior and exterior membranes that regulate molecular traffic into and out of the cell; proteins that catalyze chemical reactions; a 'library' of information in the form of DNA which the proteins continually consult; and RNA, errand-runners who provide blueprints for the formation of new proteins. A cell is a complete package – it has everything it needs to grow and reproduce provided it has access to minerals and energy in its immediate environment. The chemical process that enables a cell to transform these elements and energy into action is called *metabolism.* Its presence, along with replication and evolutionary change, is the foundation of life on Earth.

A cell is a sophisticated organism, but in the early, harsh days of Earth's history, life had to be *much* simpler – but not too simple. It's the Goldilocks Principle: organic life had to be simple enough to be created by inorganic processes and yet complex enough to replicate itself and initiate evolution. Life had to be *just right* – 'hot' enough to be weaned from the physical processes that gave it birth but 'cold' enough to synthesize molecules and tap chemical nutrients and solar energy in order to fuel its cells. The *just right* part was the creation of metabolism, scientists say.

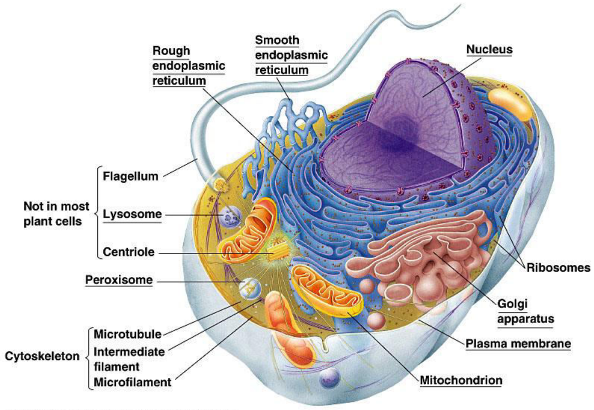
But how did metabolism come to be?

One theory targets RNA as the likely suspect. Experiments have demonstrated that in the presence of certain mineral catalysts, nucleotides, which are molecules that form the building blocks of life, can join together to form RNA (though nucleotides themselves have not yet been built from scratch in a laboratory). Furthermore, it is has been observed that relatively short RNA molecules can author their own replication, which is the first big step toward metabolism. However, a second theory says proteins can do the same thing – as the famous Miller-Urey experiment demonstrated back in the 1950s when it proved that amino acids can form under inorganic conditions. This is another path to metabolism.

Thus, depending on environmental conditions, RNA *and/or* proto-proteins could have evolved in primeval oceans.

Not surprisingly, there's a third theory: metabolism came first, followed by RNA and proteins. This theory, which was considered quite radical when it was first proposed a few years ago, involves thermal vents, deep undersea, where hydrogen sulfide from a vent reacts with iron monosulfide, lying around, to create pyrite, a common mineral commonly called 'fool's gold.' It is a process that allows the fixation of carbon dioxide, found in the seawater, forming organic compounds on the pyrite, leading to the creation of the basic functions of metabolism. The nucleic acids and proteins came later.

And of course, carbon is involved in nearly every stage of these processes.



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An animal cell

Is a computer alive? After all, a computer is a type of cell. It has a membrane through which energy and bits of data flow; it has DNA-like coded instructions in the form of programs and files that are constantly being changed and updated; its codes and files can be copied and shared with other computers; it has RNA-like wiring that carry electrical messages; it has a kind of metabolism, consuming electricity from its environment, generating paper printouts and creating heat as a waste product. And there's lots of carbon in a computer – silicon too. It's a carbon-and-silicon-based life form!

Of course, a computer is not alive. For one thing, it can't reproduce itself, not yet anyway. Cells make copies of themselves, which is how an organism grows, and computers cannot do this or else Apple and Dell would be out of business. Robots might be a different matter, however. Science fiction is littered with dark fantasies about self-reproducing robots run amok, usually the violent expense of humanity. Is it a possibility?

Here’s a list of what biologists consider the basic ingredients of life: living things take in energy; they get rid of waste; they grow and develop; they respond to their environment; they reproduce and pass their traits onto their offspring; they evolve in response to their environment. Sounds like a robot to me!

Life is a Force

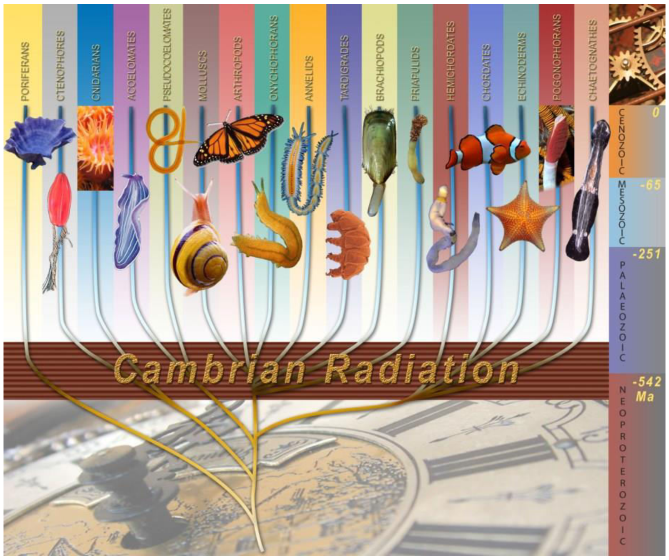
If the origin of life on Earth is a mystery wrapped inside a black box then so is the great explosion of life that happened during the Cambrian period, beginning 540 million years ago, when carbon went wild.

Nearly four billion years after Earth’s formation, life was still mostly bacteria, plankton, and algae. Complex, multi-celled organisms developed only 600 million years before today, during the Precambrian period, just as the planet emerged from a long period of intense glaciation (Ice Age). A mini-explosion of life swiftly followed, including the appearance of soft-shelled tubular and frond-shaped organisms, all of which lived in the sea. Although it is not clear to scientists what caused this mini-explosion, it is probably not a coincidence that it occurred as a massive supercontinent called *Rodinia* began to break up, likely causing temperatures on the seafloor to warm.

Whatever the reason, it was just the opening act to the Main Show.

Early on, geologists recognized that the sudden appearance of complex animals with mineralized skeletons in the fossil record of the Cambrian period represented an ‘explosion’ of life. Further research revealed it to be a biological eruption of extraordinary diversity and quantity ("radiation" is the scientific term). All major animal body plans and most of the major animal groups that we know today appeared during this unprecedented event. To many scientists, it was the most important evolutionary transformation in the history of life on Earth, which is why it is sometimes called the "biological Big Bang." Of course, this event didn't take place overnight – ten million years is more accurate – but in geological terms it was still a blink-of-the-eye. And it was never repeated again on this scale.

The creatures that came into existence during the Cambrian Period were relatively small, widely dispersed and entirely aquatic. Thanks to their reproduction in legions of school books, the exotic shapes of these creatures are familiar to us, including brachiopods, with their clam-like shells, trilobites, which were armored arthropods, early mollusks and beautiful echinoderms, known today as starfish. Despite their proliferation, however, many Cambrian creatures eventually went extinct, including the exotic *Opabinia*, which had five eyes and a nose like a fire hose, and *Wiwaxia*, an armored slug with two rows of scales.



Along with all this biological diversity came a radical new ecological development: predation. The fossil record clearly shows that some creatures were hunters and some were prey, a development that had profound evolutionary consequences for life from this point forward. Ecosystems became much more complex as a result and many animals moved (or were chased) into a variety of new marine habitats. Soon, Cambrian seas teemed with animal life of various sizes, shapes, and ecologies; some lived on the sea floor, while others swam around in the water. By the end of the period, a few animals had also made revolutionary (and temporary) first forays onto land, soon to be followed by plants, changing life on Earth profoundly once again.

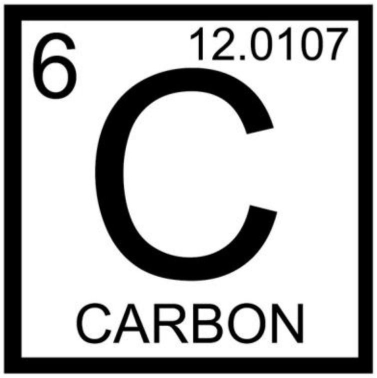
All of this was a great worry to Charles Darwin, who fretted that his theory of evolution, which postulated a steady, gradual process of change over the eons, would be attacked by religious critics who believed that such an explosion of life was indisputable evidence of God's hand at work – a belief that persists to this day. Darwin assumed the answer to his concern lay in the sketchy Precambrian fossil record (soft-shelled creatures make poor fossils). He hoped new discoveries would eventually support his theory – which has more or less happened. Meanwhile, a theory of rapid ("punctuated") evolution was put forward in the 1970s by biologists as an alternative to Darwin's 'gradualism' thesis. This theory argues that evolution can happen in bursts when conditions are right.

Why did life explode like that? Some scientists point their finger at a rise in oxygen levels that started around 700 million years ago which might have provided 'fuel' for an evolutionary explosion. Others believe that a biological extinction event just prior to the start of the Cambrian opened up ecological niches for new creatures (the way that mammals filled the big niche left by the sudden extinction of dinosaurs 65 million years ago). Then there was the so-called 'carbon anomaly' at the Precambrian-Cambrian boundary, in which the normal ratio of carbon isotopes in the carbon cycle were dramatically upset by something, possibly a result of the earlier extinction event. Other researchers say the animals themselves were responsible. One of the evolutionary consequences of predator-prey behavior, for example, might have been the development of shells and bony skeletons for protection. Maybe creatures were forced into 'marginal' ecological niches where they had to adapt to survive, creating new body types where none existed previously. Or maybe it was something else.

One thing is clear: life is a force that will not be denied.

Four billion years ago, against every conceivable odd, life came into being where no life existed previously. Chemistry yielded biology and once life gained a perch it tenaciously clung on, enduring billions of years of environmental stress. Seas boiled and froze; land flooded, rose, sank, and rose again. Oxygen levels – essential to life – were dangerously low for much of Earth's history, an issue that was only resolved in favor of existence by the miracle of photosynthesis – an invention of life. Life perpetuating life. Undaunted by circumstance, biology pushed forward, urged on by evolution, overcoming whatever physical challenge or toxic condition chemistry could throw at it. Life endured because it had one overriding purpose: to keep living.

And carbon has been there from the start.



The End