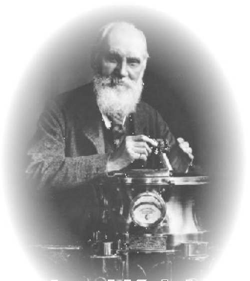
A Very Deep Question:

Just How Old is Earth?



Lord Kelvin

Early efforts to understand the Earth's age cannot be categorized fairly as a battle between science and religion. Rather, those early efforts reflected two different approaches to collecting and interpreting evidence. The chronologists' approach was to carefully analyze historical texts of all sorts, including the Bible, to estimate the lifetimes of historical figures, and then determine the Earth's age by placing them in order according to ancestry. The naturalists' approach was to carefully study the natural world, referring to it as "the Book of Nature", to understand the Earth's history. People of faith were found in both of these camps.

The naturalists argued that the Earth is old, but how old remained a mystery. Many naturalists, including James Hutton, showed no interest in plotting a chronology of geological history, and even explicitly rejected that task. Chronologists, on the other hand, sought to determine *temporal sequence* arguing that 'what happened when' mattered. Even if determining precise dates was not possible, getting events in the right order was important to them. Most scholars became convinced throughout the nineteenth century that the naturalists were correct in their assertion that the Earth had a deep history. Many of them began to wonder if the Earth's age and other geological events could ever be determined with precision.

The first generation of geologists included men like James Hutton who were independently wealthy and spent their free time practicing geology. The following generations of geologists made their living doing geological research in the field, reporting it to their colleagues, and teaching it in universities. Professional societies increased greatly in the nineteenth century, and they provided a place for scholars to share ideas with other intellectuals. In 1807, the Geological Society of London began as a dinner club at a pricey tavern in order to keep away men from lower society. In 1825, it opened its doors somewhat, and admitted any man with an interest in geology. Reflecting the gender role norms in society that existed at that time, women were forbidden. The geological society aimed to understand the Earth and concentrate solely on geological matters. However, this sole focus did not last long. Politicians sought geological evidence to help locate valuable coal. Moreover, Charles Darwin's mechanism for biological evolution — natural selection—was in need of geological evidence supporting an Earth that was at least hundreds of millions years old. Motivated by an interest in the Earth itself, but also by the importance of geology in many fields of study, geologists sought to understand the Earth's structure, its features, and the very difficult problem of its timescale.

In the 1850s many methods were being used to determine the timing of geological events. Three were particularly popular – stratigraphy, fossils, and sedimentation. At the time, none of these methods could be used to establish exact ages of the Earth, but they were used to determine the order that geological events had occurred. Stratigraphy studies the order of rock layering, or strata, and it remains a staple of modern geology. As geologists studied these rocks, they found remnants of what appeared to be plants and animals embedded in the strata. Throughout human history, these remnants had been used in religious and cultural ceremonies and collected like memorabilia. But not until the late 1700s did anybody seriously think they were fossils of long-dead, and possibly extinct, animals. In the 1850s some thought that the placement of these fossils within the strata could be used to determine the Earth's age.

Others thought that the process of sedimentation would provide the only reliable estimate of geological events. As rocks wore away, or 'denuded,' from rain, wind and floods, particulate matter (ranging from large grains to silt) and dissolved ions would be sent to settle in lower lying areas such as valleys, rivers, and oceans. Some geologists thought they could measure this flow of sediment and calculate how long it would take to make some of the enormous rock formations. For instance, if the thickness of a modern sedimentary deposit is measured, and the rate that sediment is added to it over a period of a year is known, then the length of time that the sedimentary deposit has been forming can be easily calculated.

1. John Phillips, in 1860, used the idea of sedimentation to estimate the Earth's age. Based on the rate of sedimentation he observed occurring today, he assumed that approximately one foot of land eroded into the ocean every 1,330 years. He speculated that geologic columns would have a maximum height of 72,000 feet. Using his approach and numbers, calculate the approximate age of the Earth he determined.

This approach relied upon uniformitarianism, the idea held by many geologists that forces presently acting on the Earth are the same as those that have acted in the past. Thus, the uniformitarian view holds that the rates of sedimentation processes occurring today have occurred at the same rate in the past. Shortly after 1860, a variety of approaches relying on sedimentation had been used to provide an approximate age of the Earth, and values ranged from 38 to 300 million years.

While this age range is enormous, geologists were all in agreement that the Earth is very old.

William Thomson (better known as Lord Kelvin, the namesake of the Kelvin temperature scale), argued that he could approximate the Earth's age by estimating the amount of heat it lost over time. A schooled physicist, Kelvin had no formal training in geology. He made his name in the 1850s as a technical advisor on the transatlantic telegraph cable, and he made several contributions to our scientific understanding of heat. His work in this area contributed to the foundations of the second law of thermodynamics, known as 'entropy.' To him, entropy was the measure of heat lost when two bodies of different temperatures interacted and came to equilibrium of temperature. For example, when ice cubes are placed into a glass of water, energy in the form of heat moves from the water to the ice. The water loses heat and cools. The ice gains the heat and melts. This meant that the total amount of energy could not be lost (or created), but just reallocated to the air, the glass, the table, or something else. He thought this reallocation of energy applied to the sun and the Earth, and could be used to estimate the Earth's age.

Kelvin's approach was in opposition to the sedimentary technique used by geologists. The basis of his argument was that in every interaction, energy must be transferred. This would be the case for the Earth and sun as well. Thus, since their respective beginnings, both have been losing heat. He first turned his approach on the sun. Because the sun gave off enormous heat over a long time, it must be fueled by something. Many scientists thought the sun's heat was a product of chemical reactions, but nobody understood how chemicals could react to produce such enormous energy. Kelvin suggested that meteors crashing into the sun powered the reactions, analogous to meteors that were known to strike the Earth. He thought that the sun's enormous gravity pulled in these unseen meteors. That interaction, he speculated, would provide enough reallocated energy to keep the sun burning for a long time.

In 1850, however, scientists had no evidence that anything similar had been going on with the Earth. Kelvin took this to mean the Earth had been losing energy since its birth. He then collected data on temperatures inside caves and volcanoes to determine the Earth's interior heat. He compared this to the surface temperature and estimated how long it would take the Earth to cool to its current temperature. At first he calculated about 100 million years, but this calculated number fell as he considered other variables and additional information. By 1900 Kelvin placed the Earth's age at 24 million years old. Despite the many uncertainties in his calculations, Kelvin maintained that his approach clearly refuted theories that had put forth an Earth that is hundreds of millions of years old.

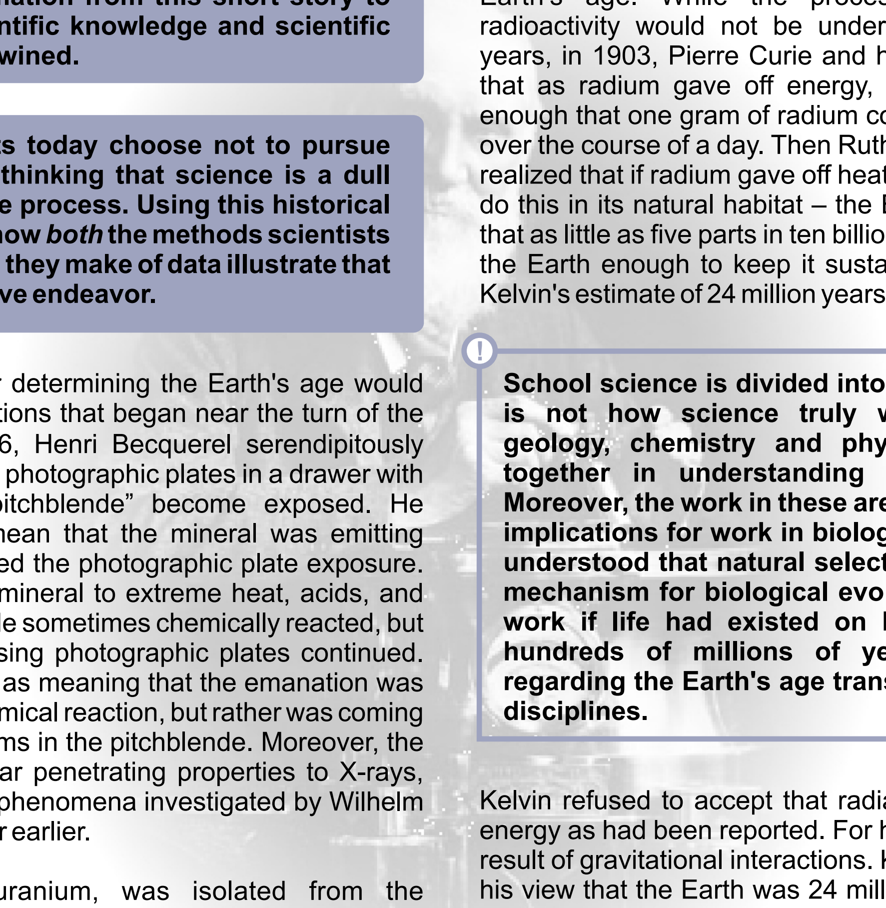
Kelvin's conclusion raised concerns about the viability of uniformitarianism because his calculated time frame was far shorter than uniformitariansim would require. However, the Earth's age was not as important to Kelvin as emphasizing that geological theory must be consistent with well-established physical principles. In 'On the Secular Cooling of the Earth,' Kelvin argued that geologists, particularly those advocating uniformitarianism, had neglected the principles of thermodynamics in their speculations. Kelvin also denied catastrophism, maintaining that geological speculation must be physically and philosophically sound. Kelvin thought that scientific laws reflected regularity in nature, which in turn he believed was the working of a providential intelligence. However, the universe for Kelvin was mechanical and worked on physical relationships.

But geologists were not arguing against a mechanical universe that worked on physical relationships. John Joly's work provides, perhaps, the best example of the geologists' adherence to these two assertions. He and other geologists were using different data, and their calculations based on it gave a much older Earth. Joly applied the technique of sediment analysis to the salinity, or salt content, of the oceans. He assumed the oceans began as entirely fresh water, and that through erosion of rocks had slowly acquired its current salinity. This argument hinged on the realization that sodium appears in the ocean paired with chlorine, magnesium, and potassium. He had to measure the respective amounts of each salt present in the ocean and then factor the chemical weight of sodium. He concluded that there was $14.151\text{x}10^{12}$ tons of salt in the ocean, and then divided this by what was accepted at that time as a good estimate of the annual flow of sodium into the ocean. The result of this calculation was that 90 million years would have to pass to reach the ocean's current salinity level. Announcing this result in 1899, he and many other geologists had reached a similar conclusion that the Earth was approximately 100 million years old.

At the turn of the century, then, two quantitative, 'scientific' estimates of the Earth's age had two very different results. Kelvin measured the loss of heat by the Earth and arrived at 24 million years, while the geologists had measured the accumulation of sediment and concluded that the Earth was 100 million years old. Each of these methods made sense, and few scientists were willing to change their minds.

2. Note that how scientific research is conducted (the *processes* of science) is intertwined with prevailing ideas about natural phenomena. This, in turn, affects new thinking about the natural world. Use information from this short story to explain how scientific knowledge and scientific process are intertwined.

3. Many students today choose not to pursue science careers, thinking that science is a dull and unimaginative process. Using this historical episode, explain how *both* the methods scientists use and the sense they make of data illustrate that science is a creative endeavor.



The next method for determining the Earth's age would come from investigations that began near the turn of the 20th century. In 1896, Henri Becquerel serendipitously noticed that wrapped photographic plates in a drawer with a mineral called "pitchblende" become exposed. He interpreted this to mean that the mineral was emitting something that caused the photographic plate exposure. After subjecting the mineral to extreme heat, acids, and bases, the pitchblende sometimes chemically reacted, but the emanation exposing photographic plates continued. This was interpreted as meaning that the emanation was not the result of a chemical reaction, but rather was coming from deep within atoms in the pitchblende. Moreover, the emanation had similar penetrating properties to X-rays, the name given to a phenomena investigated by Wilhelm Röntgen just one year earlier.

A new element, uranium, was isolated from the pitchblende, and it was determined to be responsible for the penetrating rays. In 1898, Pierre and Marie Curie announced they had isolated two new elementsradium and poloniumand called the energy they gave off "radioactivity." A few years later, Ernest Rutherford determined that X-rays and radioactivity were actually two different events. Whereas X-rays were high energy electromagnetic radiation (the same kind of energy that made up visible light), radioactivity was the process by which elements *changed* into other elements. Put simply, unstable *parent* elements gave off protons and neutrons and form a *daughter* element. At the time, Rutherford's claim that one element could change into another sounded like old-fashioned and now rejected alchemy. Nonetheless, research progressed quickly and just after the turn of the century, researchers had determined that three kinds of radiation existed. Weak and easily absorbed radiation that could be deflected by a magnetic field was called *alpha* radiation. Somewhat penetrating radiation that was deflected by a magnetic field in the opposite direction of alpha radiation was called *beta* radiation. And highly penetrating radiation that was not deflected by a magnetic field was called gamma radiation.

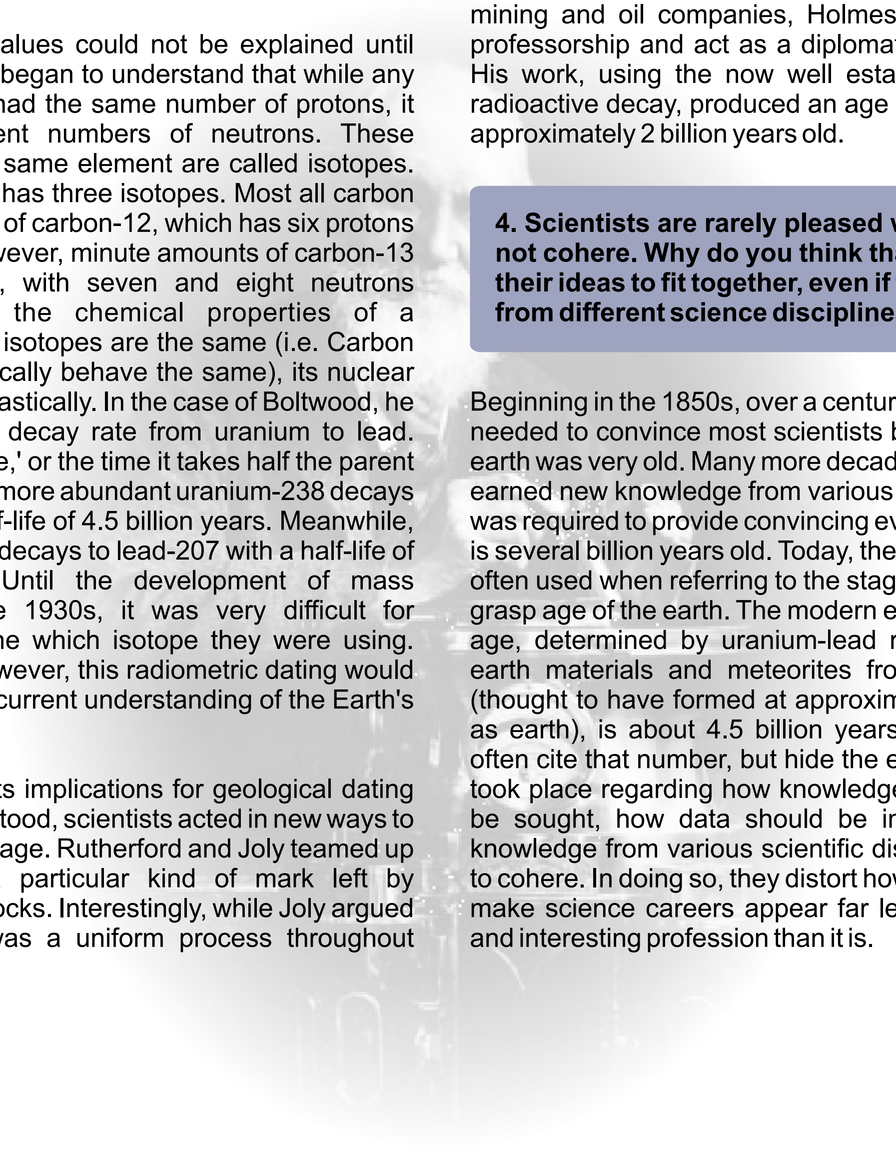
This newly observed phenomenon, radiation, would soon play the key role in the fifty-year struggle to determine the Earth's age. While the processes responsible for radioactivity would not be understood for another 20 years, in 1903, Pierre Curie and his student announced that as radium gave off energy, it also gave off heat; enough that one gram of radium could melt a gram of ice over the course of a day. Then Rutherford and his student realized that if radium gave off heat in the lab, it must also do this in its natural habitat – the Earth. They calculated that as little as five parts in ten billion of radium would heat the Earth enough to keep it sustainable far longer than Kelvin's estimate of 24 million years.

School science is divided into subjects, but that is not how science truly works. Note how geology, chemistry and physics are all tied together in understanding the Earth's age. Moreover, the work in these areas had significant implications for work in biology. Charles Darwin understood that natural selection, his proposed mechanism for biological evolution, would only work if life had existed on Earth for at least hundreds of millions of years. Thus, work regarding the Earth's age transcended scientific disciplines.

Kelvin refused to accept that radiation actually gave off energy as had been reported. For him, all energy was the result of gravitational interactions. Kelvin remained firm in his view that the Earth was 24 million years old, and this produced some awkward situations. At one conference, Rutherford was set to give a lecture that would essentially discredit Kelvin's theory. As Rutherford took the stage, he saw Kelvin sleeping in the back. Momentarily relieved that the famous physicist may not hear his speech, Rutherford began. To his horror, Kelvin awoke as he began talking on radiation. Rutherford would later recall that, "I saw the old bird sit up, open an eye and cock a baleful glance at me!" Rutherford's point was not to mock Kelvin, but to say that he had found a new way of estimating the age of the Earth.

Most physicists and geologists soon recognized that this newly understood natural phenomenon was a likely solution to the previously irreconcilable difference between the physical and geological estimates of the

Earth's age. Using Rutherford's ideas, Bertram Boltwood pioneered a method of radiometric dating in 1907. If one knew the time it took for a parent element to decay into a daughter element, then measuring the ratios of each element in a sample and calculating how long it would take to get the observed ratios was a simple matter. This method sent estimates of the Earth's age skyrocketing as high as two billion years. But many samples also came back with a date of 400 million years.



This wide range of values could not be explained until 1913 when scientists began to understand that while any one kind of element had the same number of protons, it could contain different numbers of neutrons. These different forms of the same element are called isotopes. Carbon, for example, has three isotopes. Most all carbon on Earth is in the form of carbon-12, which has six protons and six neutrons. However, minute amounts of carbon-13 and carbon-14 exist, with seven and eight neutrons respectively. While the chemical properties of a radioactive element's isotopes are the same (i.e. Carbon 12, 13, and 14 chemically behave the same), its nuclear properties can vary drastically. In the case of Boltwood, he tried to measure the decay rate from uranium to lead. Measured in a 'half-life,' or the time it takes half the parent element to decay, the more abundant uranium-238 decays to lead-206 with a half-life of 4.5 billion years. Meanwhile, the rare uranium-235 decays to lead-207 with a half-life of 700 million years. Until the development of mass spectrometers in the 1930s, it was very difficult for scientists to determine which isotope they were using. Once understood, however, this radiometric dating would play a key role in our current understanding of the Earth's age.

As radioactivity and its implications for geological dating became better understood, scientists acted in new ways to determine the Earth's age. Rutherford and Joly teamed up in 1913, studying a particular kind of mark left by radioactive decay in rocks. Interestingly, while Joly argued that sedimentation was a uniform process throughout history, he never accepted that radioactive decay was uniform. He tried unsuccessfully to reconcile the 100 million year estimate of the Earth's age calculated using his salinity dating process, with results that came from calculations using radioactive decay. Meanwhile Arthur Holmes, perhaps the first geologist to fully grasp the implications of modern physics, was willing to try all the new methods to get the two fields working with each other. A lifelong geologist who had traveled the world working for mining and oil companies, Holmes would settle into a professorship and act as a diplomat between scientists. His work, using the now well established regularity of radioactive decay, produced an age of the Earth that was approximately 2 billion years old.

4. Scientists are rarely pleased with ideas that do not cohere. Why do you think that scientists want their ideas to fit together, even if those ideas come from different science disciplines?

Beginning in the 1850s, over a century's worth of work was needed to convince most scientists by the 1950s that the earth was very old. Many more decades of work, and hard-earned new knowledge from various scientific disciplines, was required to provide convincing evidence that our earth is several billion years old. Today, the phrase 'deep time' is often used when referring to the staggering and difficult to grasp age of the earth. The modern estimate of the earth's age, determined by uranium-lead radioactive dating of earth materials and meteorites from the asteroid belt (thought to have formed at approximately the same time as earth), is about 4.5 billion years. Science textbooks often cite that number, but hide the extensive debate that took place regarding how knowledge of the earth should be sought, how data should be interpreted, and how knowledge from various scientific disciplines is expected to cohere. In doing so, they distort how science works, and make science careers appear far less than the creative and interesting profession than it is.

A Very Deep Question: Just How Old is Earth? written by Blair Williams, Michael P. Clough, Matthew Stanley, Jane Pedrick Dawson & Cinzia Cervato

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