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The Limits of Physics: Lord Kelvin's Estimate for the Age of the Earth

William Thompson, also known as Lord Kelvin, was a prominent 19th century physicist who made significant contributions to various scientific disciplines, including but not limited to thermodynamics, geophysics, and electromagnetism. Kelvin's work included formulating a version of the second law of thermodynamics, an absolute temperature scale, and the dynamical theory of heat (Sharlin). However, despite Kelvin's prolific achievements in thermodynamics, he still made an erroneous calculation of the age of the Earth based on thermodynamic principles, drastically underestimating it and putting it in contention with Darwin's theory of natural selection.

Kelvin's Estimate for the Age of the Earth

Lord Kelvin leveraged thermodynamics to calculate the age of the Earth through its cooling. By finding the rate that the Earth was losing energy through heat, Kelvin hoped to place an upper bound on its age, as the conservation of energy implies that the total energy lost by the Earth due to cooling must be finite and bounded by the initial energy contained in the Earth after its formation. To calculate the rate of energy loss, Kelvin used the concept of thermal diffusivity, building off the work done by Fourier, who "had shown that temperature changes within a solid obey the diffusion equation" (England et al. 342). Essentially, the rate of heat transfer is proportional to the temperature gradient, so for a cooling planet, the temperature gradient between the hot planet and cold space would be much greater than the temperature gradient within the hot inner layers of the planet. This meant that the outer layers of the planet would cool more rapidly than the inner layers, creating a measurable temperature gradient within the body of the planet itself as the planet cools. By measuring this gradient, Kelvin hoped to be able to calculate the rate at which the Earth was cooling, using that rate to then estimate the age of the Earth given some initial state for a newly formed molten Earth.

To obtain values for the thermal gradient of the crust of the Earth, Kelvin used temperature measurements from deep mines, where it was possible to observe that temperature increased with depth. The average geothermal gradient that Kelvin estimated based on these measurements was roughly a 1 degree Fahrenheit increase for every 51 feet descent, and combining this with an estimate of the initial temperature of the Earth at 7000 degrees Fahrenheit, Kelvin estimated the Earth to be only around 98 million years old (Richter 396). Kelvin obtained his estimate for the initial temperature of the Earth as well as values for other properties of thermal diffusion in rocks through laboratory experiments, but uncertainty in the measured values for the geothermal gradient and conductivity meant that Kelvin could only determine that the Earth was “between 24 million and 400 million years” old (England et al. 344). Furthermore, in making these estimates, Kelvin had to make several assumptions about the thermodynamic properties of the Earth. First, to be able to apply Fourier’s mathematics to the Earth, Kelvin had to assume that the Earth was a homogenous solid, which was contradictory to the idea that the Earth began as a molten sphere. Kelvin worked around this contradiction by arguing that the Earth must have at some point uniformly solidified from a molten mass. Kelvin knew that the outer layer of the originally molten Earth must have solidified first, forming a solid crust on top of molten magma. However, he “assumed that the solidified rock would be heavier than the underlying liquid and would sink through it,” falling to the center of the Earth, where the pressure and thus melting point of rock was higher, leading to the Earth solidifying from the center outwards (Wilson 203). This process would have led to the Earth becoming a uniform solid, validating his application of mathematics intended for heat conduction through solids.

Because the principle of the conservation of energy was critical for Kelvin's calculations, he had to make an additional assumption on the energy contained in the Earth. Kelvin assumed that there were no unknown sources of energy within the Earth that could contribute to its heat. He reasoned against the presence of any chemical reactions fueling the thermal gradient by stating how the heat in the Earth was uniform, and that scattered chemical reactions would lead to "hot spots on the earth's surface that could not be explicable solely in terms of the sun's action and weather" (Hattiangadi 505). By eliminating the idea of additional hidden energy sources within the Earth, Kelvin was able to calculate the Earth's age based on only the initial heat of the molten Earth and its gradual loss over time, leading him to his estimates in the order of at most a few hundred million years.

To then further validate his estimates on the age of the Earth, Kelvin also calculated the age of the Sun. He similarly assumed that there was no source of additional energy fueling the Sun's heat output, basing this assumption on the absence of any known chemical reaction that could sustain the immense amount of energy coming from the Sun (Hattiangadi 505). With this assumption, Kelvin calculated that "the Sun could sustain its present rate of radiation for no more than 100 million years" (England et al. 344). Since this figure agreed closely with his estimate of the Earth's age, Kelvin had additional confidence that his estimates were correct, limiting the age of the Earth to a maximum of a few hundred million years and the age of the habitable Earth much shorter. This provided a significant challenge to both uniformitarian geology as well as Darwin's theory of natural selection, as both required the age of the Earth to be significantly longer, yet Kelvin had used seemingly rigorous physics to refute this notion. While Kelvin's calculations themselves were not erroneous, it would be later discovered that his initial assumptions were incorrect, allowing physics to be reconciled with natural selection and geology.

Controversy with Uniformitarianism and Natural Selection

The uniformitarian theory of geography gained prominence with the publication of *Principles of Geology* by Charles Lyell, where it was proposed that the Earth was "constantly and slowly changing," with the present geological condition of the Earth being the cumulative result of these gradual changes over a vast period of time rather than as the product of brief, cataclysmic events (Desmond and Moore 117). Uniformitarianism emphasized that the forces governing the evolution of Earth's geography were uniform, meaning that natural processes that shaped the Earth in the past were the same processes occurring in the present. Because uniformitarianism did not rely on cataclysmic events, it predicted that the Earth was extremely old, with a vast stretch of time being necessary for slow geographic processes to produce features such as mountains or canyons seen in the present.

Darwin, in devising his theory of natural selection, was heavily influenced by Lyell and uniformitarian geology. Having taken a copy of *Principles of Geology* on his Beagle voyage, Darwin saw firsthand evidence of the slow accumulation of geological change in phenomena such as volcanic islands and fossilized trees in the Andes. Convinced by Lyell's geological views, Darwin applied the principles of uniform laws governing minute changes accumulating over deep stretches of time to his own theories on the evolution of species. Darwin's theory of natural selection also relied on uniform processes acting to create drastic changes over immense periods of time. With competition for resources acting as a sieve, variants with advantageous traits were more likely to survive and reproduce, molding species to be better adapted to their specific environments over numerous generations. However, because Darwin's natural selection was not guided by any supernatural powers or by conscious efforts by individuals of a species themselves, but rather relyed on variation produced by random chance, it was necessary for the Earth to have been close to its present condition for "an enormously long time" (Hattiangadi 505). This condition on not only the Earth's overall age, but also on the persistence of environmental conditions similar to the present, is necessary because natural selection acts according to environmental conditions. If the Earth had experienced any recent major alterations, species would not have had enough time to become so suitably adapted to their present environments through natural selection. Uniformitarian geology would have provided sufficient time for natural selection to act; however, with Kelvin's estimates of the age of both the Earth and the Sun, the habitable age of the Earth was predicted to be no more than tens to only a few hundred million years at maximum.

Kelvin's use of rigorous mathematics and application of thermodynamics to limit the age of the Earth posed a direct challenge to natural selection, giving a "preposterously inadequate" amount of time for species to evolve as Darwin claimed (Desmond and Moore 566). Being unable to argue directly against Kelvin's physics, Darwin was forced to alter his theory to accelerate the process of adaptation. By having the environment contribute to increasing useful variations and adopting Lamarck's idea of the usage of organs leading to heritable change, Darwin altered his mechanism to be less random and more guided, cutting the required time down to "a mere 100 million years" (Desmond and Moore 567). Despite this effort to reconcile biology with physics, Kelvin's estimates still stretched the viability of natural selection, with physicists believing that even 100 million years was too generous for the Earth's age. Not only did Kelvin's estimate conflict with Darwin's natural selection, but it also conflicted with geology and paleontology. Since Darwin's theory based its time scale on uniformitarian geology supported by his discoveries of natural phenomena and fossils while on his Beagle trip, this meant that the relatively young limit for the Earth's age would also disagree with geological models based "on sedimentation and erosion" as well as being inconsistent with "the fossil record" (Singham). While the arguments for the Earth's age based in biology, geography, and paleontology were not considered as rigorous as Kelvin's estimates backed by sophisticated physics and mathematics, there was still substantial evidence suggesting that the Earth was much older than predicted by thermodynamics. Being unable to directly find fault in Kelvin's physics or his calculations, Darwin and others in those fields could only try to ignore the limit set by physicists, hoping that a future discovery would be able to reconcile physics with an older Earth. Indeed, it would be later revealed that the Earth actually was much older than a few hundred million years old, both through the discovery of a critical flaw in Kelvin's reasoning as well as through alternative methods for calculating the age of the Earth.

Kelvin's Faulty Assumption of a Rigid Earth

Kelvin required the Earth to have been uniformly solid at some point to validate his application of Fourier's mathematics intended for heat conduction in solids. He assumed that this must have been true, arguing for the complete solidification of the Earth from its originally molten state due to his assumptions that cooled, solid crust would sink into underlying magma and that higher pressures within the Earth would lead to solidification from the center outwards. While these arguments seemed reasonable, they were based not on empirical evidence, but rather only on Kelvin's own assumptions. Kelvin's assumptions on the properties of rock and magma were in reality critically flawed, undermining his reasoning for the solidification of the Earth and thus his entire calculation of the Earth's age.

Kelvin's assumption of a uniformly rigid Earth was challenged by the physicist John Perry, one of Kelvin's former pupils. Perry recognized that if the interior of the Earth was even partially fluid rather than fully rigid, instead of relying solely on conduction for heat transfer, the fluid would be able to form convection currents. This was significant because fluid convection "could transfer heat much more effectively than does diffusion" through a solid (England et al. 346). Even though a higher rate of heat transfer means that the rate of cooling is faster overall, allowing for convection in Earth's mantle actually greatly increased the estimates for the Earth's age. Because convection would be able to keep the interior of the Earth at a more uniform temperature, it could sustain a higher thermal gradient at the Earth's solid crust. As the outer part of the fluid mantle cooled due to conduction by the crust, convection currents would cause the cooler fluid to sink and bring hotter fluid back up to the crust. This effectively meant that the crust had access to a much greater reservoir of heat, as heat transfer from the interior of the Earth out to the crust was not limited by diffusion as would occur through a solid, "thereby helping maintain the surface flux at a higher and more uniform level" (Richter 398). Perry calculated that even with only a tenfold increase in heat transfer in the mantle compared to slow conductivity in the crust, "the age of the Earth would have to be multiplied by a factor of fifty-six," significantly extending the limit from tens or hundreds of millions of years into the range of billions of years (Wilson 206). Perry supported the idea that the Earth could have an at least partially fluid mantle by drawing an analogy with "cobbler's wax," stating how even though rock can appear solid, with immense forces and a long enough time scale, even rock could deform and move like a fluid (England et al. 347). While Perry did not disprove Kelvin's assumptions through this calculation, he did show that it was possible to reconcile thermodynamics with biological and geological theories by accounting for more efficient heat transfer within the Earth from fluid convection. By applying similar physical principles to an alternative yet still relatively simple model, Perry showed that the age of the Earth could be greatly extended while retaining the rigor of physics and mathematical modeling, with the only change being his assumptions about the interior of the Earth. This high dependence on initial assumptions meant that even if the correct thermodynamic principles were applied, until the assumptions could be validated, Kelvin's calculations could not concretely limit the Earth's age.

Additionally, not only was Kelvin's assumption of solid crust sinking liquid magma lacking experimental confirmation, but it also actually contradicted related experimental results on the buoyancy of metals and rock. It was found that brass and iron, when dropped into liquid metal, would first float to the surface before being melted, and experiments with basalt showed that it similarly would float on top of molten rock before melting (Wilson 204). While these experiments were conducted when Kelvin was making his estimates on the Earth's age, Kelvin essentially disregarded the contrary evidence, choosing to believe his own assumption that solid mantle would sink and thus the Earth must have solidified uniformly. Despite ignoring both Perry's argument of convection in a non-rigid mantle as well as experiments suggesting that his assumptions were flawed, Kelvin did not alter his estimates to incorporate these possibilities. Even so, because of Kelvin's reputation and status earned through his other highly influential work in thermodynamics and physics, Kelvin's estimates were still highly regarded until the discovery of radioactivity helped to more conclusively refute them.

The Impact of Radioactivity on Estimating the Earth's Age

With the discovery in 1903 that "radioactive decay releases heat," it seemed possible for radioactive decay to explain why Kelvins estimates were too low by being an energy source violating his assumption of the absence of additional hidden energy sources rather than his assumption of a rigid Earth (England et al. 346). However, the thermal contribution by radioactive elements was small enough compared to the thermal energy of the Earth from molten rock that the inclusion of radioactivity would not have altered Kelvin's estimates significantly. Even though radioactive decay generates "about 2×10^{13} watts, equivalent to about half the total amount of heat flowing out of the planet at present," because the thermal energy produced is distributed uniformly throughout the mantle, much of the heat production would be too deep in the mantle to significantly affect the thermal gradient near the outer part of the mantle which Kelvin was concerned with (England et al. 347). Since heat diffusion in the mantle was so slow, only "the outermost 100 kilometers of the Earth" would be relevant to Kelvin's calculations of the thermal gradient, and the volume of this outer shell compared to the entirety of the Earth's mantle was small enough that radioactive contributions would be practically negligible (England et al. 347). Numerically calculating the impact of radioactive heat production with "a total heat production of 2.25×10^{13} watts" throughout the crust and mantle shows that even though the surface thermal gradient would be higher, the time needed to reach the observed present gradient would still be in the order of 100 million years, which is around Kelvin's estimates and still insufficient to support geological models or Darwin's theory of natural selection (Richter 396). This calculation aligns with the previous reasoning that radioactivity was not the hidden factor skewing Kelvin's estimates, showing that Perry's model of fluid convection was most likely to be the actual reason Kelvin's calculations were incorrect.

Even though radioactive heat generation did not explain the inaccuracies in Kelvin's estimates, radioactive decay still did help refute his estimates by providing an alternative method to finding the age of the Earth. Because radioactive decay is exponential with a constant half-life depending on the material, radiometric dating can use proportions of radioactive elements found on Earth to give much more accurate estimates for its age. Using "the ratio of uranium-to-lead atoms" in rocks to estimate their age, the oldest rocks "yield an age of about 4.56 billion years," meaning that the age of the Earth must be similar (Hazen 203-204). This estimate is close to Perry's estimate which accounted for fluidity in the mantle, substantiating Perry's argument for convection currents within the liquid magma underneath Earth's solid crust. With Earth's age extended, Darwin's natural selection had sufficient time to act. Furthermore, not only did the longer estimate allow for uniformitarian geology, but Perry's theories of a fluid mantle also helped support the theory of plate tectonics, helping reconcile physics with biology and geology.

While a missing energy source was not the reason for Kelvin's erroneous estimate of the Earth's age, it does explain why Kelvin's estimate for the Sun's age was also too low. Kelvin had originally argued against a hidden energy source for the Sun by stating that no known chemical reactions could sustain the Sun's output, but with the discovery of fusion, nuclear reactions could supply the enormous quantity of energy required by the Sun. With "the fusion of hydrogen into helium" at its core, the Sun was able to sustain its energy output for much longer than Kelvin predicted (England et al. 345). The extension of the age limits of both the Earth and the Sun into the range of billions of years ended the controversy with the time necessary for natural selection.

The Limits of Physics in the Real World

Lord Kelvin was a brilliant physicist, but despite the sophistication of his thermodynamic arguments or his advanced mathematics, he was critically incorrect on his estimate for the Earth’s age. This was not because of any error in his mathematics or thermodynamic laws, but rather because of his heavily flawed assumptions in modeling the Earth. Even though Kelvin was ultimately incorrect, he brought many important ideas from physics into geology, including that the age of the Earth must have been limited, even if its limit was much greater than he thought. Kelvin’s error shows how physics is not always correct, even with its apparent rigor, as if the model used does not match the real world, neither will any results derived from it. Additionally, Kelvin’s error also shows that even if reputation and sophistication are important, they cannot be the sole reasons for believing an argument, as skepticism and experimental confirmation are crucial for advancing scientific understanding.

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