Science & Education **12:** 213–228, 2003.

Lord Kelvin and the Age-of-the-Earth Debate: A Dramatization

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Abstract. This is a dramatization of a fictitious debate about the age of the earth that takes place in the Royal Institution, London, England, in the year 1872. The debate is among Sir William Thomson (later Kelvin), T.H. Huxley (Darwin's 'Bulldog'), Sir Charles Lyell, and Hermann von Helmholtz. In 1862 Thomson published his celebrated and widely studied 'The Secular Cooling of the Earth' that raised the post-Darwinian debate of the age of the earth above the level of popular controversy. He entered the debate with all the arrogance of a newly established 'science of the century', namely the recently drafted laws of thermodynamics. The debate is partly based on a lively exchange of comments and arguments that occurred between T.H. Huxley and William Thomson, starting in 1868, when Thomson addressed the Glasgow Geological Society. This long public discussion also involved the ideas and the work of geologist Charles Lyell and those of the celebrated German physicist Hermann von Helmholtz. The confrontation is between the unyielding physicists and the insecure biologists and geologists who required a much longer time for the age of the earth than the physicists were prepared to give them. However, the debate ends on a conciliatory note, suggesting that perhaps Sir William's 'storehouse of creation' may contain a hereto undiscovered source of energy that is more bountiful than gravitational energy.

Introduction

Since WWII there have been many dramas written that focussed on the role scientists ought to play in society. An excellent review of this topic can be found in 'The Image of the Physicist in Modern Drama' (Parts 1 and 2) by W. Brouwer (1982, 1993). Brouwer discusses plays such as Brecht's *The Life of Galileo*, Dürrenmatt's *The Physicists* and Kipphardt's *In the Matter of Robert Oppenheimer*, to name only a few. He argues that in most of these plays the scientist is portrayed sympathetically, but research is viewed much more as an individual activity than it is in actual practice. He concludes his papers by suggesting that 'These plays serve as an excellent introduction to a discussion of the social responsibility of scientists, and scientific organizations, and might form a useful element of in the ethical education of scientists or science teacher' (1993, p. 239).

More recently, the international success of the plays *Oxygen* by Carl Djerassi and Ronald Hoffmann, and *Copenhagen* by Michael Frayn suggest a wide public interest in the history of science as well as in the science itself. The first is a two act play that tries to answer the question 'Who discovered oxygen?' The play is also about doing science, politics and ambitions. The second play is based on the meeting between Bohr and Heisenberg in 1941 in German-occupied Denmark where they discussed the possibility and consequences of harnessing nuclear power. The play is also about loyalty, suspicion and friendship.

The setting for *Oxygen* is based on a fictional encounter between Lavoisier, Priestley, Sheele and their wives, at the invitation of King Gustav III. The place of the discussion is Stockholm in the year 1777. The setting for Copenhagen is more modest: Heisenberg is in the home of the Bohrs, with Mrs. Bohr as an important participant.

Both plays have been praised for the excellence of their dramatic design as well as the correctness their historical and scientific content. They received high acclaim from historians of science and scientists alike. Moreover, both plays have elicited much public and academic discussion.

The Pedagogical Use of Drama

The pedagogical use of drama has been promoted by science educator Joan Solomon (1989). She has worked on preparing scripts of dramas for students to participate in role playing. One such drama is 'Galileo's Trial' where students prepare by assuming a role (Cardinal Bellarmine, for example) and after reading a script participate in the trial.

Richard Ponting (1978) has successfully produced student-initiated drama based on Durrenmatt's *The Physicists* and other plays in a high school physics class. V. Raman (1980) has written dialogues to dramatize to allow famous scientists to be interviewed by students, for example, Aristotle and Copernicus. In my history of science classes at the University of Manitoba we have developed dramatic settings to illustrate confrontations, for example, 'Copernicus and the Aristotelians', 'Newton discusses the nature of light with Robert Hooke'. Recently, Pantidos et al. (2001), experimented with the re-enactment of a famous in-house drama by Bohr's students in 1932. The play is based on Goethe's Faust and was inspired by the need for discussing the rapid development of physics in those turbulent years.

The Manitoba group believes that new ideas in science become more accessible through dramatization.

Background Information for the Dramatization

In the second half of the 19th century the question of the age of the earth and the sun elicited great excitement, both in scientific circles and the general public. This problem was especially interesting and challenging for physicists. After firmly establishing the conservation of energy principle, there was little doubt that the mysterious source of energy of the sun, and therefore the existence of the earth, were limited. Already toward the end of the 17th century, Newton and others calculated the cooling rate of a hot metallic earth and arrived at an answer of about 50,000 years (Dalrymple 1991. p. 28). However, such a high estimate was in direct contradiction to the theologians' claim that the earth was created by God about 6000 years earlier. John Lightfoot, Vice-Chancellor of the University of Cambridge, first published his calculations of the age of the earth in 1644, thus anticipating Bishop Ussher's famous statement made in 1650. Guided by a careful interpretation of Mosaic chronology, he succeeded in working out the date of the creation of the earth exactly. According to Dr. Lightfoot: 'The earth was created on October 26, 4004 BC, at nine o'clock in the morning in Mesopotamia, according to the Julian calender'. (Dalrymple 1991, p. 14). On the other hand, the Scottish geologist James Hutton declared in 1798: 'We find no vestige of a beginning, no prospect of an end'. By about 1830, geologists, led by Charles Lyell, argued that the earth must be very old, if not infinite as Hutton thought, then certainly billions of years. Their reasoning was based on the discovery that very long times were required for geological processes to take place.

Enter William Thomson, later Lord Kelvin, as the main player of the debate. In 1862 he published his celebrated and widely studied 'The Secular Cooling of the Earth', raising the post-Darwinian debate of the age of the earth above the level of popular controversy. He entered the debate with all the arrogance of a newly established 'science of the century', namely the recently drafted laws of thermodynamics.

These laws were chiefly based on his ideas and those of Hermann von Helmholtz. The first law, according to Helmholtz, says that heat, work and internal energy were but different manifestations of the same quantity, namely *energy*. This quantity can be identified, measured and shown to be conserved in a closed system. The second law, according to Kelvin, states that it is impossible to extract heat from an object and convert it *entirely* into work.

Kelvin believed that in an effort to replace the diluvian hypothesis and to break free of Mosaic chronologies, geologists had gone too far. He argued that the principle of uniformitarianism and its demands for unlimited time had to be reassessed. This was a central principle that Charles Lyell stated in the first edition of his famous *Principles of Geology* in 1830. It was the claim that forces and geological activity have remained constant, both in kind and activity, over 'interminable ages'. Kelvin pointed out that according to the laws of thermodynamics, the energy available for geological activity must have decreased constantly and using the 'irrefutable principles of natural philosophy', he concluded that the earth could be as young as 20 million years and could not be older than 400 million years. He finally settled for 98 million years as the most acceptable value for the age of the earth.

The following is a dramatization of a fictitious debate about the age of the earth. It is partly based on a lively exchange of comments and arguments that occurred between T.H. Huxley and William Thomson, starting in 1868, when Thomson addressed the Glasgow Geological Society (GGS), as described in detail in Smith and Wise (1989). In this address he mounted a ‘full scale attack on excessive time scales’ (p. 584). A year later Huxley responded in a paper, countering each of the hypotheses proposed by Kelvin. Huxley was prudent and did not criticise the physics or mathematics of Kelvin, but expressed strong doubts about the correctness of some of his assumptions about the value of the physical quantities he used in his equations.

A year later, Kelvin answered Huxley’s criticisms, again in an address to the GGS. He cleverly turned Huxleys arguments against him, suggesting that both Huxley and Lyell were ‘guilty of the ‘direct opposition to the principles of natural philosophy” (p.589). This long public discussion also involved the ideas and the work of geologist Charles Lyell and those of the celebrated German physicist and cosmologist Hermann von Helmholtz.

An earlier version of this science drama was performed in Como, Italy, in October of 1999, at the ‘Fifth International Conference of the History and Philosophy of Science Teaching’. It was also performed (in German) in November of 2000 at the Deutsches Museum, Munich, as one of the popular series ‘Wissenschaft für Jedermann’ (‘Science for Everyone’) to a capacity audience of over 500. The performance was shown by the Bavarian TV network’s education channel on two occasions.

What may be unique in this dramatization is that the ‘personae dramatis’ were all professors or practising scientists in geology, physics, and biology. These experts first acquainted themselves with the original script and then researched the history of science in the period appropriate for the time of the debate. This double preparation allowed them to present the ideas not only with authority and authenticity but allowed them to go beyond the text and respond spontaneously to the ‘demands of the moment’. Going beyond the text produced spontaneous responses that were unexpected, often humorous, sometimes emotional, clearly showing the human side of science. Indeed, the numerous digressions to the black board in order to illustrate ideas relieved the presentation from being a static conversation around a table. Finally, the moderator was also a professor representing the ‘intelligent lay person’, thus making the drama appear as a contemporary ‘talk show’.

The Age-of-the-Earth debate

Personae Dramatis:
Sir William Thomson
Hermann von Helmholtz
Sir Charles Lyell
T.H. Huxley
Moderator
Time: 1872
Place: Royal Institution, London, UK

Moderator:
Good evening, ladies and gentlemen.
How old is the earth? This question has fascinated people for a long time. Tonight we will try to tell the story of a scientific confrontation that attempted to answer that question. This confrontation lasted for more than 50 years. It reached a high point around 1870 (the time for our fictitious debate), with the 'public debate' between Sir William Thomson and Thomas Henry Huxley that lasted several years. It began with an address given by Sir William to the Glasgow Geological Society and the response to that address in a publication by Huxley. In this confrontation the ideas of the geologist Charles Lyell and those of the great German physicist and physiologist Hermann von Helmholtz were fundamentally involved.

Tonight, we want to present the excitement of science, the human face of science. We are trying to show that science is a human endeavour, a creative act, full of surprises and cannot be captured by a specifiable method.

First, we will welcome Sir William Thomson, the famous physicist and one of the founders of the second law of thermodynamics. Sir William has used the new physics of thermodynamics and his powerful mathematical skills to calculate the age of the earth.

Sir William Thomson:
Good evening, ladies and gentlemen. I am convinced that the method of the geologists and biologists is missing systematic experiments as well as a good mathematical theory. I think that my calculations show clearly that the earth cannot be older than about 100 million years. They clearly contradict the estimates of billions of years of geologists and the very long, if not infinite time that biologists require for the processes of evolution to take place. I will state at the beginning that I believe that British popular geology as well as the biologists are guilty of direct opposition to the principles of natural philosophy.

Sir William shakes hands with the moderator, then sits down and bows to the audience.

Moderator:
Thank you, Sir William. Our next guest is the celebrated German physicist and physiologist, Professor Hermann von Helmholtz. He is one of the architects of the conservation of energy principle, or the first law of thermodynamics. He used this principle to calculate the age of the sun based on the energy contained in the gravitational collapse of a primordial cloud of masses.

Hermann von Helmholtz:
Good evening, Mr. Chairman, Sir William, ladies and gentlemen: Thank you for inviting me to England for this unique occasion. Let me apologize for my poor English. I assure you my physics is much better.

The conservation of energy principle which seems to hold for the whole universe, is the most significant discovery of the nineteenth century. It is most important, not only for all the physical sciences and technology but I think also for geology.

Let me just say that I am completely sympathetic toward Darwin's theory of evolution. Here I stand a little in opposition to my friend and colleague Sir William.

Helmholtz bows to the audience, shakes hands with Sir William and sits down beside him.

Moderator:
Thank you, Professor Helmholtz. Next we have Sir Charles Lyell. Sir Charles is generally regarded as the leading geologist of this century. His Principles of Geology, first published in 1830, changed the way geologists think and work.

Sir Charles Lyell:
Good evening, Mr. Chairman, Sir William, Professor Helmholtz, and ladies and gentlemen.

I am acutely aware of the fact that I must be by far the oldest of this August group of scientists here tonight debating the problem of the age of the earth.

Geology requires, not millions, but billions of years to explain processes we have observed and studied. With due respect to the findings of natural philosophy I am convinced that there is something missing in Sir William's calculations. However, we all hope that eventually there will be a reconciliation between our geochronology and the demands made by the laws of physics.

Sir Charles, bows to the audience, shakes hands with the two physicists and then discreetly moves to the other side of the table.

Moderator:
Thank you, Sir Charles. Finally, we turn to Professor T. H. Huxley, affectionately known as 'Darwin's Bulldog'. Professor Huxley is well known as a biologist and public defender of Darwin's theory of evolution. His fame was secured about 10 years ago when he debated in a public forum Bishop Wilberforce and defended Darwin's ideas so eloquently. I would like to mention that the word 'agnostic' was coined by him.

Huxley:
Good evening, esteemed colleagues, Mr. Chairman, ladies and gentlemen.

I never know how to respond to being called 'Darwin's Bulldog'. I suppose one should take it as a compliment, in view of the fact that Darwin is considered the foremost biological philosopher of our age.

I agree with Darwin that the age of the earth must be significantly greater than the 100 million years the physicists grant us, perhaps orders of magnitude greater. We biologists agree with Sir Charles that there is something significant missing in the physicists' calculation of the age of the earth.

Perhaps I should make a comment at the outset of this meeting about the word 'agnostic'. that is now banded about so freely. If you describe yourself as an agnostic, that does not mean that you profess to be an atheist. Rather, I invented this word to describe the questioning and critical scientific attitude of many scientists of my generation.

Huxley bows, shakes hands with the two physicists and moves over to sit down beside Lyell.

Moderator: Thank you Professor Huxley.

Moderator pauses, looks to his left and then to his right and smiles.

It looks like we have a natural separation between the physicists and the geologists and the biologists.

Please make yourself comfortable. Having set the background and given the position for each participant, we will now begin our discussion about the age of the earth.

The Debate

Moderator:
Sir William, your papers about the age of the sun and the earth, published ten years ago, mark the beginning of this now famous debate. We realize that in solving the problem of the age of the earth, you applied the recently developed laws of thermodynamics. Did you study the physics used by earlier natural philosophers in connection with that problem?

Sir William:
Of course, I am not the first physicist to deal with the question of the age of the earth and certainly I will not be the last. There have been noted thinkers who concerned themselves with this question, but it must be said, they have had only modest success. Newton, Leibnitz and even the experiments of the naturalist Count de Buffon immediately come to mind. Newton suggested that the rate of cooling of a hot metal was proportional to the difference in temperatures between the metal and the surrounding air, and Leibnitz was an early subscriber of the concept of an initially molten earth. He actually tried to measure the increase in temperature as he descended into the mines of the Harz Mountains in 1680. In 1730, Count de Buffon measured the cooling time of very hot iron spheres of increasing size. He found that the cooling time was roughly linearly proportional to the diameter. This, of course, is not surprising. Actually, no experimental testing is necessary here.

Sir Charles:
Even a humble geologist knows that the experiment of De Buffon, at least the first part, was not necessary to perform. If I recall correctly, Newton argues that, because of the cube square relationship between heat content and heat radiation, cooling time should be proportional to the diameter of the sphere. I seem to recall that Newton actually did estimate the cooling time of the earth to be about 50,000 years and Buffon arrived at a number like 75,000. By the way, Professor Helmholtz, is Newton's approach not an example of what German physicists call a 'Gedankenexperiment'?

Helmholtz:
You are right, Sir Charles. Newton's short passage in the *Principia* suggests he argued that a one inch iron sphere at a very high temperature (the temperature of molten iron) would cool in about 1 hour to room temperature. A simple calculation then shows that, assuming that cooling time is linearly related to diameter, the Earth must be at least 50,000 years old. He stopped here, except to suggest that an experiment should be done to check this idea. But we must remember that this was a short passage, and only a passing remark made in connection with the heating effect of the sun on comets that come very close to the sun. He wanted to calculate the duration of time for the retention of that heat.

Huxley:
So, in a sense, De Buffon seems to have followed Newton's suggestion and checked the cooling time of a large sphere made of earth material and then extrapolated to a sphere of the size of the earth?

Helmholtz:
Yes, I think that is right.

Huxley:
But, gentlemen, let me emphasize that this is not a very promising number for the age of the Earth for us biologists. I much prefer the estimate of James Hutton: 'There is no vestige of a beginning, no prospect of an end'. Or at least Sir Charles' estimate of 'unimaginably long' time.

Sir William:
Sir Charles, recently the geologist, Professor Geikie, gave a brilliant lecture on the geological history of the actions by which the existing scenery of Scotland was produced. I think you attended that lecture. How long a time would you allow for that history?

Sir Charles:
Many of my colleagues would be reluctant to suggest any limit to it.

Sir William:
You don't suppose things have been going on always as they are now? You don't suppose geological history has run through 1000 million years?

Sir Charles:
Certainly I do.

Sir William:
10,000 million years?

Sir Charles:
Yes!

Sir William:
Let me remind you, Sir Charles, that the Sun is a finite body. You can tell how many tons it is. Do you think it has been shining on for million million years?

Sir Charles:
I am incapable of estimating and understanding the reasons which you physicists have for limiting geological time – as you are incapable of understanding the geological reasons for our unlimited estimates. You must remember that the earth consists of continents and oceans and that we can only guess the contents and the physical makeup of the earth below about 10 miles.

Sir William:
You can understand our reasoning if you give your mind to it.

Sir Charles:
Sir William, in your calculations you use a very fast cooling rate that we geologists cannot accept.

Huxley:
Gentlemen, allow me to just say that we biologists, too, find it unacceptable that physicists, based on a simple model of the earth, extrapolate to a definite age with such self-confidence. The age of the earth could be orders of magnitude higher than the 100 million years the physicists are granting us.

Moderator:
Alright, gentlemen. We don't want to come to an early impasse in this panel discussion. I urge you to come to a friendly position where we can 'agree to differ', so that we can go on. Let's go back to the early physics. How far then can we go with these laws?

Sir William:
We can go quite far. Using the law of conservation of energy and the mathematics of Fourier I have shown that, assuming a wide variation in the values of the physical properties of the Earth. the most likely value is about 100 million years. As to the sun, we can now go both backwards and forwards in the sun's history, upon the principles of Newton and Joule. My calculations of the age of the Sun agree well with those of Professor Helmholtz.

Helmholtz:
It is a good thing that there are two physicists here tonight to protect our emerging science against the mighty opposition of geology and biology. I am convinced that the earth is very old and that it has been cooling for many millions of years. However, I am not sure I understand how it is possible that the surface temperature of the earth has remained more or less constant, as Sir William's claims.

Leaving that problem behind for the moment let me go to the blackboard and discuss something very fundamental.

H Goes to the BB and draws carefully diagrams to illustrate his arguments.

A simple calculation that young students can do shows that if the Sun were made of coal its life expectancy would be less than 10,000 years. So chemical energy as the source of the radiation is clearly out. On the other hand, assuming that the Sun is the result of the contraction of gaseous material, I calculated the gravitational potential energy and estimated the Sun to be about 20 million years old.

H shows the formula for the gravitational potential energy. H turns to the audience and points to the formula (H's formula is $E = 3 G M^2/5 R$).

Notice that the potential gravitational energy of the sun is proportional to the square of the mass! So that if you doubled the mass of the sun the potential gravitational energy would be four times as large.

Sir Charles:
That is very impressive. But you have only given us a formula based on a theory. There may be other theories we have not yet considered.

Sir William (*turning to the moderator*):
Allow me to interject at this point. Sir Charles: The formula that Professor Helmholtz has shown us is based on the principles of natural philosophy. We know of no other source of energy, no other viable 'theory'. In the recent edition of your *Principles of Geology*, I was shocked to see that you are still committed to a cyclical view of the solar system. This view is untenable because it violates the law of the conservation of energy.

There is no response from Sir Charles.

Helmholtz:
I just want to mention that Sir William and I agree on the gravitational implosion model. Originally, he proposed another theory to explain the energy of the sun, namely his meteoric theory. Sir William, I believe has now abandoned this idea in favour of my gravitational contraction theory.

Sir William:
Yes. I was first attracted to the meteoric theory because of the enormous kinetic energies of the masses that are pulled in by the large gravity of the sun (about 27 times that of the Earth). It is easy to show that the velocity of escape from the Sun must be about 390 miles per second, or 624 kilometers per second. So, when a one pound mass falling in from space is absorbed by the Sun it gives up 65 billion foot-lbs of energy! I have also shown that in about 6000 years the Sun would be augmented by 1/5000 in mass. Unfortunately, as the consequence of this addition of mass, the period of the Earth would change and we would loose about 3/8 of a year, or about a month and a half since the beginning of the Christian era. But this magnitude of change would have been detected.

Helmholtz:
I am pleased that you have adopted my ideas of gravitational contraction. The mathematics involved in this theory is much simpler than your Fourier analysis required to calculate the cooling of the Earth.

Moderator:
Sir William: perhaps this would be a good time for you to tell us how you calculated the age of the earth. Perhaps we could persuade you go to the BB and explain. But please, only simple mathematics!

SW goes to the BB, turns to the audience ad explains by drawing a graph that shows two curves: the temperature change and the temperature change (gradient) and the temperature of the earth as we descend.

Sir William:
I have sketched a simplified version of the graph that you can find in my paper of 1862: 'On the Secular Cooling of the Earth'. I assumed that after the 'molten globe' (temperature of about 7000 °F) was originally generated by gravitational energy, and argued that it took a relatively short time, probably only a few thousand years, for the surface of the globe to become sufficiently cool to walk on. I also assume that the temperature of the surface has remained approximately what it is today since that time. Moreover, in all parts of the earth a gradually increasing temperature has been found in going deeper. This implies a continual loss of heat by conduction.

SC interrupts.

Sir Charles:
Sir William: I would be interested in knowing what other assumptions you made, the physical properties you used and what values you chose for them. We geologists are interested and do know a little about the physical properties of rocks.

Sir William:
I was about to do that, Sir Charles. I assumed that the earth is mostly a solid and that heat loss is due primarily to conduction. The physical constants that I needed were: the temperature gradient of the surface of the earth, the specific heat of the earth's crust and the thermal conduction coefficient for the crust. I then applied one of Fourier's elementary solutions to the problem of finding at any time the rate of variation of temperature from point to point, and the actual temperature at any point, in a solid extending to infinity in all directions. As I have already said, I assumed that at an initial epoch the temperature had two different constant values, namely 7000 °F everywhere except at the surface where the temperature was just above 0 °F.

Sir William points to his graph on the BB and explains.

Sir Charles:
I would be interested to know the values of these physical constants you used, Sir William.

Sir William:
I estimated an average for the temperature gradient to be 1/50 °F per foot of depth and decided that the thermal conduction coefficient of the earth's crust was 400 BTU/y.ft.°F.

Sir Charles:
These values may be what you call reasonable 'guesses' but they are based on scanty data. In my opinion such values as the thermal conduction coefficient of 400 BTU/y.ft.°F rests on shaky grounds Moreover, it is well known that the rate of increase in temperature with depth varies widely from place to place, ranging between 1/100 °F and 1/15 °F. Finally, we geologists know that the melting temperature of crustal rocks has not been ascertained with any great reliability.

Sir Charles goes to the black board (BB) to explain the geological complexities of the surface of the earth and why geologists believe the earth must be billions of years old.

Then turning to Sir William he concludes:

We don't really know what the conduction is deep in the earth. In fact, the earth may have a considerable part made of molten iron and, if my physics serves me right, then the effect of convection will have to be considered. And then your mathematical analysis based on Fourier's work cannot be applied.

Sir William (*SC remains standing at the BB*):
Yes, I did make a few plausible 'guesses' but these are based on sound scientific thinking! I have discussed these and similar objections in some detail in my article, if you care to re-read it.

I assumed that on the average temperature increases by 1/50 °F for every foot of descent. and that the melting point of crustal materials is between 7000 and 10,000 °F. On the basis of the higher figure, I calculated that the consolidation of the crust may have taken place about 200 million years ago. Using the lower figure I obtained a value of 98 million years.

What is interesting here, Mr. Moderator, is the following: If consolidation had taken place less than 20 million years ago, we should have more heat underground than we actually have; if more than 400 million we should not have as much heat as indicated by the smallest increment of increase with depth.

Sir Charles:
But is it not possible that some of the earth's heat is generated by ongoing chemical reactions and not just the result of residual heat from an original melt? Because if that is so, then your estimate of the age of the earth must be changed in our favour.

Sir William:
Yes, of course. But we must not assume that there are compensating sources of heat in the form of a 'circle of perpetual motion with no discernible beginning or end', as you argued in the first edition of your *Principles of Geology*.

Sir Charles:
I can now see in retrospect that the mechanism I proposed to account for the internal heat of the earth violated the laws of thermodynamics. But, remember, these laws were not formulated until about 20 years after the publication of my book. I would like to remind Sir William, that we geologists are as much interested in explaining the operations of the Earth in terms of ascertainable laws as the physicists are. We too have developed quantitative methods that I think are just as reliable as those of physics.

Moderator:
I think it is time to redirect this debate. Sir William, you have invested much personal energy and time in developing your model to calculate the age of the sun and the earth. I suspect that the source of this energy goes beyond the academic pursuit of physics.

Sir William:
Of course. I remember my friend Joule writing a letter to me early in 1861. Referring to the biologists he said: 'I am glad you feel disposed to expose some of the rubbish which has been thrust on the public lately'. I responded very positively. Unfortunately, I was unable to present my calculations to the meeting of the British Association in Manchester in September 1861, because of a serious leg injury. This is unfortunate, because in the previous year at this meeting at Oxford, Bishop Wilberforce and Thomas Huxley engaged in their celebrated debate. You do remember, Huxley?

Huxley:
I do remember very well. I am afraid, though, a similar public debate about the age of the earth would not have been possible, even if you had been able to attend. The issues at that meeting were clearer and more comprehensible by the public. I am convinced that as soon as mathematics is introduced into the argument as being decisive, we naturalists, not unlike the general literate public, must defer to the physicist.

Sir William:
But to answer your question, Mr. Moderator, I do admit that my intention in tackling this enormous problem was much more than just to correct what I saw as false assumption in Darwin's text. I sought ultimately to undermine both Darwinian natural selection as well as Sir Charles' totally unacceptable perspective on geological time.

Sir Charles:
Sir William, let me briefly go back to your statement that your figures and Professor Helmholtz's agree that the Sun is about 20 million years old. How can the Earth be 100 million years old and the Sun only 20 million?

Sir William (*seeming a little annoyed but then turning to SC*):
I thought I already explained that. I also discussed this apparent discrepancy in a paper about ten years ago. Depending on what assumptions you make about the energy radiated by the early contracting Sun, you can set limits to the age of the Sun. So I concluded then that the Sun could be as young as young as 20 million years (as Professor Helmholtz calculated) and as old 500 million years. I still stand by this range, but emphasizing that 500 million years is the definitely the upper limit.

Sir Charles:
So why were you so single-mindedly against very long time periods? You stated clearly that the laws of physics allowed for a time of 100 million years for the Earth and as much as 500 million for the Sun, then why not 1000 million years?

Sir William:
I could not accept the idea of natural selection as being able to account for the origin of life, because it would require far more time for its operation than the laws of physics would allow. And, besides, its emphasis on chance did not allow for design. However, most people misunderstand the import of my calculations. I am less concerned with the exact age of the sun or the earth than with the rescuing of geological theory violating the established laws of physics. I only wanted to set limits demanded by the laws of physics.

Huxley:
Do you then reject the idea of evolution?

Sir William:
I am not opposed to evolution, but I am against natural selection because it leaves no room for the operation of design or a divine order in the evolution of life. For me design is just as much a principle of nature as the laws of thermodynamics. The idea of design and scientific laws go hand in hand.

Moderator:
Perhaps Herr Professor von Helmholtz can say a little more about that. After all, he was been described by the British mathematician Clifford as 'a physiologist who learned his physics for the sake of his physiology, and mathematics for the sake of his physics, and is now in the first rank of all three'. And he is one of the architects of the final form of the general law of the conservation of energy.

Helmholtz:
Thank you, Mr. Moderator. In my Konigsberg address in 1854, that has been translated into English as 'On the Conservation of Force', I summarized the physical as well as the philosophical reasons that underlie the idea of 'conservation of energy'. In German we use the word Kraft which can be translated either as force or energy. I actually used the expression *lebendige Kraft*, or 'living force'. So we are really talking about conservation of energy, or nature's great universal law that cuts across the disciplines of physics, biology and chemistry. Together with the second law of thermodynamics, that Sir William helped to develop, we know that perpetual motion cannot exist and that the universe will ultimately run down into an inevitable 'heat death'.

We can now confidently calculate the age of the Sun and the Earth. I, too, see these laws as the evidence for a grand design in nature that is missing in Darwin's mechanism of natural selection.

Sir Charles:
It is well known that I am a late convert to evolutionary theory, rejecting it when I wrote my Principles about 40 years ago, albeit after rejecting Lamarckian theory. However, I do now accept Darwinian evolution that to me had long suggested a balanced, self-regulating geological economy as befitted a wise Creator.

Sir William:
Whichever view you champion, Sir Charles, the conclusions drawn must be subordinated to the laws of physics.

Sir Charles:
We do pay attention to the demands of the laws of physics. Although we geologists are not well tutored in modem mathematical methods of physics we have been trying to use more quantitative approaches. And that is why we shifted our estimate of the age of the earth from an 'indefinitely long' to a definite period of over 1000 million years.

Sir William:
Are you referring to Charles Darwin's gratuitous insertion into the *Origins of Species* of the estimate of the time for the 'denudation of the Weald'? That was a very amateurish attempt at using quantitative methods in geology that even geologists found unacceptable. And Darwin, of course, was wrong!

Huxley:
Let's be fair here. It was simply his way of admitting that the time involved in evolution may have been limited. Darwin later entertained the idea that a good estimate may be obtained by using the methods and the laws of science but he could never accept the high-handed and arrogant way a time limit was imposed by the physicists on the geologists and biologists.

Darwin later regretted having included this calculation in his book because it gave Sir William fodder for his cannon, and he expunged it in a later edition of the *Origins*.

Sir William:
Gentlemen: at the risk of being high-handed I want to say that biology takes her time from geology. If the geological clock is wrong, all the naturalist has to do is to modify his notions of the rapidity of change accordingly. Since James Hutton introduced the idea of uniformitarianism about eighty years ago, it has become British 'popular geology' and most geologists seem to be still strict uniformitarians.

Huxley:
I do not agree with you, Sir William. Catastrophism still claims many able adherents among us. I suspect that you expected me to defend uniformitarianism. Instead of doing that, I will suggest

that there are good reasons for eliminating the weaknesses while preserving the strengths of both, catastrophism and uniformitarianism. We could use a new approach that I have recently described and dubbed Evolutionism, that would allow for catastrophes in a natural but not a supernatural sense. By that I mean that the biblical story of the flood cannot be counted. And if necessary, it could even accommodate the severely limited timescale of Sir William's.

Sir William:
Again, let me reiterate: I will endorse your idea of Evolutionism only if in pursuing this approach you do not violate the laws of thermodynamics.

Moderator:
I see Professor Huxley is ready to respond. Before he does, however, let me summarize. All of us seem to agree that the laws of physics and those of geology must ultimately work together in setting a time for the age of the earth. Unfortunately, the physicists are unmovable in pushing the upper limit of the age of the earth beyond about 100 million years. The geologists and the biologists, on the other hand, are convinced that their evidence is clear: the time must be much longer, maybe 10 or even 100 times longer. It seems to me a consensus could be reached if we examined the assumptions underlying our calculations.

Huxley:
Sir William, it is just possible that your assumptions of initial temperature, the average thermal conductivity of the earth material, heat of fusion, the temperature gradient, specific heat etc., could be wrong?

Sir William:
I do not think so. We have actually already discussed this. I made allowances for a wide range of values for all of those assumptions, if you care to refer to my paper of 1862. The upper limit of 100 million years is firm. I am, of course, convinced that even 400 million years would not satisfy the demands of the uniformitarians!

Helmholtz:
As a physicist I, too, would question some of Sir William's' assumptions but as a mathematician I do agree with his solutions. Clearly, if we grant the correctness of his assumptions his conclusions must be right. It is crucial, therefore that we examine his assumptions.

Huxley:
Thank you Professor von Helmholtz for your support. I think mathematics may be compared to a mill of exquisite workmanship, which grinds you stuff of any degree of fineness; but, nevertheless, what you get out depends on what you put in: and as the grandest mill in the world will not extract wheat -flower from peascod, so pages of formulae will not get a definite result out of loose data.

Sir Charles:
Hear, hear, Huxley! The fascinating impressiveness of rigorous mathematics, with its atmosphere and precision and elegance, should not blind us to the defects of the premises that condition the whole process. There is perhaps no beguilement more insidious and dangerous than an elaborate and mathematical process built upon unfortified premises.

Moderator:
Thank you, Professor Huxley, Professor von Helmholtz, Sir William and Sir Charles for this informative and very entertaining debate. We hope that this debate will contribute to a more amicable co-existence between physics, biology and geology in the future and lead to a reevaluation of the assumptions made in calculating the age of the earth for each discipline. Perhaps physicists will even

consider the possibility of a hitherto undiscovered source of energy that will be able to satisfy the requirements of all three, physics, geology and biology. Using your own word, Sir William, 'the storehouse of creation' may contain other forms of energy not even dreamt of by physicists.

Everyone nods in agreement, except SW.

Helmholtz:
I agree with you Mr. Moderator. I think we have to keep an open mind about both the limits of the presently known laws of physics and how we apply those limits and have an open mind toward the possibility of discovering new energy sources in what Sir William has so aptly called 'the storehouse of creation'.

Everyone responds by nodding with agreement, except SW.
Professor Huxley is indicating that he wants to say something.

Moderator:
Professor Huxley: You may have the last word.

Huxley:
As an agnostic I may be permitted to make a theological reference for the sake of levity and thus ensure that this will be the last word on this weighty subject. If my good friend bishop Wilberforce were here tonight, he would have surely reminded us of one of his favourite quotes by St. Augustine: 'Ask not how the heavens go but rather ask how to go to heaven'.

Moderator:
Thank you Professor Huxley for that memorable ecclesiastic utterance.

Thanks to the audience.

Concluding Remarks by Moderator (Postlude)

By the end of the century the methods geologists used to determine the age of the earth, based on sedimentation rates, reached a sophisticated level. The turning point came around 1903, when George Darwin, the second son of Charles Darwin and an eminent theoretical astronomer, after a talk with the young Ernest Rutherford, made some simple calculations based on the new energy source of radioactivity and published them in *Nature*. Geologists and biologists quickly sensed the liberating possibility of 'very long times' and George Darwin saw the vindication of his father's theory of evolution. However, it was not until 1926 that a consensus was finally reached between the disciplines of physics, geology and biology and all agreed that radioactivity provided the only reliable geological time scale.

The discovery of radioactivity had two dramatic effects on the age of the earth debate. First, it quickly became clear that since radioactive sources were found everywhere, including deep in the crust of the earth, the heat budget of the earth could not be reliably estimated. Secondly, by about 1910 the new methods of radioactive dating held the promise of finding a reliable way to determine the age of the earth. These were successfully pursued by the English geologist Arthur Holmes and written up in his *Age of the Earth* (1913) (see Lewis 2000).

The arguments for and against the sun being powered by radioactive energy continued but by the 1920s the problem of the sun's energy was overshadowed by the problem of finding reliable methods for dating the earth and accounting for the heat energy observed coming from the earth.

If the sun is not a chemical or radioactive furnace then what drives this mighty source of constant energy flow? By the late 1930's it became clear that the sun does not burn coal but hydrogen in a nuclear furnace and not in a chemical or atomic one. The German-American physicist Hans Bethe was the first to describe this process that we call thermonuclear or fusion. We now have very reliable evidence that the earth is 4.5 billion years old an that the sun will provide energy for another 5 billion years.

Questions from the Audience.

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