On the Nature of Science

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March 31, 2022

Abstract

A 21st century view of the nature of science is presented. It attempts to show how a consistent description of science and scientific progress can be given. Science advances through a sequence of models with progressively greater predictive power. The philosophical and metaphysical implications of the models change in unpredictable ways as the predictive power increases. The view of science arrived at is one based on instrumentalism. Philosophical realism can only be recovered by a subtle use of Occam’s razor. Error control is seen to be essential to scientific progress. The nature of the difference between science and religion is explored.

1 Introduction

The idea that empirical knowledge, i.e. knowledge obtained through observations, is unreliable has a long history going back to the ancient Greeks. They were very good at philosophy and mathematics but made rather little progress in the empirical sciences. Aristotle’s philosophy is still studied but most people do not know that there is an Aristotelian physics let alone what it is. The modern study of physics or indeed of science goes back rather to Galileo and Newton with an honorable mention to Francis Bacon for his formulation of scientific induction[1]. This development continued up to Einstein’s 1905 papers. The 1900 understanding of science is nicely described in “A pilgrimage to Popper” by Adam Gopnik in The New Yorker[2].

Scientists, it seemed clear, began with careful observations, cautiously proceeded to a tentative hypothesis, progressed to more secure but still provisional theories, and only in the end achieved, after a long process of verification, the security of permanent laws. Newton saw the apple fall, hypothesized that it had fallen at one speed rather than another for a reason, theorized that there might be an attraction between all bodies with mass, and then, at long last, arrived at a law of gravitation to explain everything. This “observation up” or “apple down” picture of how science works was so widespread

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that it defined what we mean by science: when Sherlock Holmes says that
he never theorizes in advance of the facts, he is explaining why he can be
called a scientific detective. Various thinkers poked holes in this picture, but
generally their point was that, while the program was right, it was harder to
do than it appeared.

The problem with this description of science was pointed out by David Hume (1711-1776); namely that it was impossible to deduce from a finite series of observations a
generalization that applies to all. For example, I have seen many crows. All of them
are black. Does this make the statement “All crows are black.” a fact? Indeed not,
there may still be white crows. I have read that albino crows exist but have never seen
one. While others noted Hume’s objection it was regarded as something to disprove.
Furthermore, they noted it was the job of philosophy to explain what was wrong with
Hume’s argument. Kant’s “Critique of Pure Reason” was, in part, a response to Hume.
Einstein’s 1905 papers which showed the shortcomings of classical mechanics also made
Hume’s arguments much more immediate and highlighted problems in Kant’s response.
Despite the great success and great predictive power of classical mechanics it was shown
to have a limited region of validity. The vast number of observations that confirmed
classical mechanics did not prove it universally correct. Indeed, as Hume stressed, no
number of observations can prove a model correct.

A new understanding of science and how it worked was needed. A major contribution
to this new understanding was made by Sir Karl Popper. His first point was that
all empirical knowledge, scientific models, and scientific laws are only tentative. It is
impossible to scientifically prove anything. It is impossible to empirically establish any
fact. This is actually a slight over statement; there are three empirical facts. Descartes
in his “Meditation 2” has the famous statement “I think, therefore I am” or in Latin,
“cogito ergo sum”. Thus we have the two facts: “I think” and its corollary “I am”. I
would add “I observe” to this list of facts (sum, cogito, inspecto). Beyond that everything
depends on assumptions that can not be rigorously proven.

Popper’s second point was that although models could not be verified they could
be falsified. Actually the idea of using false predictions as a filter has a long history,
much predating Popper or even the scientific revolution. Deuteronomy 18:21-22 says
false prophets can be distinguished because their predictions do not come true. The
basic idea of falsification of models is this: While seeing any number of black crows does
not prove all crows are black, seeing one white crow disproves it. Thus science proceeds
not by proving models correct but by discarding false ones or improving incomplete ones.
While the concept of falsification is widely used in science it is also not straightforward.
Is that white bird I see really a crow? Have I misidentified a pigeon or is it an altogether
new species? The problem is that no theory or model exists in isolation but is always
supported by subsidiary theories and models. Thus any test is not just of one model but
of all the subsidiary ones simultaneously. This has led to claims that theories are not
even falsifiable. In turn this leads to the postmodern idea that all theories or models are
equally valid. Thus we have returned to where we have started with empirically derived
knowledge in dispute.
In the next section I will present a post-postmodern view; namely that Popper is essentially correct but with predictive power replacing naive falsification. The distinguishing feature of any scientific model is that it must make predictions that can be tested against careful reproducible observations.

2 The Scientific Method

2.1 Observations

How do we get around the problem of Descartes or Hume’s skepticism? To a large extent we can not: except for the three facts mentioned above all empirical knowledge is tentative. Following Popper, we can make a model and see how well it describes past observations and predicts future observations. The fundamental idea of model building (hypothesizing) and testing against observation actually goes back much farther, at least to 1267 and Roger Bacon’s *Opus majus*. It even predates the idea of scientific induction. The first model assumption we have to make is that it is interesting or useful to study the information our senses provide *i.e.* observations. It is not necessary to assume the sensory information corresponds to an objective reality only that the studying of it is interesting or useful.

That observations should be studied, although widely ingrained in Western thought, is a relatively new idea. The clash between Galileo and the church was primarily one between received wisdom based on the Bible and Aristotle versus observations, especially those through the telescope. Sunspots, the phases of Venus, mountains and valleys on the moon, and the moons of Jupiter all challenged the received wisdom of the perfect unchanging heavens with the earth at its center. The ultimate question was which do you believe: your eyes or the sacred texts as interpreted by the religious authorities. The wisdom of the time was that observations were inherently untrustworthy *i.e.* you should not trust your eyes but rather the authorities. Ultimately the scientific method, which is being considered here, allows useful information to be extracted from observations.

Observations are any sensory input. At the simplest level they are direct sensory input. At the next level we use instruments to augment our senses, for example Galileo’s telescope. However, observations are not just the passive observation of what nature presents to us. We also do controlled experiments that actively manipulate nature in order to isolate different effects and test specific aspects of the models. The experiments are designed to maximize the information that can be obtained while eliminating uninteresting and spurious effects. An extreme example is the ATLAS detector at the Large Hadron Collider (CERN, Geneva, Switzerland) which is about the size of a five story building and involves approximately 1500 physicists from 36 countries. As the instrument gets larger and more complex the observations become more model dependent. A model of the apparatus is needed or even models of parts of the apparatus. However, even when the apparatus is as simple as Galileo’s telescope, a model is needed to understand its behavior. One of the attacks against Galileo was that he was seeing an artifact of the telescope. Thus we have the idea that observations are not freestanding but take on their meaning within the context of a model or models.
2.2 Models

Having briefly considered what an observation is we now turn in more detail to defining the concept of a model. A model is any theoretical construct used to describe or predict observations. Thus classical mechanics, evolution, special creation, and road maps are models in the present sense of the word. To be science, a model must be internally consistent and logical. The word model has been chosen following the practice in subatomic physics with “the standard model of particle physics” or “the shell model”. It implies that the model is not reality but, at best, an image of it.

Consider a road map. It is a very simple example of a model. It provides predictions about where the streets are and what their names are. Thus we encounter Vine Street, Yew Street and Arbutus Street when we drive down 16th Avenue; the same as the map tells us (See maps.google.ca for Vancouver, BC, Canada). Now just because the street sign does not agree with the map does not mean the map is wrong — the street sign could be incorrect. This illustrates the problem with naive falsification. There are two models in play, one the map and the other that the street sign correctly identifies the street. While normally the street sign is correct, city work crews have been known to make mistakes. Or part of the sign has been destroyed so “Vine Street” becomes “ne Street”. The map and street signs could also be in different languages. Thus one observation, the name on the street sign, does not necessarily indicate that the map is incorrect. However if the map consistently has the wrong names and streets in the wrong place, it is not useful. The map must have predictive power to be useful.

A much more sophisticated example of a model is Kuhn’s paradigm. A paradigm is the set of interlocking assumptions and methodologies that define a field of study. It provides the foundation for all work in the field and a common language for discourse. While observations exist independant of the paradigm, their interpretation depends on the paradigm. No natural history or any set observation can be interpreted or even usefully discussed in the absence of the intertwined theoretical and methodological system provided by a paradigm. Paradigms help scientific communities to bound their discipline and create avenues of inquiry. They determine which are the important question to be considered (for examples see the discussion in Sec. 4 on the shape of the earth). Students and new practitioners learn the paradigm in order to become effective members of the community. The paradigm can also act to prevent progress when members of a community are too committed to their current set of models. Hence outsiders, like Wegener who proposed continental drift, are sometimes at an advantage in seeing past the current models to propose striking new approaches. However, scientific progress cannot take place without the framework provided by a model or paradigm.

A theory, defined by the American Heritage Dictionary as “Systematically organized knowledge applicable in a relatively wide variety of circumstances, especially a system of assumptions accepted principles, and rules of procedure devised to analyze, predict, or otherwise explain the nature or behavior of a specified set of phenomena”, is another example of the model concept. A theory is closely related to Kuhn’s paradigm but more restrictive, not covering methodologies. The special theory of relativity or the theory of evolution are models in the current sense of the word. The word theory has an unfortunate alternate meaning of hunch or conjecture so even well supported theories
like special relativity or evolution tend to be tainted by the use of the word. As an example of this see the Answer to the Complaint in the Kitzmiller v. Dover Area School District court case on the role of evolution in the classroom where it is stated that the “Defendants deny that the term theory, as used in science, has a distinct meaning and does not suggest uncertainty, doubt or speculation.” When speaking to people with such a limited understanding, the term “theory” should be avoided to reduce confusion. It is partly for this reason that the present work uses the term “model”.

Hooke’s Law on the force required to stretch or compress a spring, Boyle’s Law on relation between the pressure and volume of an ideal gas, or the OZI rule on the decay properties of hyperons are also examples of models but with a more limited scope than either theories or paradigms.

Historically there was a change in the nature of scientific models with Newton. Ptolemy, Copernicus and Newton all developed models that correctly predicted planetary motion. While it is sometimes claimed that the Ptolemaic and Copernican models were only descriptive in contrast to Newton’s which was explanatory, it is more precise to say that Newton introduced a higher level of abstraction using ideas farther removed from the observations. He used the concept of force, universal gravitation and his laws of motion while Ptolemy and Copernicus just worked with the positions of the planets. The abstraction level in physics increased significantly farther with Maxwell’s equations for electromagnetism and with the development of statistical mechanics. The ether was an attempt to make the rather abstract Maxwell’s equations more concrete. When first introduced molecules, essential in understanding chemistry and statistical mechanics, were also a very abstract concept and, like quarks, they were considered to be just a convenient theoretical construct. They were rejected by many scientists including Mach. This rejection was probably a contributing factor in Boltzmann’s suicide. Quantum mechanics and quantum field theory are progressively more abstract. The many worlds interpretation of quantum mechanics (discussed in sec. 5) is an attempt to make the very abstract concepts in quantum mechanics more concrete. Like Newton in physics, Darwin increased the level of abstraction in biology with the idea of evolution and especially natural selection. Even his idea of heredity was rather abstract for the time. Error control and estimation also involves rather abstract concepts. An increase in the level of abstraction is common when science advances. This has the twin effects of making the models more powerful but also less comprehensible.

N.T. Wright in his defense of the historicity of Jesus against post-modernism uses the term “explanatory story”. This is largely synonymous with model. “Explanatory story” also has a similar connotation to Kuhn’s paradigm although in that case “controlling narrative” might be a better terminology. If you replace “explanatory story” with “model”, Wright’s description of extracting information from the historical record is essentially the same as the approach to scientific model building given here (see in particular the last paragraph on page 37). In his case the “observations” are historical records including the Bible. However, the approach in the present work leads to instrumentalism rather than the critical realism Wright advocates.

While in order to be useful in science a model must be logical and internally consistent it does not have to be “reasonable”. When there is major change of models, what Kuhn would call a paradigm shift, the new model is, by definition, unreasonable or
even aberrant in the context of the old model. For example, the action at a distance in Newton’s law of gravity was considered unreasonable by Leibniz, Huygens and even Newton himself. Similarly, several of the founders of quantum mechanics — Planck, Bohr, Schrödinger, Einstein — considered quantum mechanics unreasonable. Planck apologized for Einstein taking his quantum idea seriously. Niels Bohr said\textsuperscript{13} “Anyone who is not shocked by quantum theory has not understood a single word.”. Erwin Schrödinger said\textsuperscript{14} “If we are going to stick to this damned quantum-jumping, then I regret that I ever had anything to do with quantum theory.” Einstein was a critic of quantum theory and his most cited paper\textsuperscript{15} was an attempt to show that quantum mechanics must be incomplete. It introduced what is now known as the Einstein, Podolsky, Rosen (EPR) paradox and quantum entanglement. Unfortunately for Einstein, observations agree with quantum mechanics and it is reality that is unreasonable. The theory of continental drift first proposed by Alfred Wegener in 1915\textsuperscript{7} was rejected as unreasonable — indeed it was. How could continents plow through the oceans? It was not until the model of plate tectonics was developed in the 1960’s that continental drift was accepted. The idea in evolution that complex structures and interdependencies can arise through natural selection is regarded by many as unreasonable. String theory, the currently proposed model of everything, is unreasonable with at least eleven dimensions instead of the perceived four. However, it is predictive power not reasonableness that is the final arbiter in science. Even very unreasonable models, like Newtonian gravity, quantum mechanics, continental drift, evolution or string theory, must be accepted \textit{if but only if} they correctly predict observations. Simply because a model is unreasonable does not mean it is correct. Most unreasonable models are simply that — unreasonable.

Finally in the discussion of models I quote\textsuperscript{16,13} Niels Bohr again: “There is no quantum world. There is only an abstract physical description. It is wrong to think that the task of physics is to find out how nature is. Physics concerns what we can say about nature.” Models are what we can say about nature and are the essence of science.

2.3 Predictive Power

We now have some idea of what is meant by observations and models. Next we turn to the idea of falsification stressed by Popper. Popper’s basic idea is correct, models cannot be proven but still can be tested by comparison with observations. However, rather than strict falsification we judge a model by its predictive power. Popper recognized that models which made more predictions were also more easily falsified by having some of the prediction proven incorrect. In spite of this, such models are preferred as having more information content. This is moving in the direction of predictive power. Predictive power simply refers to the ability of a model to describe past observations and especially predict new ones. The greater the ability to make correct predictions and not make false ones the greater its predictive power. In some cases the predictive power is quantitative as in $\chi^2$ fits to data but frequently it is more qualitative. However, the more precise the prediction the better. The new predictions must be made without additional assumptions. In general what is important is the number of predictions for a given number of assumptions. Increasing the number of assumptions should only be done if there is a significant increase in the number of correct predictions that can be made. Although models can not be
Older theories are falsified, or to be more precise, they are shown to have a limited range of validity usually by a series of observations. The Michelson-Morley experiment on the speed of light in moving frames and experiments on atomic structure were inconsistent with the predictions of classical mechanics. This led respectively to special relativity and quantum mechanics. The models that replaced classical mechanics had greater predictive power, keeping the success of the previous models while also describing the new observations. Special Relativity has more predictive power than classical mechanics describing both slowly and quickly moving objects. Quantum mechanics replaced Newton’s Laws because of its greater predictive power — it described microscopic as well as macroscopic systems. Following the Correspondence Principle as stated by Niels Bohr, quantum mechanics must reduce to and indeed does reduce to classical mechanics in those instances when classical mechanics provides a good description of the observations. Evolution replaced animals reproducing after their kind because it has more predictive power. It makes correct predictions about fossils and the distribution of species that are outside the scope of the animals-reproducing-after-their-kind model.

A single false prediction usually does not doom a model. Like the example given above with the road map, where the road sign was wrong not the map, the problem may be with the observation. When a model disagrees with an observation something has been falsified, it is just not clear what. It could be the model (the map), the observation (the street sign wrong or incorrectly read) or the model misapplied (we are on 41st Avenue not 16th). The model may also need to be slightly modified (a street added since the map was made) to accommodate the new finding. However if separate modifications for a wide of range of new observation are needed the model loses its ability to predict and must be improved or rejected.

A prime example of one experiment (actually a series of experiments by the same person) not being sufficient to falsify a model is the Dayton Miller followup to the Michelson-Morley experiment. Miller, in a series of experiments, found an effect on the speed of light due to the earth’s motion. If accepted this would have falsified special relativity. While this experiment was widely discussed at the time, Einstein largely dismissed it. In the end it was the Michelson-Morley experimental result that could be reproduced not the Miller result. Experimental results must be reproducible to be useful. As discussed in the next section most exciting new results are wrong. It was the Michelson-Morley experiment not the Miller experiment that was the exception to this rule. Models frequently provide useful insight into which results will be reproduced and which will not. Einstein’s faith in special relativity turned out to be justified.

In some cases naive falsification does work and models are abandoned. For, example the minimal $SU(5)$ grand unified theory in particle physics was abandoned because the proton did not decay as predicted. On the other hand, the quark model of hadron structure was accepted because of the discovery of the $J/\psi$ particle. The confirmation of a striking prediction gives a model significant credibility and is the surest route to get a model accepted. Thus, the discovery of the three degree Kelvin microwave background led to the acceptance of the big bang model of the universe. The alternate models were not falsified so much as the new models, the quark model or big bang model, shown to have superior predictive power. These models were not developed by scientific induction,
which Hume showed does not really exist, but rather were tested by observation and survived.

Predictive power is related to testability. To be science, models must make predictions that can be tested against future observations. It is the predictions that are falsifiable rather than the models. Describing past observations (sometimes referred to as postdictions or retrodictions) is necessary but not sufficient. It is easy to describe past observations. For example: Why is the sky blue? Why is the mass of the proton $1.6726 \times 10^{-27}$ kg? Why is the mass of the electron $9.10938188 \times 10^{-31}$ kg? Answer: Because God (or whoever) made it that way. While this may be true and can account for all observation it is completely lacking in predictive power and suggests no new research directions. It is not science but rather the end of science.

While we have discussed how models are tested we have not discussed how models are constructed. These are two very different procedures both logically and practically. The testing is done through comparison with observations. But before the testing we need a model to test. The pre-1905 view was that models were inductively deduced from experiment. The “apple down” approach quoted from Gopnik. In this view the creation and testing were inextricable linked together with the model deduced from the observations through induction. This is not correct. Rather model construction is a creative activity — as creative as anything in literature or the fine arts. There is no algorithm saying how to go from observations to a model. A falling apple inspired Newton, rising water in a bath inspired Archimedes, a dream inspired Kekulé (the structure of benzene). Or at least that is how the stories go. For model construction, Feyerabend is correct, anything goes — dreams, divine inspiration, pure luck, or even hard work. General relativity, inspired by the equivalence between inertial and gravitation mass, was largely due to Einstein’s creative genius and his concept of elegance. However, it is the testing of models that separates science from other human endeavors. Regardless of how the model is constructed or how elegant it is, to be science, it must be tested against careful reproducible observations.

3 To Err is Human, to Control Errors, Science

The first thing one learns in trying to gain knowledge through observation is that it is easy to make mistakes. Thus much of the day to day work of a scientist is error control. In first year university physics courses you are taught that a measurement consists of the measured number plus an estimate of the error; the so called error bar. In science, a measurement without an error estimate is mostly useless.

Most exciting new results are wrong — canals on Mars, Prof. Blondot’s n-rays, polywater, the 17 kev neutrino, cold fusion, superheavy element 114 and penta-quarks. The list goes on and on. Occasionally one survives like the $J/\psi$ discovery in particle physics. The ones that survive become well known, everyone quotes Galileo (1564 - 1642), while the ones that are wrong, like Prof. Blondot, are forgotten. All physicists know about Michelson and Morley, very few about Dayton Miller. Thus there is a popular misconception about scientists being unduly harsh on new ideas and unexpected results. Science is justifiably leery of accepting new unexpected results. The degree of fit
with existing models is a valuable, but not decisive, criterion in judging new results. The weight of evidence for an extraordinary claim must be proportioned to its strangeness. Unlike in the justice system, unexpected new results are assumed “guilty” until “proven” innocent. It is up to the proponents of the new result to convince the rest of the community that the results are correct. It is not up to the rest of the community to show the new results are wrong. Since there are many more ways, an uncountable infinity of them, to do an experiment wrong than to do it correctly, one has to be very critical of new results, especially unexpected ones. It is very easy to fool oneself. Prof. Blondot’s “discovery” of n-rays is an archetypal example of self delusion. From the examples given, it might seem that error control is mainly important for observations. This is not true. Errors can also occur in the construction and use of models. Models can be internally inconsistent or their predictions may be incorrectly calculated.

So how is error controlled? First, observations and model testing must be done carefully with attention at every step to the possibility of error. One of the hallmarks of science as compared to pseudo-science (see ref. 29 for a discussion of pseudo or pathological science) is the concern taken to control errors — double blind clinical trials in medicine, blind analysis in physics for example. The most important discovery of modern medicine is not vaccines or antibiotics, it is the randomized double-blind test, by means of which we know what works and what doesn’t (quoted from ref. 30). Strict error control on both observations and models is necessary to prevent science from being overrun with bogus results. Alternate medicine proponents, for example, do not seem to pay enough attention to error control.

Secondly, results must be independently reproducible. Different independent scientist must be able to reproduce the results. To be reproduced, the results must be made known and made known in sufficient detail that others can understand how to repeat the procedure. The experience is that results that can not be repeated are probably wrong. An unexpected result can be due to error or in some cases outright fraud. Occasionally it may be correct. Repeatable observations, even unexpected ones, are probably correct. Independent replication is a strong line of defense against both error and fraud. In some cases independent replication is difficult or nearly impossible. For example, high energy physics experiments are very expensive and even nominally independent experiments share common features like the inputs to Monte Carlo computer simulations. In this case even greater care must be taken. In medicine, there is the additional problem of the trade off between additional tests and not immediately implementing a new treatment that may save lives.

Repetition is not doing exactly the same experiment again and again. Rather, the subsequent experiments should be as different as possible to eliminate common sources of error. The first experiment is usually the most difficult. It identifies an interesting effect and says where to look to find it again. The second experiment can then use this information to refine the technique. Consider again the Michelson-Morley interferometry experiment. The following summary is taken from ref. 31. The initial experiment was done in 1881 by Michelson. The limit on the shift in the interference line he obtained was half that expected based on the ether model. The famous Michelson-Morley experiment in 1887 had reduced that to 0.025 of the predicted shift. An experiment in 1930 by Joos reduced that to 0.0027 of the predicted shift. Dayton Miller in 1926 was claiming an
effect of 0.077, much larger than Joos but still much less than expected from a simple application of the ether model. Ignoring Miller for the moment, we have over fifty years an improvement of over two order of magnitude. Modern experiments with lasers have reduced this an additional sixteen orders of magnitude. Thus we see the initial experiment repeated over time, with different techniques, and dramatically improved. The Miller result is an anomaly but not an unique one. In any sequence of measurements it is usual for one or two to be wrong by more than expected from the quoted error. In difficult experiments it is easy to make mistakes. The subsequent, much more accurate measurements, make the Miller results only an historical curiosity. It is not necessary to explain exactly what the error was. However, ref. 31 does suggests thermal gradients are at least partly to blame. Again we stress the role of repeatability to establish experimental or indeed any results. In science, as this example illustrates, the observations become more accurate over time as the experiments improve. A sure sign of pathological science or pseudo-science is when the signal does not improve but stays at the barely detectable limit as the experiment is improved.

Reproducibility does not mean science cannot study historical events because the event cannot be reproduced. When a plane crashes, it is possible to use science to learn what caused the crash without waiting for future crashes. Rather one models the crash and tests predictions of the model against observations of the properties of similar the planes and the materials making them up and also against observations of the debris from the crash. Other historical events can be studied similarly. In the case of evolution one studies modern biological and ecological systems and the “debris” in the form of fossils and the present distribution of species. Thus evolution is tested by comparing its predictions against observations of these.

Next for error control is peer review. This is a simple concept. The people who know about a topic are peers of the person who did the original experiment and they look to see if there are any errors. It is only the peers who would have the knowledge to spot errors. The first line of peer review is the informal discussions a scientists has with his colleagues. Many errors are caught at this stage. The second line of peer review comes from the anonymous reviewers who act as gate keepers for scientific journals. Third is the review a paper receives after it has been published. The first and third types of peer review are much more important than the second. Important papers are probably correct, not because the author is infallible, but because many people have independently checked the results and looked very hard for errors. It is only after this independent checking that a paper should be assumed correct. Unimportant or less studied papers probably lack the third level of review and should be treated more suspiciously. The third type of peer review can take place without the second or even the first. This happens to papers that appear on the web archives (lanl.arxiv.org for example) with critical papers commenting on them appearing before the first paper is formally published. This is quite valid and very important peer review.

Secrecy and intellectual property rights when they lead to secrecy are the enemies of scientific progress since science depends on the sharing and checking of results for error control. Two heads are definitely better than one. Without the independent checking, errors last for a long time — especially when there is an economic gain from keeping the error hidden.
The peer review process also works in software development. The Free (free as in speech not beer) Software and the Open Software Movements encourage a peer review process for software development. Program source code is made widely available usually on the world wide web. People can then build on the work of others. It was discovered that many eyes looking at programs found and fixed errors faster than in other approaches. The internet protocol, the world wide web, the Apache web server (which powers the majority of web sites in the internet), the Linux kernel and the Fedora operating system, to name a few, are the products of an open development process. This illustrates the power of openness and peer review that is the hallmark of science. “Given enough eyeballs, all bugs are shallow” applies equally to science and software development.

4 The Graveyard of Departed Models

4.1 The Relativity of Wrong

What happens to models that have been disproven? Are they buried somewhere with a large tombstone? No, either they are forgotten or, like the Night of Living Dead, they stay around forever as approximations to more complete models. The latter idea is lucidly presented in an article by Isaac Asimov called “The Relativity of Wrong”. The ideas expressed there are as important as Popper’s, Kuhn’s or even Hume’s in understanding science. The basic concept is that one should not ask if a model is right or wrong but rather how wrong is it. Experimental error bars are the experimentalists’ estimate of how wrong the experimental number might be.

To clarify the relativity of wrong concept, consider the value of $\pi$. A simple approximation is $\pi = 3$ (1 Kings 7:23). This is wrong but by less than 5%. A better approximation is $\pi = 3.14$. The error here is 0.05%. Strictly speaking both values are wrong. However, the second value is less wrong than the first. In computing as a graduate student I used $\pi = 3.141592653589793$. This is still wrong but much less wrong than the previous approximations. There was no sense using a more accurate value of $\pi$ since the computer used only about 15 digits (single precision on a CDC computer). We see that wrong is a relative concept. None of the values of $\pi$ are absolutely correct. That would take an infinite number of digits, so all are wrong. However the initial values are more wrong than the latter values. They all are useful in the appropriate context. The value from Kings probably reflects the accuracy with which the measurements were made.

The same logic applies to models. Consider the flat earth model (see also the discussion in ref. 33). For the person who never travels farther that 100km from his birthplace the flat earth model is quite accurate. The curvature of the earth is too small to be detected. However when the person is a sailor the question of the shape of the earth takes on more urgency. The flat earth model suggests questions like: Where is the edge of the earth? What will happen if I get too close? For the world traveler, the flat earth model is not sufficient. The spherical earth model is more useful, has greater predictive power and suggests a wider range of questions. Questions like: Does the earth rotate?
Does it move around the sun or does the sun move around the earth? But it is a wrong statement that the earth is exactly spherical. Not as wrong as the statement the earth is flat but still wrong. However being not exactly correct does not make it useless. A spherical globe allows a much better understanding of airplane routes than a flat map. But the earth is not a perfect sphere. It is flattened at the poles (a quadrupole deformation). Smaller still is its octapole deformation. The exact shape of earth will never be measured as that would require, like \( \pi \), an infinite number of digits. It would also be useless. What is needed is a description sufficiently accurate for the purpose it is being used for. Science is the art of the appropriate approximation. While the flat earth model is usually spoken of with derision it is still widely used. Flat maps, either in atlases or road maps, use the flat earth model as an approximation to the more complicated shape.

Classical mechanics — Newton’s law of motion and Maxwell equations of electromagnetism — although superseded by relativity and quantum mechanics are still useful and taught. The motion of the earth around the sun is still given by Newton’s laws and classical optics still works. However, quantum mechanics has a much wider realm of reliability. It can describe the properties of the atom and the atomic nucleus where classical mechanics fails completely.

Animals reproducing after their kind is the few generations limit of evolution. Thus over the time scale of few human generations we do not see new kinds arising. The offspring resemble their parents. Evolution keeps the successes of the previous model; cats do not give birth to dogs nor monkeys to people even in evolution. The continuity between animals-reproducing-after-their-kind and evolution is not sufficiently appreciated by the foes of evolution and perhaps not by its proponents either.

The Ptolemaic model with the earth at center of the universe can be considered as an approximation to the Copernican model. In fact a very useful one. When giving directions to the corner store, an earth fixed model is used. The directions in an heliocentric model would be quite complex and ghastly to contemplate. Actually this case is even more subtle. According to the general theory of relativity, the laws of motion can be expressed in any inertial or accelerated frame. Thus the choice between a heliocentric model and an earth-centric one is not a matter of right or wrong but one of convention and convenience. What is a model assumption and what is convention is not always clear. Poincaré, one of the leading mathematical physicists of the late 19th century, claimed\(^{21}\) that much of what is regarded as fact is convention.

There is a general trend: new models reduce to the previous model for a restricted range of observations. Ideally the new model would contain all the successes of the old model, the correspondence principle of quantum mechanics applied more widely, but this is not always the case. A subset of the correct predictions of the previous model may not survive. This loss of predictive power is sometimes called Kuhn loss. But overall the new model must have more predictive power otherwise its adoption is a mistake. Thus we have the view of science producing a successions of models, each less wrong (none are 100% correct) than the one it replaces and we see progress. Science does progress, new models are constructed with greater and greater predictive power. The ultimate aim is to have a model of everything with a strictly limited number of assumptions. This model would describe or predict all possible observations. Quantum indeterminacy suggests that such a model does not exist. However, progress in science is moving closer to this
It is worth considering further science as the art of the appropriate approximation. Exact calculations are never done. Consider calculating what happens when you drop a pencil. You start with Newton’s law of gravity and Newton’s laws of motion. This is a very good approximation. Next you have to consider the effect of the interaction with the air. This may be important on very windy days or for long drops. Then there are the effects of special relativity, general relativity and quantum mechanics. There are also the tidal forces due to the moon, the sun, Mercury, Venus, Mars, Jupiter, Saturn, Neptune, Uranus, Pluto and the asteroids. Even including all this is not sufficient. There is also the gravitational effect of the stars, the cat and the canary. This is clearly ridiculous but so is the idea of an exact calculation. So we do not do an exact calculation. Rather we include only the effects that are large enough to have a noticeable effect on the pencil. Classical mechanics and Newtonian gravity are probably enough although in some cases the air may have an observable effect (the terminal velocity of an object dropped from a great height is due to air resistance). One of the most important things in science is deciding which effects are large enough to have to be taken into account and which can be neglected.

### 4.2 Paradigm Shifts

Kuhn discusses two kinds of science — normal science and extraordinary science. Normal science is puzzle solving within the context of a paradigm while extraordinary science is the overthrowing of the paradigm. The present analysis gives a different view of the distinction although the distinction itself remains useful. In extraordinary science the model being challenged is the main model in the field, the paradigm (or model) which provides the framework for the field. In normal science it is the subsidiary models, those models that in principle could be derived from the main model, that are being tested. Frequently it is only in retrospect that it becomes clear which type of model is under attack. Normal science can often resemble scientific induction with models apparently deduced from observations. This is especially true in cases like the color of crows or Hooke’s Law where a regularity is apparent in the observations. Operationally, scientific induction can be considered an approximation to the more general method of model building and testing. However, the approximation is only useful in a limited range of situations. General relativity or even the structure of benzene can not be considered to have been derived by induction.

When there is a paradigm shift, *i.e.* when the main model in an area of research changes, the new model usually expands the range of observations that can be described. Quantum mechanics describes both microscopic and macroscopic objects. Maxwell’s equations described electricity and magnetism with one model. Special relativity plus quantum mechanics (quantum field theory) describes both mechanics, like Newton’s law and electromagnetism like Maxwell’s equations but over a wider range of energies. While the reproducing-after-their-kind model applies mainly to plant and animal husbandry, evolution also describes fossils and the distribution of species. Basically the old model worked well for a limited range of observations. Paradigm shifts typically occur when the old model is being pushed into a new area that has not been explored before or not
explored in as much detail. The new model must describe both the observations in the regions where the old model worked and in the new regions where it doesn’t.

The picture, just given, is of an orderly progression striving to ultimate perfection. But something else is happening, especially with extraordinary science. Consider the case of Newtonian mechanics replacing Aristotelian mechanics. While a vase slid across the table still came to a stop, hopefully before reaching the edge, the Aristotelian concept of causality broke. Much of the concept of cause and effect was forever altered. Newtonian mechanics, in turn, led to the concept of the clock-work universe. With the advent of quantum mechanics the clock-work analogy no longer applied. The basic understanding of reality changed. The basic understanding of how science progressed also changed. With the advent of special relativity the ether disappeared. From the present viewpoint this looks like a small change but consider the definition of physics given in a 1902 high school physics text book.

"Physics is the science which treats of matter and its motion, and of vibrations in the ether". Thus the very understanding of the nature of physics changed. The kinetic theory of heat destroyed caloric but the Carnot cycle and Carnot’s principle developed on the basis of the caloric model survived. Evolution changed the basic understanding of biology and the relationships among different species including Homo sapiens. Its theological repercussions are still vibrating. The discovery of non-Euclidean geometries and their application in special and general relativity destroyed the Kantian idea that Euclidean geometry is synthetic a priori knowledge and perhaps even the idea that synthetic a priori knowledge is possible.

This change of world view when the main model in a given field of study changes is closely related to Kuhn’s incommensurability (see also Feyerabend). Proponents of the new model and the old model use a different language and different concepts. They have different ideas about what the important questions are. Their whole framework for understanding observations is different. Hence, it may be difficult to compare the old and new models in detail. Despite these dramatic differences, the Ptolemaic system, the Copernican system, Newtonian mechanics, special relativity, quantum mechanics and general relativity can all quite accurately describe Jupiter’s apparent motion through the night sky. If string theory wants to be accepted as the model of everything it too must describe Jupiter’s motion. Thus we have, on the one hand, the previous models continuing to be good approximations to the new models at least for a limited range of observations while, on the other hand, the philosophical and metaphysical implications having a profound and frequently disturbing break. When the main model in an area changes the perception of reality can change in dramatic and unexpected ways. Philosophy and metaphysics based on the current models of science are very precarious and can be rendered obsolete by new and improved models. If the past is any guide, the next great advance in science will change our understanding of the nature of reality and/or the relation of humans to the rest of creation. However, animals will still reproduce after their kind as stated in the book of Genesis and the earth’s motion around the sun will still be accurately described by the model Newton developed in the 17th century. Old models live on as approximations to later models. However, the metaphysics and internal constructs of old models are buried without headstones where only historians can or would want to find them.
5 Scientific Equivalence

In science, models are judged on their ability to describe and predict observations. If two models give the same results for all observations they are scientifically equivalent. In quantum mechanics there is a mathematical technique known as unitary transformations that while making the mathematics quite different leave all predictions of observables the same. Canonical transformations play a similar role in classical mechanics. Observations can not distinguish between such models and it can be argued that equivalent models are not really different.

There are more low brow examples of equivalent models. Consider Last Thursdayism. This is the model that the universe was created last Thursday but in such a way that it is indistinguishable from an old universe. If we had the universe created 6000 years ago rather than last Thursday this is essentially the Omphalos Hypothesis, a 19th century attempt to reconcile geology with the a literal interpretation of the Bible. The light from distant stars, which would not be seen if they just started shining last Thursday, is created in transit. Memories are created in place without referring to actual events. Similarly everything else is created to be indistinguishable from an old universe. Since by construction this model has all the same predictions as the old universe model the two models can not be separated based on observations. The only criteria is simplicity. Last Thursdayism is rejected because it has an additional assumption, namely that the world was created last Thursday. This assumption does not increase the model’s predictive power. While this example is contrived, it is not trivial and does illustrate the point. It is easy to construct equivalent models with rather different content with only simplicity (or prejudice) to use to eliminate them. This use of simplicity is sometimes called Occam’s razor after William of Occam who said “one should not increase, beyond what is necessary, the number of entities required to explain anything”. A modern paraphrase is that there should be no more assumptions than the minimum needed. Since it easy to change the internal properties of a model without changing the predictions great care should taken in attaching meaning to such features of the model.

In addition to full equivalence there is effective equivalence. For example, quantum mechanics and classical mechanics give the same result for planetary orbits to the accuracy of any foreseeable calculation. Thus for planetary orbits the two models are effectively equivalent. For objects moving much less than the speed of light special relativity and classical mechanics are effectively equivalent. For a low number of generations evolution is effectively equivalent to animals reproducing after their kind. More generally when one model provides a good approximation to another model for some range of observation they can be considered effectively equivalent for that range of observations.

The philosophical idea of realism is that behind observations there is an objective reality. The observations are the same whether or not there is an objective reality. Thus models with and without objective reality are scientifically equivalent. The only tool in our tool box to deal with this situation is Occam’s razor or equivalently simplicity. A priori it might seem that the existence of objective reality is just an additional assumption that simplicity says we should eliminate. However, objective reality is an integral part of most scientific models. For example, in both the Ptolemaic and Copernican models, the earth and planets are objectively real. Removing the objective reality from these
models would involve an additional and unnecessary assumption. This is much like Last Thursdayism where everything since last Thursday is assumed to have objective reality but things before last Thursday are assumed not to have objective reality. By moving the cutoff time from last Thursday to the present time we have essentially removed all objective reality. One could also have Next Thursdayism where things only take on an objective reality after next Thursday. Models without objective reality can usually be eliminated, like Last Thursdayism was eliminated, by the use of Occam’s razor. Keeping realism as an integral and significant part of the models while maintaining the models tentativeness leads to critical realism.

Another example of equivalence is the many worlds interpretation of quantum mechanics. The fundamental idea of this interpretation is that there are myriads of worlds in the universe in addition to the world we are aware of. In particular, every time a quantum experiment with different possible outcomes is performed, all outcomes are obtained, each in a different world. However, we are aware only of the world with the outcome we have seen. To the extent this is just an interpretation it is scientifically equivalent to the usual Copenhagen interpretation i.e. all predictions will be the same. There is an argument about if the two are practically equivalent rather than fully equivalent but for the present discussion this is not significant. The many-worlds interpretation is just an extra assumption that has no testable consequences. It can, therefore, be eliminated by Occam’s razor.

One could also have a theistic interpretation of quantum mechanics in which God determines exactly which outcome will occur but lets mere mortals only predict the probability. Thus, although God does not play dice (perhaps keeping Einstein happy), to mortals, through ignorance, it appears he does. It also allows God to control the evolution of the universe without violating any physical laws. The theistic interpretation is equivalent to ordinary quantum mechanics and just provides another way around the philosophical implications of quantum mechanics that some people find repugnant. Like the many worlds interpretation it can be eliminated from science by the use of Occam’s razor.

The present work suggests, rather than a many worlds or theistic interpretation, an instrumental or phenomenal approach to quantum mechanics. The important and lasting part of quantum mechanics is the mathematical formulation which provides the basis for making predictions for observations. As the theistic interpretation illustrates, different conflicting interpretations can be easily constructed. Poincaré expressed the role of mathematics even more strongly. "But what we call objective reality . . . can only be the harmony expressed by mathematical laws. It is this harmony then which is the sole objective reality, the only truth we can obtain."

From the point of view of predicting and describing observations the statements “God made it that way” and “It is that way because it is that way” are equivalent. Both perfectly describe all past observations and predict no future observations. Each observation explained this way needs its own assumption. The cosmic anthropological (or anthropic) principle is also equivalent. The cosmic anthropological principle states that the reason the universe is the way it is, is because otherwise people would not exist. However we could equally have a zoological principle, or an agrostological principle, or a geological principle or a planetary principle. These principles all are just the statement that the
universe is the way it is because if it wasn’t it would be different. The different part being emphasized by the anthropological principle is the presence or lack of people. The agrostological (agrostic) principle, in contrast, emphasizes grasses: farmers are grasses’ way of competing with trees and golf courses mainly benefit grass. The “It is the way it is because that is the way it is” or equivalently “God made it that way” are show stoppers in science. They have no predictive power and are essentially an admission of defeat. It cuts off further progress in the given direction.

There is another way to construe the admission of defeat. Namely, some of the parameters in the model have to be determined phenomenologically. In the past there has been a need for phenomenological input, but this always was assumed to be due to ignorance or uninteresting initial conditions. The mass of the proton is determined phenomenologically but could be determined, in principle from Quantum Chromodynamics. The mass of the earth is determined phenomenologically and is presumably due to conditions in the early solar system. Now we have the possibility that more fundamental parameters like the mass and charge of the election must be determined phenomenologically. The situation is rather like statistics in quantum mechanics. Before quantum mechanics, statistical approaches were used but only as approximations to deterministic models. Quantum mechanics, in contrast, is inherently statistical. If the idea being discussed in this paragraph is correct, parameters that were previously believed to be obtainable theoretically will only be determinable phenomenologically. Ideally all the parameters in a model would be determined theoretically. This is probably too much to hope for and would reinstate Kant’s synthetic a priori information — nontrivial information determined without phenomenological input.

6 Science and Religion

6.1 Observation vs. Divine Revelation

Science and religion are not always in harmony, whether Galileo versus the Catholic Church or the modern anti-evolution teaching of some churches. It is therefore important to understand the relation between the two. It is not fundamentally one of faith versus logic. Any system of epistemology has assumptions, even science. While religion places more emphasis on faith, many claim their religious beliefs are based on sufficient reason. Wright in a series of books (ref. and other books in that series) argues for the historicity of Jesus from historical analysis. Both science and religion use models. The literal interpretation of Genesis is a model for the creation of the world. So the difference is not in model building versus absolute truth.

Similarly the distinction based on natural versus supernatural is not valid. At one level the introduction of the supernatural in the form “Because God made it that way”, as discussed above, is a show stopper in science. The problem is not that it is supernatural but that it lacks predictive power. At another level saying that science is based on natural explanations is just a tautology since supernatural can be defined as that which has no explanation in the current models of science. The National Academy of Sciences says: “Anything that can be observed or measured is amenable to scientific investigation.”
Presumably this is true even if the thing being observed is considered to be supernatural. For example Matthew 17:20 says[11] “for truly I say to you, if you have faith the size of a mustard seed, you will say to this mountain, ‘Move from here to there,’ and it will move; and nothing will be impossible to you.” Clearly mountains moving around would be observable and thus amenable to scientific study. Hence the scientific method is not methodological naturalism[22] Merely because something is supernatural does not exclude it from scientific study. The question of supernatural phenomena in situations like this should be settled by observation, not a priori. It is amazing how far observation-based models have gone in describing observations without explicitly invoking the supernatural. To some extent this is because once science describes something it is no longer considered supernatural. In part, scientists’ reluctance to admit the explicitly supernatural into their work is because so much success has been obtained without it. It is also in part because the supernatural usually adds no predictive power. While I know of no studies of the effect of prayer on mountains, there have been controlled studies on the effect of prayer on healing[43] showing little or no effect. Presumably the biblical quote above is not meant literally otherwise most Christians must have faith smaller than a mustard seed.

So what is the distinction between science and religion? The main difference is that in science the ultimate authority is careful observation with an emphasis on predictions while in religion it is divine inspiration or revelation. The inspiration may come directly through a person’s religious experiences in their daily lives or the revelation may come through a prophet or sacred texts. The Vedas, the Torah, the Christian Bible, the Koran, and the Guru Granth Sahib are examples of such scared texts. When the divine revelation comes through a person that person becomes the authority. The difference in the two approaches is highlighted in the conflict between Galileo and the Catholic Church. Galileo looked through his telescope while the church leaders consulted the Bible. One can debate whether the church officials correctly interpreted the Bible but one can not dispute that it was their ultimate authority. They did not look through the telescope since they “knew” the scriptures were more important than observations.

What Galileo was proposing was very revolutionary. That the earth goes around the sun was the least revolutionary part. The real revolutionary part was that you should look through the telescope and compare what you saw with what the church and other authorities were teaching. This was a whole new way of studying reality. It also directly questioned the authority of the church. The church leaders naturally reacted with horror. Their whole edifice of belief and authority was under attack. They accused Galileo of undermining Christianity. Eventually an uneasy truce was reached between science and religion. Observation would be used to study natural history. The relationship between God and man, and morality would be left to the church. The truce was broken by evolution which many in the church regarded as challenging their understanding of the relationship between God and man. It was considered a threat to their religion, a parallel to the reaction to Galileo. Similar skirmishes are expected in the future as observation-based science invades more of the traditional domain of religion.

In principle, observation based models and models based on divine revelation do not have to be in conflict. There is no reason a model created through divine revelation could not have predictive power — in creating models anything goes. The conflict arises when a model based on someone’s divine revelation or interpretation of divine revelation conflicts
with models based on observations. In this case one has to decide between observation and divine revelation. Atheists and deists would claim divine revelation does not even exist. The defense of divine revelation and the thorny problem of deciding between the different purported divine revelations is not part of the present work but rather is left to the theologians.

One of the traditional methods to reconcile science and religion is the God of the gaps theology. This says that science accounts for what it accounts for and whatever is leftover (the gaps) is due to God. The cause of the big bang and the origin of life are two of the gaps in current scientific understanding. A miracle defines as “An event that appears inexplicable by the laws of nature and so is held to be supernatural in origin or an act of God” is another example of the gap concept. Irreducible complexity has been advanced as an attack on evolution and is, along with much of creationism, very much in the God of the gaps tradition. The God of the gaps theology attributes everything not currently described by scientific models as due to God either directly or by implication. This is a special case of the more general technique known as “Proof by lack of imagination”. The argument goes like this: I can not imagine how this can happen naturally therefore it does not or God must have done it. This argument only works until someone with more imagination comes along. For the example of irreducible complexity, the judgment in the Kitzmiller vs. Dover Area School District court case found that many more imaginative people have already come along. The general problem with the God of the gaps theology is that as more imaginative people come along, the gaps disappear and so does the God. With the present view of science as being primarily descriptive, the God of the gaps theology makes little sense anyway. God, if he/she/it exists, would presumably be responsible for what science describes as well as for what it does not describe. To the deist or theist, science is simply the description of God’s handiwork as made manifest through observations.

The crux of the science vs. religion debate is where to demarcate the boundary between where we allow observation to be the final authority and where we allow sacred texts or sacred texts interpreted by religious leaders to be the final authority. There are advocates of both extremes and many places in the middle. Deuteronomy 18:22 suggests that if the “divine revelation” does not come true i.e. is not consistent with observations “that is a thing that the LORD has not spoken”. Hence the worry on the part of some Christians that if the Bible is not literally true the LORD has not spoken it. Be that as it may, the semantic argument is very clear: models, beliefs and natural history based on divine revelation are religion, models and natural history based on careful observations are science, models and beliefs based on less than careful observations are pseudo-science and superstition.

The difference between science and religion is that science has observation as its ultimate authority while religion has divine revelation. Because of this basic difference other differences follow. Since science is based on observation it appears materialistic. Religion being based on divine revelation assumes that the divine exists and is important. The role of individual people is also fundamentally different. Christ is central to Christianity: 1 Corinthians 15:1 “and if Christ has not been raised, then our preaching is vain, your faith also is vain.” Islam is based on the idea “There is no God but Allah and Mohammad is his prophet”. Individuals also play a leading role in defining other
religions and philosophic traditions — Abraham and Moses (Judaism), Buddha (Buddhism), Confucius (Confucianism), Lao Tzu (Taoism), Guru Nanak (Sikhism), Zoroaster (Zoroastrianism), and Bahá’u’lláh (Bahá’í Faith). Even at an operational level certain people have an elevated position and are considered authorities, for example the Pope in the Catholic Church or the Grand Ayatollahs in Shi‘ite Islam. In science, on the other hand, the people are incidental. If Charles Darwin had not been there, Alfred Russel Wallace would have been known as the discoverer of evolution. At the present time, neither Darwin nor Wallace are relevant to the validity of evolution. The validity of relativity does not depend on Einstein’s greatness nor quantum mechanics on Bohr’s. Rather Darwin, Einstein and Bohr are considered great because of the greatness of the models they helped develop. Darwin, Einstein and Bohr are not the ultimate authorities in science, the observations are. When people are taken as the authority in science the field stagnates. An example is the physics in England after Newton. The physicists were so in awe of Newton that they used him as the authority and thus fell behind their colleagues on the continent. When anti-evolutionists attach Darwin to modern evolutionary models and try to discredit them through him, scientists look on in bewilderment. Conversely, the western largely secular and observation based society does not understand why the Muslim world is so upset at attacks or perceived attacks on Mohammad. An attack on Mohammad is an attack on the center of the religion he started. It calls the whole of the religion into question since Mohammad is the authority that defines Islam. A similar argument holds for Christ and Christianity. On the other hand, an attack on Darwin, Einstein or Bohr is an irrelevancy.

Finally we note that having science and religion cooperate is not always a good thing. In warfare, the motivation is all too frequently provided by religion and the means by science.

6.2 Creationist Natural History

There is currently an attack on evolution by one segment of the Christian Church. This comes across as an attack on Darwin and what he represents. However their argument is really with Galileo and his telescope. Once we are allowed to take what we see through the telescope, i.e. observations, as the ultimate authority rather than scripture the rest of science follows. See for example “The Wedge Strategy” where the attack on evolution is promoted as the beginning of an assault on natural history based on observation (materialism) rather than scripture. It is the thin edge of the wedge since Darwin is considered more vulnerable than Galileo. They want to “To replace materialistic explanations with the theistic understanding that nature and human beings are created by God.” In principle, there is nothing wrong with developing a natural history based on theistic concepts derived from divine revelation. However, enlightenment thinkers like Kant and Voltaire argued that the Middle Ages were the Dark Ages because independent thinking and observation took a back seat to divine revelation or, at least, the church leaders’ interpretation of divine revelation. In any case, natural history based on divine revelation rather than observation is religion not science. Note the distinction between natural history and science. Natural history is any study of how nature works. To be science it must be based on careful observations. Creation science and creationism are
not science since the ultimate authority in this field of study is the Bible rather than observations. They are religion and creation science should rather be called creationist natural history. How accurately it represents Biblical authority is another issue and is again left to the theologians.

The evolution-creationism controversy provides insight into how science works. Evolution is attacked as being unreasonable. As previously noted, many successful models have been rightly considered unreasonable. In addition, unreasonableness, like beauty, is in the eye of the beholder. Many scientists, myself included, regard natural selection as an extremely intelligent way to do design, resembling Monte Carlo techniques in computer science. Another line of attack on evolution is through “proof by lack of imagination” as typified by irreducible complexity. Proof by lack of imagination is related to naive falsification: I can not imagine how your model can describe this result hence your model must be wrong. However, with enough imagination any negative result can be explained away. The white crow is really a black crow covered with snow or the sun is reflecting (specular reflection) off the black crow in such a way it looks white. Thus attempts to attack evolution through naive falsification will fail. Similarly attacks on creationist natural history based on naive falsification will fail. Although the Omphalos hypothesis is ad hoc, like Last Thursdayism, it can only be eliminated by appealing to simplicity. Imaginative people will find ways around any possible falsification. However, modifying models to circumvent falsification usually reduces their predictive power. In the case of creationist natural history and the Omphalos hypothesis it destroys it altogether. As the 1902 textbook quote illustrates, the 1887 Michelson-Morley experiment did not immediately falsify the ether model. Creative people came up with explanations such as ether entrainment and the Lorentz-Fitzgerald contraction to explain the unexpected results. Both explanations reduced the ether’s predictive power. In the end, the ether model was eliminated by Einstein’s special theory of relativity which had fewer assumption and more predictive power than the competing models. Michelson and Morley provided the ammunition, Lorentz the gun (the Lorentz transformation), but it was Einstein that pulled the trigger. His defense lawyer would argue that the ether was not shot but rather had its throat slit with Occam’s razor. Einstein did not prove that the ether did not exist. Rather he showed that the ether hypothesis, like the Omphalos hypothesis, has no predictive power, and in the end it was eliminated by appeals to simplicity.

The proponents of intelligent design argue that there must be an intelligent agent behind the design of the universe. Unfortunately intelligent design, like creationism in general, is not well defined. At one extreme it is considered a replacement for not just natural selection but even evolution in its entirety. At the other extreme it is just theistic interpretation of quantum mechanics applied more widely; God controlling the universe without explicitly appearing in the models. The main arguments for intelligent design are by analogy and proof by lack of imagination. I can not imagine how the universe could have arisen without a designer, therefore it didn’t. The argument from analogy is based on perceived similarities between humanly designed machines and biological systems. The weaknesses in this analogy are given in the Dover court case decision. The arguments for intelligent design are remarkably similar to those for the ether: analogy and proof by lack of imagination. At the time Maxwell discovered the wave equation for electromagnet radiation, many types of waves were known: sound in
various media, water waves, vibrations in membranes, etc. All had one thing in common, a physical medium. By analogy it was argued that the electromagnetic waves must also have a physical medium — the ether. The physicists of the time could not imagine a wave without such a physical medium, much like some people currently cannot imagine the lack of a designer for biological systems. The argument against intelligent design is the same one that killed both the ether and Last Thursdayism — simplicity. Intelligent design, like the ether or the theistic interpretation of quantum mechanics, is just an extra assumption that does not lead to new predictions.

The real criteria for judging models is predictive power — not naive falsification nor analogy nor lack of imagination. Recently a new fossil, *Tiktaalik roseae* — a tetrapod-like fish or a fish-like tetrapod, has been found. One can engage in futile semantic arguments about whether it is a fish, or a tetrapod, or a missing link or whether it is the work of the devil. However, the significant point is that a striking prediction has been confirmed by a peer-reviewed observation. Using evolution, a model of fossil formation and a model of the earth’s geology, a prediction was made that a certain type of fossil would be found in a certain type of rock. *Tiktaalik roseae* dramatically fulfilled that prediction and provides information on the fish-tetrapod transition. It is just one of the many strikingly successful predictions of evolutionary models. Creationist natural history and intelligent design will only be taken seriously by the scientific community when they are used to make similarly striking predictions (not postdictions) that are confirmed by careful, reproducible, peer reviewed observations. Currently creationist natural history and intelligent design have only demonstrated minimal predictive power. Evolution will only be replaced as the dominate model in biology when a competing model is shown to have more predictive power. Even then evolution will probably continue as a useful approximation to the more complete model much like classical mechanics continues to be used as an approximation to quantum mechanics.

## 7 Conclusions

### 7.1 A Meta-Model of Science

In this paper a meta-model of how science progresses has been presented. Like a scientific model a meta-model of science must be logically consistent, as simple as possible and consistent with observations on how science has developed. As in science, there has been a sequence of meta-models for how science develops — Plato’s idealism, Bacon’s induction, Cartesian skepticism, Hume’s empiricism, Kant’s idealism, Kuhn’s paradigms, Popper’s falsification and Asimov’s relativity of wrong. Looking at this progression we see concepts being introduced and refined — Kant’s “Critique of Pure Reason” is a response to Hume. Echos of Kant and even Plato are seen in Kuhn’s work. The “relativity of wrong” principle applies equally to the meta-models. Newer meta-models are less wrong than the previous models but the older meta-models are not so much wrong as incomplete. As in science, new observations led to new understanding — the fall of classical mechanics played a large role in the motivation and development of Kuhn’s and Popper’s ideas. In addition to emphasizing the role of the paradigm, Kuhn also showcased the need to look
at how science has actually developed rather than trying to develop a meta-model of science based on pure thought. Following his lead, examples of how science has actually developed are presented in this work.

The meta-models of science should also make predictions on how science will develop in the future. The main predictions of the present work are: 1) New models will replace older models when and only when they have more predictive power. 2) The replacement rate will be highest in fields with highest number of new distinct observations, 3) The replaced models will be good approximations, i.e. they will be effectively equivalent, to the newer models for a limited range of observations. 4) The philosophical and metaphysical implications of the new models will be significantly different from that for the replaced models.

7.2 Summary

The scientific method is observationally constrained model building, not induction, falsification nor methodological naturalism. The observations must be carefully done and reproducible. The models must be logical, internally consistent, predictive and as simple as possible. Both observations and models should be peer reviewed for error control. The goal of science is to construct models that make the maximum number of correct postdictions and predictions with the minimum number of assumptions. Supernatural explanations are rejected not a priori but when, as is usually the case, they lead to no testable predictions for future observations. In general, if you want your model to be accepted you must show that it makes more correct precise predictions with fewer assumptions than the competing models. There is a surfeit of models that make fewer predictions. As models are improved their predictive powers increase. We see progress with time, the models become less wrong, probably not absolutely right, but less wrong. There appears to be convergence towards the probably unreachable goal of a model of everything. The same can not be said for the philosophical and metaphysical implications of the models. Here there is no obvious convergence or at least the convergence is much slower. There is no overwhelming reason to believe the philosophical and metaphysical implications of presently accepted models. They will probably change in unpredictable ways when new improved models comes along. The only important, enduring property of a model is its predictions for observations. Thus the metaphysical baggage — the action at a distance, the ether, the caloric, the many worlds, the objective reality — should not be taken too seriously. However, they frequently play a useful pedagogical role.

Models and observations have a symbiotic relation. The atomic nucleus both shapes the nuclear mean field and is shaped by it. Similarly observations shape the models and in turn are shaped by them. The most exalted model can be dethroned by mundane observations while even the most extraordinary observation is meaningless without the context provided by the models.

It is often stated by anti-evolution forces that evolution is not a fact; a rhetorically powerful but ultimately meaningless statement. As should be obvious from the discussions in this paper, evolution is a model. A model, by its very nature, never becomes a “fact” that is it never becomes certain but always remains tentative. Trying to classify evolution or any empirical model as fact or not-fact is a failure of categories and indicates
a profound ignorance of the nature of empirical knowledge. Evolution is a model, hence
tentative, but a model with extraordinary predictive power. That is high praise, the
highest science can give. Similar arguments are also made against other models: science
has not proven X. For example X might be global warming due to green-house gases.
Of course science has not proven X. Proofs are the domain of mathematics, not the
empirical sciences. When people use the X is not a fact or Y is not proven gambits it is a
tacit admission they have lost the science argument and they are just trying to downplay
the significance of that failing.

ACKNOWLEDGMENTS: E.D. Cooper, S. Coutu, B.S. Davids, H.W. Fearing, D. Frekers,
S.W. Hong, M.M. Pavan, L. Theußl, E.W. Vogt and R. Woodside are thanked for
reading the manuscript and for useful comments. The Natural Sciences and Engineering
Research Council of Canada is thanked for financial support. TRIUMF receives federal
funding via a contribution agreement through the National Research Council of Canada.

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