Chapter 1

Introduction

1.1 Overview

These notes cover the development of the current scientific concepts of space and time through history, emphasizing the newest developments and ideas. The presentation will be non-mathematical: the concepts will be introduced and explained, but no real calculations will be performed. The various concepts will be introduced in a historical order (whenever possible), this provides a measure of understanding as to how the ideas on which the modern theory of space and time is based were developed. In a real sense this has been an adventure for humanity, very similar to what a child undergoes from the moment he or she first looks at the world to the point he or she understands some of its rules. Part of this adventure will be told here.

Every single culture has had a theory of the formation of the universe and the laws that rule it. Such a system is called a cosmology (from the Greek *kosmos*: world, and *logia* from *legein*: to speak). The first coherent non-religious cosmology was developed during ancient Greece, and much attention will be paid to it after a brief overview of Egyptian and Babyonian comologies [1] The system of the world devised by the Greeks described correctly all phenomena known at the time, and was able to predict most astronomical phenomena with great accuracy. Its most refined version, the Ptolemaic system, survived for more than one thousand years.

[1] A few other comologies will be only summarily described. This is for lack of erudition, Indian, Chinese and American comologies are equally fascinating.

These promising developments came to a stop during the Middle Ages, but took off with a vengeance during the Renaissance; the next landmark in this saga. During this time Copernicus developed his system of the world, where the center of the Universe was the Sun and not the Earth. In the same era Galileo defined and developed the science of mechanics with all its basic postulates; he was also the creator of the idea of relativity, later used by Einstein to construct his Special and General theories.

The next great player was Isaac Newton, who provided a framework for understanding all the phenomena known at the time. In fact most of our daily experience is perfectly well described by Newton's mathematical formulae.

The cosmology based on the ideas of Galileo and Newton reigned supreme up until the end of the 19th century: by this time it became clear that Newton's laws were unable to describe correctly electric and magnetic phenomena. It is here that Einstein enters the field, he showed that the Newtonian approach does not describe correctly situations in which bodies move at speeds close to that of light (in particular it does not describe light accurately). Einstein also provided the generalization of Newton's equations to the realm of such high speeds: the Special Theory of Relativity. Perhaps more importantly, he also demonstrated that certain properties of space and time taken for granted are, in fact, incorrect. We will see, for example, that the concept of two events occurring at the same time in different places is not absolute, but depends on the state of motion of the observer.

Not content with this momentous achievements, Einstein argued that the Special Theory of Relativity itself was inapplicable under certain conditions, for example, near very heavy bodies. He then provided the generalization which encompasses these situations as well: the General Theory of Relativity. This is perhaps the most amazing development in theoretical physics in 300 years: without any experimental motivation, Einstein single handedly developed this modern theory of gravitation and used it to predict some of the most surprising phenomena observed to date. These include the bending of light near heavy bodies and the existence of black holes, massive objects whose gravitational force is so strong it traps all objects, including light.

These notes provide an overview of this saga. From the Greeks and their measuring of the Earth, to Einstein and his description of the universe. But before plunging into this, it is natural to ask how do scientific theories are born, and why are they discarded. Why is it that we believe Einstein is right and Aristotle is wrong? Why is it that we claim that our current understating of the universe is deeper than the one achieved by the early Greeks? The answer to these questions lies in the way in which scientists evaluate the information derived from observations and experiments, and is the subject of the next section.

1.2 The scientific method

Science is best defined as a careful, disciplined, logical search for knowledge about any and all aspects of the universe, obtained by examination of the best available evidence and always subject to correction and improvement upon discovery of better evidence. What's left is magic. And it doesn't work.

James Randi

It took a long while to determine how is the world better investigated. One way is to just talk about it (for example Aristotle, the Greek philosopher, stated that males and females have different number of teeth, without bothering to check; he then provided long arguments as to why this is the way things ought to be). This method is unreliable: arguments cannot determine whether a statement is correct, this requires *proofs*.

A better approach is to do experiments and perform careful observations. The results of this approach are universal in the sense that they can be reproduced by any skeptic. It is from these ideas that the *scientific method* was developed. Most of science is based on this procedure for studying Nature.

1.2.1 What is the "scientific method"?

The scientific method is the best way yet discovered for winnowing the truth from lies and delusion. The simple version looks something like this:

1. Observe some aspect of the universe.
2. Invent a tentative description, called a *hypothesis*, that is consistent with what you have observed.
3. Use the hypothesis to make predictions.
4. Test those predictions by experiments or further observations and modify the hypothesis in the light of your results.
5. Repeat steps 3 and 4 until there are no discrepancies between theory and experiment and/or observation.

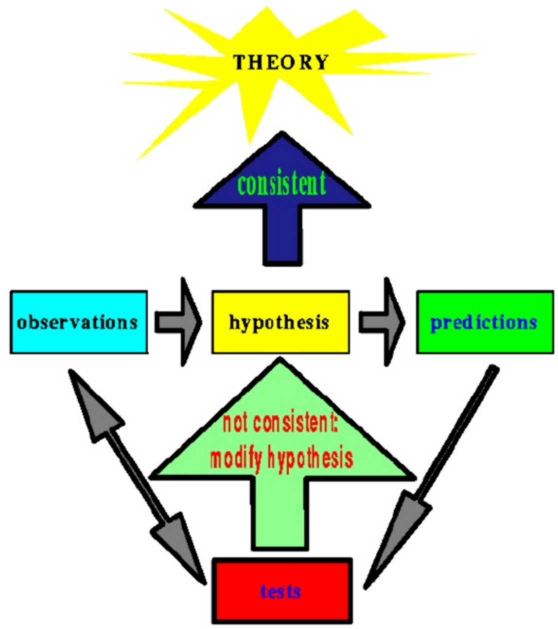

Figure 1.1: Flow diagram describing the scientific method.

When consistency is obtained the hypothesis becomes a *theory* and provides a coherent set of propositions which explain a class of phenomena. A theory is then a framework within which observations are explained and predictions are made.

The scientific method is unprejudiced

The great advantage of the scientific method is that it is unprejudiced: one does not have to believe a given researcher, one can redo the experiment and determine whether his/her results are true or false. The conclusions will hold irrespective of the state of mind, or the religious persuasion, or the state of consciousness of the investigator and/or the subject of the investigation. Faith, defined as [2] *belief that does not rest on logical proof or material evidence*, does not determine whether a scientific theory is adopted or discarded.

A theory is accepted not based on the prestige or convincing powers of the proponent, but on the results obtained through observations and/or ex-

[2] The American Heritage Dictionary (second college edition)

periments which *anyone* can reproduce: the results obtained using the scientific method are repeatable. In fact, most experiments and observations *are* repeated many times (certain experiments are not repeated independently but are repeated as parts of other experiments). If the original claims are not verified the origin of such discrepancies is hunted down and exhaustively studied.

The results obtained using the scientific method are repeatable

When studying the cosmos we cannot perform experiments; all information is obtained from observations and measurements. Theories are then devised by extracting some regularity in the observations and coding this into physical laws.

There is a very important characteristic of a scientific theory or hypothesis which differentiates it from, for example, an act of faith: a theory must be "falsifiable". This means that there must be some experiment or possible discovery that could prove the theory untrue. For example, Einstein's theory of Relativity made predictions about the results of experiments. These experiments could have produced results that contradicted Einstein, so the theory was (and still is) falsifiable.

Every scientific theory must be "falsifiable"

In contrast, the theory that "the moon is populated by little green men who can read our minds and will hide whenever anyone on Earth looks for them, and will flee into deep space whenever a spacecraft comes near" is not falsifiable: these green men are designed so that no one can ever see them. On the other hand, the theory that there are no little green men on the moon is scientific: you can disprove it by catching one. Similar arguments apply to abominable snow-persons, UFOs and the Loch Ness Monster(s?).

A frequent criticism made of the scientific method is that it cannot accommodate anything that has not been proved. The argument then points out that many things thought to be impossible in the past are now everyday realities. This criticism is based on a misinterpretation of the scientific method. When a hypothesis passes the test it is adopted as a theory it correctly explains a range of phenomena it *can*, at any time, be falsified by new experimental evidence. When exploring a new set or phenomena scientists do use existing theories but, since this is a new area of investigation, it is always kept in mind that the old theories might fail to explain the new experiments and observations. In this case new hypotheses are devised and tested until a new theory emerges.

There are many types of "pseudo-scientific" theories which wrap themselves in a mantle of apparent experimental evidence but that, when examined closely, are nothing but statements of faith. The argument [3], cited by

[3] From `http://puffin.ptialaska.net/~svend/award.html`

some creationists, that science is just another kind of faith is a philosophic stance which ignores the trans-cultural nature of science. Science's theory of gravity explains why both creationists and scientists don't float off the earth. All you have to do is jump to verify this theory – no leap of faith required.

1.2.2 What is the difference between a fact, a theory and a hypothesis?

A theory is a conceptual framework that explains existing observations and predicts new ones

In popular usage, a theory is just a vague and fuzzy sort of fact and a hypothesis is often used as a fancy synonym to 'guess'. But to a scientist a theory is a conceptual framework that explains existing observations and predicts new ones. For instance, suppose you see the Sun rise. This is an existing observation which is explained by the theory of gravity proposed by Newton. This theory, in addition to explaining why we see the Sun move across the sky, also explains many other phenomena such as the path followed by the Sun as it moves (as seen from Earth) across the sky, the phases of the Moon, the phases of Venus, the tides, just to mention a few. You can today make a calculation and *predict* the position of the Sun, the phases of the Moon and Venus, the hour of maximal tide, all 200 years from now. The *same* theory is used to guide spacecraft all over the Solar System.

A hypothesis is a working assumption

A hypothesis is a working assumption. Typically, a scientist devises a hypothesis and then sees if it "holds water" by testing it against available data (obtained from previous experiments and observations). If the hypothesis does hold water, the scientist declares it to be a theory.

1.2.3 Truth and proof in science.

Experiments sometimes produce results which cannot be explained with existing theories. In this case it is the job of scientists to produce new theories which replace the old ones. The new theories should explain all the observations and experiments the old theory did *and*, in addition, the new set of facts which lead to their development. One can say that new theories devour and assimilate old ones (see Fig, 1.2). Scientists continually test existing theories in order to probe how far can they be applied.

When a new theory cannot explain new observations it will be (eventually) replaced by a new theory. This does *not* mean that the old ones are "wrong" or "untrue", it only means that the old theory had a limited applicability and could not explain all current data. The only certain thing about currently accepted theories is that they explain all available data, which, if

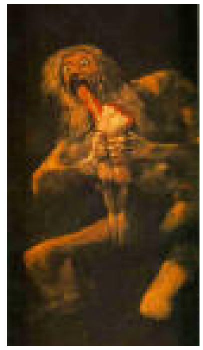

Figure 1.2: Saturn devouring his sons (by F. Goya). A paradigm of how new theories encompass old ones.

course, does not imply that they will explains all future experiments!

In some cases new theories provide not only extensions of old ones, but a completely new insight into the workings of nature. Thus when going from Newton's theory of gravitation to Einstein's our understanding of the nature of space and time was revolutionized. Nonetheless, no matter how beautiful and simple a new theory might be, it must explain the same phenomena the old one did. Even the most beautiful theory can be annihilated by a single ugly fact.

Scientific theories have various degrees of reliability and one can think of them as being on a scale of certainty. Up near the top end we have our theory of gravitation based on a staggering amount of evidence; down at the bottom we have the theory that the Earth is flat. In the middle we have our theory of the origin of the moons of Uranus. Some scientific theories are nearer the top than others, but none of them ever actually reach it.

An extraordinary claim is one that contradicts a fact that is close to the top of the certainty scale and will give rise to a lot of skepticism. So if you are trying to contradict such a fact, you had better have facts available that are even higher up the certainty scale: "extraordinary evidence is needed for an extraordinary claim".

1.2.4 If scientific theories keep changing, where is the Truth?

In 1666 Isaac Newton proposed his theory of gravitation. This was one of the greatest intellectual feats of all time. The theory explained all the observed facts, and made predictions that were later tested and found to be correct within the accuracy of the instruments being used. As far as anyone could see, Newton's theory was "the Truth".

During the nineteenth century, more accurate instruments were used to test Newton's theory, these observations uncovered some slight discrepancies. Albert Einstein proposed his theories of Relativity, which explained the newly observed facts and made more predictions. Those predictions have now been tested and found to be correct within the accuracy of the instruments being used. As far as anyone can see, Einstein's theory is "the Truth".

When a theory is said to be "true" it means that it agrees with all known experimental evidence

So how can the Truth change? Well the answer is that it hasn't. The Universe is still the same as it ever was. When a theory is said to be "true" it means that it agrees with all known experimental evidence. But even the best of theories have, time and again, been shown to be incomplete: though they might explain a lot of phenomena using a few basic principles, and even predict many new and exciting results, eventually new experiments (or more precise ones) show a discrepancy between the workings of nature and the predictions of the theory. In the strict sense this means that the theory was not "true" after all; but the fact remains that it is a very good approximation to the truth, at lest where a certain type of phenomena is concerned.

When an accepted theory cannot explain some new data (which has been confirmed), the researchers working in that field strive to construct a new theory. This task gets increasingly more difficult as our knowledge increases, for the new theory should not only explain the new data, but also all the old one: a new theory has, as its first duty, to devour and assimilate its predecessors.

One other note about truth: science does not make moral judgments. Anyone who tries to draw moral lessons from the laws of nature is on very dangerous ground. Evolution in particular seems to suffer from this. At one time or another it seems to have been used to justify Nazism, Communism, and every other -ism in between. These justifications are all completely bogus. Similarly, anyone who says "evolution theory is evil because it is used to support Communism" (or any other -ism) has also strayed from the path of Logic (and will not live live long nor prosper).

1.2.5 What is Ockham's Razor?

When a new set of facts requires the creation of a new theory the process is far from the orderly picture often presented in books. Many hypothses are proposed, studied, rejected. Researchers discuss their validity (sometimes quite heatedly) proposing experiments which will determine the validity of one or the other, exposing flaws in their least favorite ones, etc. Yet, even when the unfit hypotheses are discarded, several options may remain, in some cases making the exact same predictions, but having very different underlying assumptions. In order to choose among these possible theories a very useful tool is what is called *Ockham's razor*.

Ockham's Razor is the principle proposed by William of Ockham in the fourteenth century: "Pluralitas non est ponenda sine neccesitate", which translates as "entities should not be multiplied unnecessarily".

In many cases this is interpreted as "keep it simple", but in reality the Razor has a more subtle and interesting meaning. Suppose that you have two competing theories which describe the same system, if these theories have different predictions than it is a relatively simple matter to find which one is better: one does experiments with the required sensitivity and determines which one give the most accurate predictions. For example, in Copernicus' theory of the solar system the planets move in circles around the sun, in Kepler's theory they move in ellipses. By measuring carefully the path of the planets it was determined that they move on ellipses, and Copernicus' theory was then replaced by Kepler's.

But there are are theories which have the very same predictions and it is here that the Razor is useful. Consider form example the following two theories aimed at describing the motions of the planets around the sun

- The planets move around the sun in ellipses because there is a force between any of them and the sun which decreases as the square of the distance.
- The planets move around the sun in ellipses because there is a force between any of them and the sun which decreases as the square of the distance. This force is generated by the will of some powerful aliens.

Since the force between the planets and the sun determines the motion of the former and both theories posit the same type of force, the predicted motion of the planets will be identical for both theories. the second theory, however, has additional baggage (the will of the aliens) which is unnecessary for the description of the system.

If one accepts the second theory *solely on the basis that it predicts correctly the motion of the planets* one has also accepted the existence of aliens whose will affect the behavior of things, despite the fact that the presence or absence of such beings is irrelevant to planetary motion (the only relevant item is the type of force). In this instance Ockham's Razor would unequivocally reject the second theory. By rejecting this type of additional irrelevant hypotheses guards against the use of solid scientific results (such as the prediction of planetary motion) to justify unrelated statements (such as the existence of the aliens) which may have dramatic consequences. In this case the consequence is that the way planets move, the reason we fall to the ground when we trip, etc. is due to some powerful alien intellect, that this intellect permeates our whole solar system, it is with us even now...and from here an infinite number of paranoid derivations.

For all we know the solar system is permeated by an alien intellect, but the motion of the planets, which can be explained by the simple idea that there is a force between them and the sun, provides no evidence of the aliens' presence nor proves their absence.

A more straightforward application of the Razor is when we are face with two theories which have the same predictions and the available data cannot distinguish between them. In this case the Razor directs us to study in depth the simplest of the theories. It does *not* guarantee that the simplest theory will be correct, it merely establishes priorities.

A related rule, which can be used to slice open conspiracy theories, is Hanlon's Razor: "Never attribute to malice that which can be adequately explained by stupidity".

1.2.6 How much fraud is there in science?

The picture of scientists politely discussing theories, prposing new ones in view of new data, etc. appears to be completely devoid of any emotions. In fact this is far from the truth, the discussions are very human, even though the bulk of the scientific community will eventually accept a single theory based on it explaining the data and making a series of verified predictions. But before this is achieved, does it happen that researchers fake results or experiments for prestige and/or money? How frequent is this kind of scientific fraud?

In its simplest form this question is unanswerable, since undetected fraud is by definition unmeasurable. Of course there are many known cases of fraud in science. Some use this to argue that all scientific findings (especially those they dislike) are worthless.

This ignores the replication of results which is routinely undertaken by scientists. Any important result will be replicated many times by many different people. So an assertion that (for instance) scientists are lying about carbon-14 dating requires that a great many scientists are engaging in a conspiracy. In fact the existence of known and documented fraud is a good illustration of the self-correcting nature of science. It does not matter (for the progress of science) if a proportion of scientists are fraudsters because any important work they do will not be taken seriously without independent verification.

Also, most scientists are idealists. They perceive beauty in scientific truth and see its discovery as their vocation. Without this most would have gone into something more lucrative. These arguments suggest that undetected fraud in science is both rare and unimportant.

The above arguments are weaker in medical research, where *companies* frequently suppress or distort data in order to support their own products. Tobacco companies regularly produce reports "proving" that smoking is harmless, and drug companies have both faked and suppressed data related to the safety or effectiveness or major products. This type of fraud does not, of course, reflect on the validity of the scientific method.

1.2.7 Are scientists wearing blinkers?

One of the commonest allegations against mainstream science is that its practitioners only see what they expect to see. Scientists often refuse to test fringe ideas because "science" tells them that this will be a waste of time and effort. Hence they miss ideas which could be very valuable.

This is the "blinkers" argument, by analogy with the leather shields placed over horses eyes so that they only see the road ahead. It is often put forward by proponents of new-age beliefs and alternative health.

It is certainly true that ideas from outside the mainstream of science can have a hard time getting established. But on the other hand the opportunity to create a scientific revolution is a very tempting one: wealth, fame and Nobel prizes tend to follow from such work. So there will always be one or two scientists who are willing to look at anything new.

If you have such an idea, remember that the burden of proof is on you. The new theory should explain the existing data, provide new predictions and should be testable; remember that all scientific theories are falsifiable. Read the articles and improve your theory in the light of your new knowledge. Starting a scientific revolution is a long, hard slog. Don't expect it to be easy. If it was, we would have them every week. People putting forward extraordinary claims often refer to Galileo as an example of a great genius being persecuted by the establishment for heretic theories. They claim that the scientific establishment is afraid of being proved wrong, and hence is trying to suppress the truth. This is a classic conspiracy theory. The Conspirators are all those scientists who have bothered to point out flaws in the claims put forward by the researchers. The usual rejoinder to someone who says "They laughed at Columbus, they laughed at Galileo" is to say "But they also laughed at Bozo the Clown".

1.2.8 Why should we worry?

I have argued that the scientific method provides an excellent guideline for studying the world around us. It is, of course, conceivable that there are other "planes of thought" but their presence and properties, and what may happen in them is a matter of belief.

Through time "alternative" sciences regularly rise their head and are debunked. One might be bothered about their presence since it does say something less than flattering about human psychology. But even if one defends these beliefs on the basis of free speech, one should be aware that they sometimes represent more than idle talk. For example, there is this recent news article

- *ALTERNATIVE MEDICINE: REPORT SEEKS TO TAKE NIH INTO A NEW AGE! What may rank as the most credulous document in medical history was unveiled yesterday in a Senate conference room. Senator Tom Harkin (D-IA), who fathered the 1991 legislation that created the NIH Office of Alternative Medicine, admitted that the program had "gotten off to a slow start" due to opposition from "traditional" medicine. It should soar now; the 420-page report, "Alternative Medicine: Expanding Medical Horizons," lays out an OAM agenda for research into everything from Lakota medicine wheels to laying on of hands and homeopathic medicines. Homeopathic medicines employ dilutions far beyond the point at which a single molecule would remain, but the water "remembers." Where does physics fit in? Well, when really weird things happen, like mental healing at a distance, it must be quantum mechanics (Brian Josephson is cited for authority). Medical ethics are not ignored; the possibility of distant organisms being harmed by non-local mental influence is raised, and board certification of mental healers is proposed "to protect consumers from predatory quacks." An entire chapter is devoted to "Bioelectromagnetics." This is tricky stuff: "Weak EMF may, at the proper frequency and site of application, produce large effects that are either clinically beneficial or harmful."* [4]

It truly is amazing that people will even consider this statement. In fact it is not dismissed because it refers to science, but imagine a similar situation

[4] Extracted from "What's New", by Robert L. Park (March 3, 1995) produced by The American Physical Society.

where "really important matters" are involved, such as money. suppose a banker were to empty an account and claim that, even though there is no money left, the owner of the account is just as rich because his bank book still "remembers" the balance and that this miraculous memory of wealth past can be used to "cure" the owner's credit-card balance. Without a doubt this banker would end up in jail or in the loony bin.

Various tests using the scientific method have proven the fallacy of the "water with deep memory" theory. Yet these items are seriously considered and sometimes funded by Congress, diverting monies from important programs such as education. In the OAM has had an interesting and controversial history [5], despite this it has a budget of $12 million; in 1993-1994 it dispersed about 10% of this in grants.

This is not a unique occurrence. There are many many claims which use high-sounding scientific jargon; for example J. Randi [6] mentions that the NIH Office of Alternative Medicine has given credence to such claims as a cure for multiple sclerosis (despite the fact that the staff *must* know there is no such thing). When such startling claims are investigated, they are found to be merely ridiculous statements. If you are curious about these I provide a list of WWW sites for your amusement

- A page of links, ranging from free universal energy claims to antigravity, is found in `http://www.padrak.com/ine/SUBJECTS.html`
- Free energy `http://jabi.com/ucsa/` which is exposed in `http://www.voicenet.com/~eric/dennis.html`
- Perpetual motion machines `http://www.overunity.de/finsrud.htm`
- Products that miraculously improve your car's performance `http://widget.ecn.purdue.edu/~feiereis/magic.html`
- Flat Earth Society links (pro and against) `http://www.town.hanna.ab.ca/hemaruka/hemlinks.htm`.

And yes, in case you are wondering, some of these people *are* serious.

It is important to differentiate between these "pseudo-scientific" creations and true science-based developments. Pseudo-science is either not

[5] See for example, `http://www.nas.org/nassnl/2-11.htm`, `http://cyberwarped.com/~gcahf/ncahf/newslett/nl19-2.html`, `http://washingtonpost.com/wp-srv/WPlate/1997-08/10/097l-081097-idx.html`

[6] `http://www.mindspring.com/~anson/randi-hotline/1995/0046.html`

falsifiable or its results cannot be reproduced in a laboratory. If anything like this were to happen to a scientific hypothesis it would be dismissed forthright independently of the, belief, feelings, etc. of the researchers.

Below I present excerpts from an essay by R. Feynman on this same issue [7].

Cargo Cult Science (excerpts)

by Richard Feynman

During the Middle Ages there were all kinds of crazy ideas, such as that a piece of of rhinoceros horn would increase potency. Then a method was discovered for separating the ideas–which was to try one to see if it worked, and if it didn't work, to eliminate it. This method became organized, of course, into science. And it developed very well, so that we are now in the scientific age. It is such a scientific age, in fact, that we have difficulty in understanding how witch doctors could ever have existed, when nothing that they proposed ever really worked–or very little of it did.

But even today I meet lots of people who sooner or later get me into a conversation about UFO's, or astrology, or some form of mysticism, expanded consciousness, new types of awareness, ESP, and so forth. And I've concluded that it's not a scientific world.

Most people believe so many wonderful things that I decided to investigate why they did. And what has been referred to as my curiosity for investigation has landed me in a difficulty where I found so much junk that I'm overwhelmed. First I started out by investigating various ideas of mysticism and mystic experiences. I went into isolation tanks and got many hours of hallucinations, so I know something about that. Then I went to Esalen, which is a hotbed of this kind of thought (it's a wonderful place; you should go visit there). Then I became overwhelmed. I didn't realize how MUCH there was.

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I also looked into extrasensory perception, and PSI phenomena, and the latest craze there was Uri Geller, a man who is supposed to be able to bend keys by rubbing them with his finger. So I went to his hotel room, on his invitation, to see a demonstration of both mind reading and bending keys. He didn't do any mind reading that succeeded; nobody can read my mind, I guess. And my boy held a key and Geller rubbed it, and nothing happened. Then he told us it works better under water, and so you can picture all of us standing in the bathroom with the water turned on and the key under it, and him rubbing the key with his finger. Nothing happened. So I was unable to investigate that phenomenon.

[7] The complete version can be found in the World-Wide-Web at http://www.pd.infn.it/wwwcdf/science.html

But then I began to think, what else is there that we believe? (And I thought then about the witch doctors, and how easy it would have been to check on them by noticing that nothing really worked.) So I found things that even more people believe, such as that we have some knowledge of how to educate. There are big schools of reading methods and mathematics methods, and so forth, but if you notice, you'll see the reading scores keep going down–or hardly going up–in spite of the fact that we continually use these same people to improve the methods. There's a witch doctor remedy that doesn't work. It ought to be looked into; how do they know that their method should work? Another example is how to treat criminals. We obviously have made no progress–lots of theory, but no progress–in decreasing the amount of crime by the method that we use to handle criminals.

Yet these things are said to be scientific. We study them. And I think ordinary people with common sense ideas are intimidated by this pseudo-science. A teacher who has some good idea of how to teach her children to read is forced by the school system to do it some other way–or is even fooled by the school system into thinking that her method is not necessarily a good one. Or a parent of bad boys, after disciplining them in one way or another, feels guilty for the rest of her life because she didn't do "the right thing," according to the experts.

So we really ought to look into theories that don't work, and science that isn't science.

I think the educational and psychological studies I mentioned are examples of what I would like to call cargo cult science. In the South Seas there is a cargo cult of people. During the war they saw airplanes with lots of good materials, and they want the same thing to happen now. So they've arranged to make things like runways, to put fires along the sides of the runways, to make a wooden hut for a man to sit in, with two wooden pieces on his head to headphones and bars of bamboo sticking out like antennas–he's the controller–and they wait for the airplanes to land. They're doing everything right. The form is perfect. It looks exactly the way it looked before. But it doesn't work. No airplanes land. So I call these things *cargo cult science*, because they follow all the apparent precepts and forms of scientific investigation, but they're missing something essential, because the planes don't land.

Now it behooves me, of course, to tell you what they're missing. But it would be just about as difficult to explain to the South Sea islanders how they have to arrange things so that they get some wealth in their system. It is not something simple like telling them how to improve the shapes of the earphones. But there is one feature I notice that is generally missing in cargo cult science. That is the idea that we all hope you have learned in studying science in school–we never say explicitly what this is, but just hope that you catch on by all the examples of scientific investigation. It is interesting, therefore, to bring it out now and speak of it explicitly. It's a kind of scientific integrity, a principle of scientific thought that corresponds to a kind of utter honesty–a kind of leaning over backwards. For example, if you're doing an experiment, you should report everything that you think might make it invalid–not only what you think is right about it: other causes that could possibly explain your results; and things you thought of that you've eliminated by some other experiment, and how they worked–to make sure the other fellow can tell they have been eliminated.

Details that could throw doubt on your interpretation must be given, if you know them. You must do the best you can–if you know anything at all wrong, or possibly wrong–to explain it. If you make a theory, for example, and advertise it, or put it out, then you must also put down all the facts that disagree with it, as well as those that agree with it. There is also a more subtle problem. When you have put a lot of ideas together to make an elaborate theory, you want to make sure, when explaining what it fits, that those things it fits are not just the things that gave you the idea for the theory; but that the finished theory makes something else come out right, in addition.

In summary, the idea is to give all of the information to help others to judge the value of your contribution; not just the information that leads to judgment in one particular direction or another.

The easiest way to explain this idea is to contrast it, for example, with advertising. Last night I heard that Wesson oil doesn't soak through food. Well, that's true. It's not dishonest; but the thing I'm talking about is not just a matter of not being dishonest; it's a matter of scientific integrity, which is another level. The fact that should be added to that advertising statement is that no oils soak through food, if operated at a certain temperature. If operated at another temperature, they all will–including Wesson oil. So it's the implication which has been conveyed, not the fact, which is true, and the difference is what we have to deal with.

We've learned from experience that the truth will come out. Other experimenters will repeat your experiment and find out whether you were wrong or right. Nature's phenomena will agree or they'll disagree with your theory. And, although you may gain some temporary fame and excitement, you will not gain a good reputation as a scientist if you haven't tried to be very careful in this kind of work. And it's this type of integrity, this kind of care not to fool yourself, that is missing to a large extent in much of the research in "alternative science".

I would like to add something that's not essential to the science, but something I kind of believe, which is that you should not fool the layman when you're talking as a scientist. I'm talking about a specific, extra type of integrity that is not lying, but bending over backwards to show how you're maybe wrong, that you ought to have when acting as a scientist. And this is our responsibility as scientists, certainly to other scientists, and I think to laymen.

For example, I was a little surprised when I was talking to a friend who was going to go on the radio. He does work on cosmology and astronomy, and he wondered how he would explain what the applications of his work were. "Well," I said, "there aren't any." He said, "Yes, but then we won't get support for more research of this kind." I think that's kind of dishonest. If you're representing yourself as a scientist, then you should explain to the layman what you're doing–and if they don't support you under those circumstances, then that's their decision.

One example of the principle is this: If you've made up your mind to test a theory, or you want to explain some idea, you should always decide to publish it whichever way it comes out. If we only publish results of a certain kind, we can make the argument look good. We must publish BOTH kinds of results.

So I have just one wish for you–the good luck to be somewhere where you are free to maintain the kind of integrity I have described, and where you do not feel forced by a need to maintain your position in the organization, or financial support, or so on, to lose your integrity. May you have that freedom.

1.3 Large numbers

These notes deal with space and time. The first thing we notice about the universe around us is how big it is. In order to quantify things in cosmology very large numbers are required and the endless writing of zeroes quickly becomes tedious. Thus people invented what is called *the scientific notation* which is a way of avoiding writing many zeroes. For example the quantity 'one million' can be written as $1,000,000$ which is a one followed by six zeroes, this is abbreviated as 10^6 (the little number above the zero is called the *exponent* and denotes the number of zeroes after the one). In this way we have

$$\begin{aligned} \text{one million} &= 1,000,000 = 10^6 \\ \text{one billion} &= 1,000,000,000 = 10^9 \\ \text{one trillion} &= 1,000,000,000,000 = 10^{12}, \quad \text{etc.} \end{aligned} \tag{1.1}$$

So much for large numbers. There is a similar short-hand for small numbers, the only difference is that the exponent has a minus sign in front:

$$\begin{aligned} \text{one tenth} &= 0.1 = 10^{-1} \\ \text{one thousandth} &= 0.001 = 10^{-3} \\ \text{one millionth} &= 0.000001 = 10^{-6}, \quad \text{etc.} \end{aligned} \tag{1.2}$$

In order to get several times the above quantities one multiplies by ordinary numbers, so, for example, 8×10^6 =eight millions, 4×10^{-12} =four trillionths, etc.

This notation is a vast improvement also on the one devised by the Romans, and which was used up until the Renaissance. For example, our galaxy, the Milky Way, has a diameter of about 10^5 light years (a light year is the *distance* light travels in one year), in Roman numerals

$$10^5 = \quad MMMMMMMMMMMMMMMMMMMMM$$

$$MMMMMMMMMMMMMMMMMMMM$$
$$MMMMMMMMMMMMMMMMMMMM$$
$$MMMMMMMMMMMMMMMMMMMM$$
$$MMMMMMMMMMMMMMMMMMMM$$

The Andromeda galaxy is about 2×10^6 (two million) light years from our galaxy, in Roman numerals writing this distance requires 40 lines.

Appendix: Examples of large numbers

Very small and very large numbers are not the sole property of cosmology, there are many cases where such numbers appear. What is hard to do is visualize the meaning of something like a million or a billion. Below I provide several examples of large and small numbers.

In the table for temperatures the values are given in degrees Kelvin; a degree Kelvin equals a degree Celsius, but zero degrees Kelvin corresponds to -273.16 degrees Celsius. In order to change to degrees Fahrenheit you need to do the following operation:

$$\text{Deg. Fahrenheit} = 1.8 \times \text{Deg. Kelvin} - 459.$$

Absolute zero, the temperature at which all systems reach their lowest energy level, corresponds to zero degrees Kelvin, and -459 degrees Fahrenheit.

Times (in seconds)

8.6×10^4	Earth rotation time
1.6×10^9	Time between Milky Way supernovae
3×10^{13}	Time for evolution of a species
7.3×10^{15}	Orbit time for sun around galaxy center
6×10^{16}	Time for galaxy to cross a cluster
1.1×10^{17}	Primeval slime to man time
1.5×10^{17}	Age of Earth and Sun
1.5×10^{17}	Uranium-238 half-life
3×10^{17}	Sun lifetime
3.8×10^{17}	Rough age of the Milky Way
4×10^{17}	Rough age of 47 Tucanae
4.1×10^{17}	Age of the universe

Distances (in meters)

1.8	Man
8 847	Height of Mount Everest
10 000	Neutron star radius
10 000	Typical comet radius
12 000	Typical airliner cruising altitude
3.2×10^6	Length of the Great Wall of China
6.3×10^6	Radius of the Earth
7.1×10^7	Radius of Jupiter
3.8×10^8	Distance to the Moon
7.0×10^8	Radius of the Sun
1.5×10^{11}	Earth/Sun mean distance
5×10^{11}	Radius of the supergiant star Betelgeuse
5.9×10^{12}	Pluto/Sun mean distance
9.46×10^{15}	1 light-year
4×10^{16}	Nearest non-solar star to Earth
4.5×10^{16}	Rough Crab Nebula radius
1.5×10^{18}	Typical globular cluster radius
5.2×10^{18}	Distance to the supergiant Betelgeuse
6.6×10^{19}	Distance to the Crab Nebula
1.2×10^{20}	Milky Way characteristic thickness
2.4×10^{20}	Distance from Sun to galactic center
3.9×10^{20}	Milky Way disk radius
3×10^{22}	Radius of the core of the Virgo cluster
7×10^{23}	Distance to the center of the Virgo cluster
1.3×10^{27}	Distance to the quasar PC 1247+3406

Velocities (in meters per second)

1.0×10^{-9}	Sea floor spreading rate
1.6×10^{-9}	Average slip rate of the San Andreas fault
2×10^{-8}	Grass growth rate
3×10^{-6}	Typical glacial advance rate
1.3	Human walking speed
25	Car speed
100	Speed of an electric nervous pulse
330	Sound speed in air
600	Fighter jet speed
2 380	Escape velocity from Moon's surface
11 000	Escape velocity from the Earth's surface
29 000	Earth's motion around the Sun
2.2×10^5	Velocity of the Sun around the Milky Way
3.1×10^5	Escape velocity from the Milky Way
6.2×10^5	Escape velocity from the Sun's surface
5×10^6	Young (months old) supernova ejecta
2×10^8	Escape velocity from neutron star surface
3×10^8	Light in a vacuum

Masses (in kilograms)

70	Lower limit to the allowed mass for a Sumo wrestler
1 000	Car
10 000	Tyrannosaurus Rex
1×10^{13}	Typical comet mass
3×10^{14}	Typical mountain mass
1.1×10^{16}	Superterranean biomass of Earth (ocean organisms are included)
5.3×10^{18}	Total mass of Earth's atmosphere
3×10^{19}	Typical asteroid mass
1.4×10^{21}	Total mass of Earth's oceans
7.3×10^{22}	Mass of the Moon
5.98×10^{24}	Mass of the Earth
1.9×10^{27}	Mass of Jupiter
1.99×10^{30}	Mass of the Sun
2.8×10^{30}	Maximum mass for a white dwarf star
6.0×10^{30}	Maximum mass for a neutron star
1.3×10^{44}	Rough mass of the stars in the Coma galaxy cluster
1.4×10^{49}	Rough total mass in spiral galaxies
2×10^{52}	Rough total mass of a critical density universe

Temperatures (in deg. Kelvin)

7×10^{-7}	Laser cooling of cesium atoms
2.17	Liquid ^{4}He superfluid transition temperature
2.726	Cosmic microwave background temperature today
273	Water freezing temperature
311	Human surface temperature
373	Water boiling temperature
506	Paper burning temperature
740	Typical surface temperature of Venus
1811	Melting temperature of iron
5770	Solar effective temperature
1.4×10^7	Center of the Sun
5×10^7	Typical gas temperature in a cluster of galaxies
3×10^{10}	Center of a supernova.

Monies (in 1994 US dollars)

9×10^7	Development and construction cost of the Keck telescope
1.5×10^8	Rough cost of a European Ariane rocket launch
2.1×10^8	Total spending in the 1994 U.S. senate election campaigns
9×10^8	Total cost of the *Magellan* probe
1.1×10^9	Worldwide Visa and MasterCard fraud in 1993
1.8×10^9	Amount of food stamp fraud in the USA in 1993
3.8×10^9	Microsoft revenue in 1993
1×10^{10}	Rough monetary losses associated with BCCI
1.3×10^{10}	Lockheed revenue in 1993
1.5×10^{10}	Rough United Nations yearly budget
2.8×10^{10}	Planned cost for the space station
2.6×10^{11}	United States 1994 military spending
2.6×10^{11}	United States 1994 predicted deficit
8×10^{11}	United States 1994 entitlement spending
1×10^{12}	Rough total United States health care spending in 1994
1.3×10^{12}	United States 1994 tax receipts
1.5×10^{12}	United States 1994 federal government spending
4.4×10^{12}	United States 1994 national debt
6.4×10^{12}	United States 1994 gross domestic product
1.4×10^{13}	United States 1994 unfunded liabilities for entitlement programs