HOW SCIENCE WORKS: Evolution

"There is grandeur in this view of life that .. whilst this planet has gone cycling on according to the fixed law of gravity, from so simple a beginning, endless forms most beautiful and most wonderful have been, and are being, evolved."

Charles Darwin
***On the Origin of Species*, 1859**

Evolution is just a theory , isn`t it?

What is a scientific theory anyway?

Don`t scientists prove things?

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

How does scientific thinking differ from religious thinking?

Why are most leading scientists atheists?

Are science and religion compatible?

Why are there so many different religious beliefs but only one science?

What is the evidence for evolution?

If you are interested in any of these questions, and have some knowledge of biology, you are invited to read this essay

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Essay web site address: **http://template.bio.warwick.ac.uk/staff/jellis/evolution**

AN INTRODUCTORY ESSAY FOR STUDENTS OF BIOLOGY

"All our science, measured against reality, is primitive and child-like – and yet it is the most precious thing we have"

Albert Einstein

"...and freedom of thought is best promoted by the gradual illumination of men`s minds which follows from the advance of science"

Charles Darwin

PREFACE

When I was growing up, I found myself, like all young people, in a world full of adults telling me stories. Stories about the place of humans in the world and how they arose, stories about what to believe and how to behave. My problem was that there are many different stories, so how do you decide to choose between them and formulate your own views? I asked my father about this, and he advised me that, when forming my view of the world, not to take any notice of the status of people making particular claims, whether they were called prince, or bishop or professor or whether they wore fancy clothes like mitres or mortar

boards. The only thing that mattered, he said, was the quality of the evidence in support of the claims they were making, and that I should be the judge of that quality.

This essay follows my father`s advice to seek out the best-quality, empirical evidence you can find, and stick to what it implies until better evidence comes along. It is the **quality** of the evidence that you need to learn how to evaluate. In this essay I discuss the criteria you should bear in mind when evaluating the evidence for any claim, in the hope that this will help you to develop an independent, critical way of thinking. Reduced to the simplest terms, my advice to you when confronted by people making claims about any subject is not to accept their claims at face value, but to ask "How do you know that?"

This essay is taken from a set of lectures I devised at Warwick University in 2006, aimed at first year undergraduates in biology. You may find some elements of this essay controversial, so let me say right at the start that it is not my intention to tell you what to think. My intention is to help you to learn **how** to think, by discussing the sorts of consideration you should bear in mind when formulating your own views about the nature of the world, especially about how scientists study the world. The term `world` in this essay means everything that we experience. I have chosen evolution as the example for explaining how science works because it graphically illustrates the issues I wish to address, and because evolution is under increasing attack in some educational establishments.

In Part I of this essay, I describe and contrast the two principal ways in which humans try to understand the world, both now and in the past. In Part II, I discuss the type of thinking that characterises how science works, while in Parts III and IV, I present some of the evidence that supports the idea that all organisms, including humans, are related to one another and change over time. At the end of this essay you will find a Further Reading List, so that you can pursue particular topics in further depth. At the end are some Suggestions for Discussion Topics.

PART I – TWO WAYS OF EXPLAINING THE WORLD

Figure 1 describes the two aims of this essay; these aims are connected.

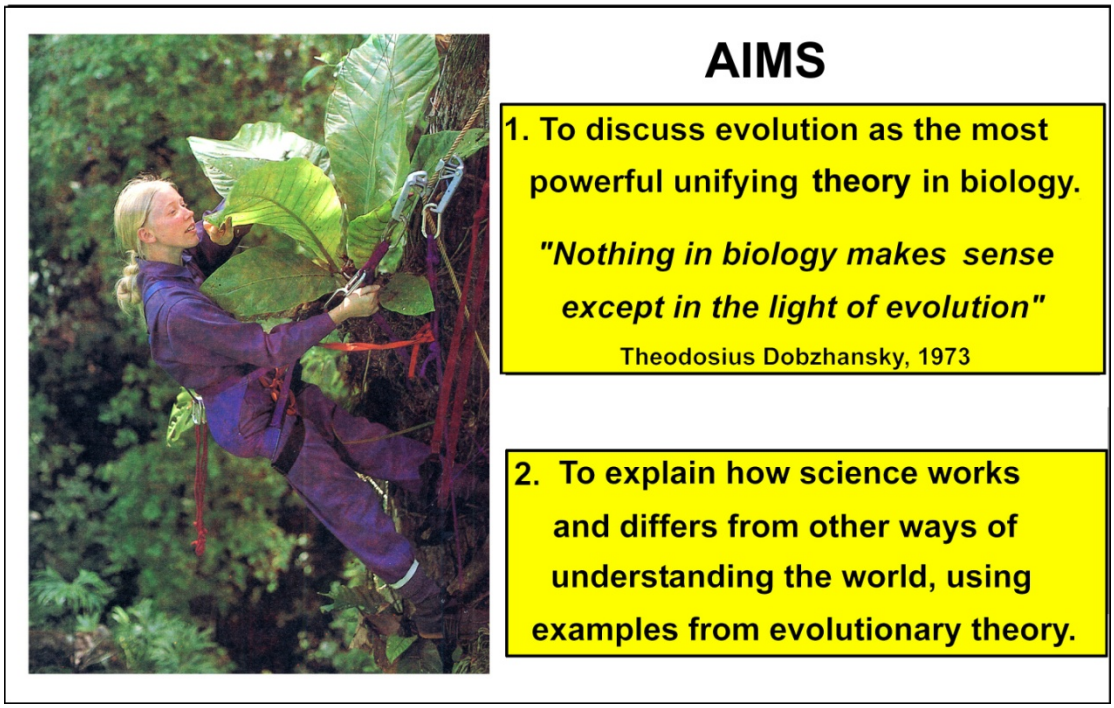

Figure 1

(*PLEASE NOTE:* all the Figures in this essay are high definition and can be enlarged by clicking on them)

The first aim is to explain the importance of evolutionary theory in biology. All the branches of science today are founded on theories. Now you have to be very careful when using the word `theory` because it has two, quite different, meanings. In ordinary conversation, the word `theory` is used to mean a `wild or fanciful speculation, a hunch`. This is what it means when, for instance, people say `One of my pet theories is that, when I am in a hurry, all the traffic lights are red`.

This is not what the word `theory` means in science. **In science**, **theories are coherent conceptual frameworks that unify and make sense of all the currently available evidence in a given field.** All the modern branches of science are founded on theories. Chemistry is founded on one theory – the theory that matter is made of atoms. Geology is founded on the theory of plate tectonics – the idea that the surface of the Earth is divided into a series of moving plates. Physics is founded on two theories – quantum mechanics that deals with the very small, and relativity that deals with the very large. Biology is, like chemistry and geology, founded on one theory, evolutionary theory, the idea that all organisms are related to one another and change over time.

It is difficult to overstate the importance of evolutionary theory for understanding the living world – evolutionary considerations permeate our understanding of biology at all levels, from ecosystems to individual organisms, from tissues to molecules.
This is because every organism in the world is the product of an evolutionary process. This fact is summarised by a famous statement made in 1973 by a biologist with the splendid name of Theodosius Dobzhansky - "Nothing in biology makes sense except in the light of evolution". Not only is evolutionary theory fundamental to understanding the biological world, but in addition, it can plausibly be argued to be the most prominent and far-reaching

theory in the whole of science. Why is this? It is because the idea of evolution has changed the way in which we view the place of humanity in the universe.

The idea of evolution can be traced back to the Ancient Greeks, but before it was substantiated by Charles Darwin in the 19th century, the prevailing view in the Western world was that we live in a universe specifically created for us a few thousand years ago by a benevolent god – a human-centred universe. However, discoveries of fossils of extinct organisms, the growing realisation by geologists that the Earth is much older than previously thought, and worst of all, that humanity is of very recent origin, were starting to raise doubts among some religious people before Darwin made his contribution. An example of this doubt is provided by the poem *In Memoriam* by Tennyson, published in 1850. In this poem, Tennyson expresses his fear and dismay that the death of his friend, Arthur Hallam, at the early age of 22, was a meaningless event in a purposeless universe, and that human life has no more significance than the life of any other animal.

The extensive evidence published in Darwin`s book *On the Origin of Species* in 1859 supported an alternative view to the human-centred one, in which humans are seen as one animal amongst many, created by a natural process that has no design, foresight or purpose, and that has been operating for many millions of years. In his later book *The Descent of Man* (1871), Darwin further argued that humans are different from other animals only in terms of degree, not in kind. This view contrasts with the older view that human nature can be explained only on the basis of the actions and intentions of a supernatural creator. The implications of this new outlook are still stimulating vigorous debate, but among biologists, evolution is regarded as a fact as well as a theory, in the same way that chemists discussing atomic theory agree that it is a fact that matter is made of atoms.

The second aim of this course is quite different – it is to explain how science works. If you listen to discussions or read articles about science in the popular media, it is obvious that there is widespread misunderstanding of how science is conducted. Teachers are partly to blame for this – professors spend too much time talking about the results**,** the so-called facts and theories of science, and not enough time explaining how science works as a discipline and how it differs from other ways of explaining the world.

Human beings are programmed by their evolutionary origins to seek explanations because this helps us to survive in a competitive world. This tendency is most obviously seen in the behaviour of young children, who drive their parents frantic by endlessly asking questions about the world, many of which the parents are unable to answer.

Historically, there have been two quite distinct ways of explaining the world – recall that, by `the world` in this essay, I mean everything that we experience. Philosophers call these two ways, **supernaturalism** and **naturalism (**Fig**.** 2).

Supernaturalism embraces all those ideas that suppose that, alongside the physical world that we are all aware of, there co-exists another world that is invisible, but which contains active agents, variously termed gods, deities, spirits, souls, ghosts, demons, fairies and so on. These agents are often believed to have their own agendas, their own views, preferences and purposes. They can behave unpredictably, that is, they may be capricious, and often, but not always, they are supposed to interact with the physical world.

Figure 2

Now this way of explaining the world in supernatural terms is extremely popular. All human cultures throughout recorded history have produced such beliefs and the vast majority of people in the world today adhere to one or other of them. Every culture has a belief in a spiritual world that contains one or more gods who are in control of powerful forces, and thus can be prayed to for advice, comfort and practical action. If we ask how this type of thinking is maintained from generation to generation, it is by accepting the authority of tradition, personal revelation and ancient texts. These sources of authority are usually regarded as sacrosanct and not open to question. Surveys show that the best predictor of peoples` religious belief is that of their parents – children tend to believe what their parents tell them because their parents are their first sources of authority.

The alternative way of explaining the world is called `**naturalism**` by philosophers (Fig. 2). **This view argues that there is only one world; it is the physical world we are all aware of, and it behaves according to inbuilt, unvarying regularities as determined by observation and experiment.** These regularities are sometimes called `laws of nature` but this term is often misunderstood to imply a lawgiver**,** which is not the intention. An example of such unvarying regularities are the three laws of motion discovered by Isaac Newton, and the four laws of thermodynamics. In this naturalistic scheme of things, there are no supernatural agents, so there is no possibility of miracles nor is there any point in praying for divine intervention.

The naturalistic view is very recent in human history. It began in a serious way only at the time of the Enlightenment in the 18th century in Western Europe. The Enlightenment is the term used to describe an intellectual movement whose members believed that reason could be used to combat both superstition and tyranny and to build a better world. The principal targets

of the founders of the Enlightenment were organised religion and the domination of society by an hereditary aristocracy. The founders of the Enlighenment were motivated by the desire to be free to pursue the truth as they saw fit, without the threat of sanction for challenging established ideas.

Naturalism argues that reason should be the prime means of understanding the world, but reason based on observation and experiments and not on an acceptance of ancient authority. Now you might say that I am an ancient authority – I am certainly ancient! - and that you are accepting what I say because I am an authority, but the difference is that any scientific claim I make can be checked by anybody prepared to take the time and trouble, whereas it is not possible to check claims derived from revelation or ancient texts - you either accept such claims or you don`t.

Now it is important to understand that **both naturalism and supernaturalism are assumptions**, **and both are logically possible, but both cannot be correct** – by definition, one excludes the other. Contrary to popular opinion, it follows that science is incompatible with religion. Why is this? It is because once you attribute any particular event to a supernatural agent, a proposition that cannot be disproven by observation or experiment, then science becomes both irrelevant and impossible. This is because science works on **the assumption that natural events have natural causes**. For example, if a scientist carries out an experiment and finds that he or she cannot initially understand the results of that experiment, the scientist does not say that is because of the actions of supernatural agents – if a scientist did say that, science would stop. What scientists do instead, is to think more imaginatively about the problem, until they come up with another testable hypothesis involving natural causes. If we could apply natural knowledge to understand supernatural agents, then by definition they would not be supernatural. I will address in Part II the reasons why some scientists nevertheless hold religious beliefs.

Historically, naturalism has been found to be the best way we have so far discovered to make any progress in understanding the world – it is naturalism, and not supernaturalism, that has made the modern developed world. So supernaturalism is not included within science because, by its very nature, it is not testable. Supernaturalism lacks a methodology by which its claims can be tested, whereas science does have such a methodology. How this methodology operates I shall discuss in a moment.

I mention this difference between supernaturalism and naturalism because some people suggest that there is no conflict between the two - that science and religion are compatible because they deal with different areas. Such people argue that science tries to discover what things are and how they work, while religion is trying to discover whether the Universe, and human life in particular, has any overall meaning. However, this view that science and religion concern different areas of enquiry is very recent.

Throughout recorded history, religions have tried to answer questions about what things are made of and how they work as an essential part of their mission, just as science does. All religious beliefs contain creation myths about how the world originated in the physical sense. What has changed over the time since science started to develop in the 17th century, is that many religions have progressively abandoned trying to explain how the world works, as the creation myths were progressively shown to be unsupported by the physical evidence. So the main-stream religions today concentrate instead

on whether the world has any purpose or moral dimension, and no longer claim to study how the world works.

The late evolutionary biologist, Steven Jay Gould, proposed in 1997 the idea that science and religion are concerned with different domains of understanding that he termed `magisteria`. `Magisterium` is the Latin word for `teacher`. This view is summarised by the acronym NOMA, for `non-overlapping magisteria`. According to the NOMA proposal, science is concerned with what the Universe is made of and how it works, while religion is concerned with questions of ultimate meaning and moral value. Because of this difference, Gould argued, religion and science cannot be combined and are not in conflict. They deal with different areas of human experience, so it follows that science and religion cannot comment on each other`s concerns.

The flaw in this idea is that there is no empirical evidence as yet that the Universe has any overall meaning or moral dimension and Gould does not attempt to offer any. NOMA also implies that religious people should not try to reinterpret their beliefs in the light of scientific discoveries, which is unfair to them. It is very clear that religion cannot, and does not, refrain from making claims that have observable consequences in the physical world, such as the occurrence of miracles and the answering of prayers, so it is untrue that religion and science do not overlap. Nevertheless, some scientists accept the NOMA principle. When doing their science, they accept the naturalistic assumption that the supernatural does not exist - if they did not, they could not practise science, as I explain above. When practising their religion, they abandon the naturalistic assumption. In this way, they enjoy having their cake and eating it.

In the developed world we find ourselves in the paradoxical situation that our advanced lifestyles have been created by the application of scientific discoveries, but despite this, the vast majority of people enjoying those lifestyles still interpret the world in a supernatural fashion. There are several possible reasons for this. One is that the evolutionary process that determined how the human mind works predisposes us to interpret the world in a supernatural fashion; I discuss this possibility later in this essay. Another reason is that most people have not been educated to understand the basic principles by which science operates, so in Part II, I talk about these. Then in Parts III and IV, I shall talk about the theory of evolution and the evidence that supports it, as an example of how science works with which I am familiar.

PART II - HOW SCIENCE WORKS

There are three features of science that distinguish it from supernaturalism.

The first distinctive feature is shown in Figure 3. `*Nullius in verba*` is the motto of the Royal Society, the premier body of scientists in Britain, founded in 1660. Other countries have similar bodies of leading scientists, called National Academies. The literal translation of this motto is `not in words`. This motto encapsulates the view that you should base your beliefs on your own assessment of the best available evidence and not take anyone`s word for it. So there is no room for dogma or for an appeal to authority, tradition or ancient texts - this is a major difference from how supernaturalism operates. This difference between supernaturalism and naturalism can be summarised by saying that, while supernaturalism has authorities who make assertions, naturalism has experts who are familiar with the best available evidence.

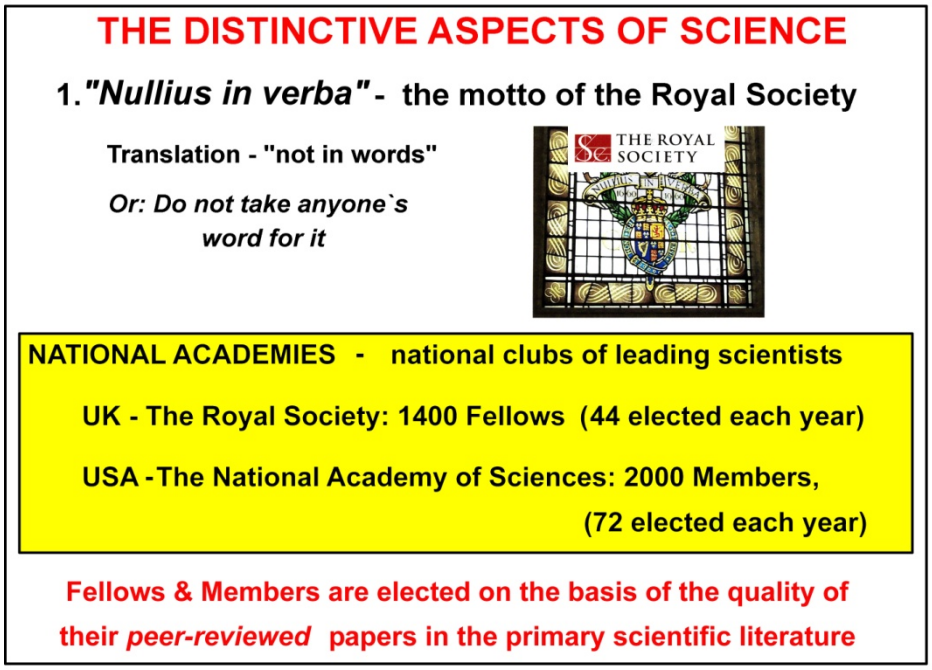

Figure 3

But now we have to ask – where is the best available evidence to be found? The answer is that the best available evidence is available in the **peer-reviewed literature**. Figure 4 explains what this means.

When a scientist, or more likely these days, a group of scientists, feel that they have made some new observations or arrived at some novel insights about some aspect of the natural world from their experiments, they write down what they have done in enough detail for other scientists familiar with the field to be able to repeat the observations and experiments.

The main reason for doing this is to ensure that the observations are reliable, in the sense that they can be repeated by other, independent scientists. The completed writing is referred to as a manuscript or paper, and this is submitted to a learned journal that specialises in the appropriate branch of science. The journal editor sends the paper out for review by several anonymous experts in the field - the peers. The term `peer` means `equal`, but is often misunderstood to mean `superior`.

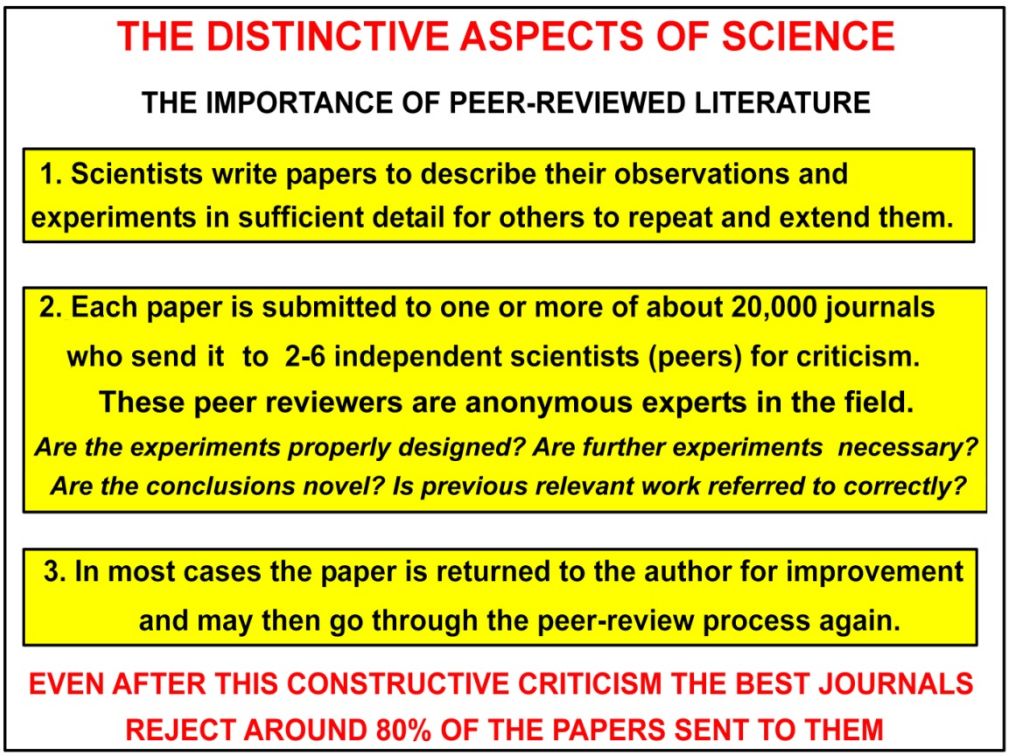

Figure 4

These peers are asked to read the paper in detail and to assess the validity of the observations, experiments and conclusions. They may suggest that some of the conclusions are not justified until further observations or experiments have been performed or point out flaws in the reasoning used by the authors. They may think that, although the conclusions are valid, they are not sufficiently important or novel to justify publication in the journal to which they have been submitted. The editor passes on these criticisms to the authors and asks them to revise the paper in light of the peers` comments. Such is the pressure on space in the best journals that only those papers that contain the most innovative observations can be accepted for publication - the others are rejected and the authors then may send them to other journals, where the entire process is repeated.

Once a paper has been accepted into the peer-reviewed literature, its assessment by other scientists does not stop but continues. Its conclusions are critically discussed at science conferences and in laboratories around the world. Eventually a general consensus on a given topic emerges. An example would be the general consensus that global warming has a human-made component. This does not mean that every climate scientist agrees with this conclusion, but it does mean that the weight of the evidence available today points in this direction. Future discoveries may of course modify this conclusion. **Scientific ideas are always open to challenge and change in the light of new evidence.**

Contrast this elaborate assessment procedure with the lack of such procedures by which religious claims can be assessed. How can you assess claims made in documents written hundreds or thousands of years ago by people whose knowledge of the world was inferior to ours? You either accept such claims based on the authority of the person making it, or you do not. What you cannot do is to assess such claims in the same way that you can assess scientific claims by reference to the peer-reviewed literature. This

does not mean that all the claims made in the peer-reviewed literature are correct – scientists are human, they make mistakes, they are prone to dogma, and are influenced by things such as seniority, charisma and oneupmanship – but the peer-reviewed literature is still the best source of information about the world that we have. The same is true for the arts and the humanities - the peer-reviewed literature in these fields of study is the best source of information about the state of understanding in these fields, which include history, philosophy and theology.

The **second** distinctive aspect of science**,** and in my view, the most important**,** is illustrated in Figure 5.

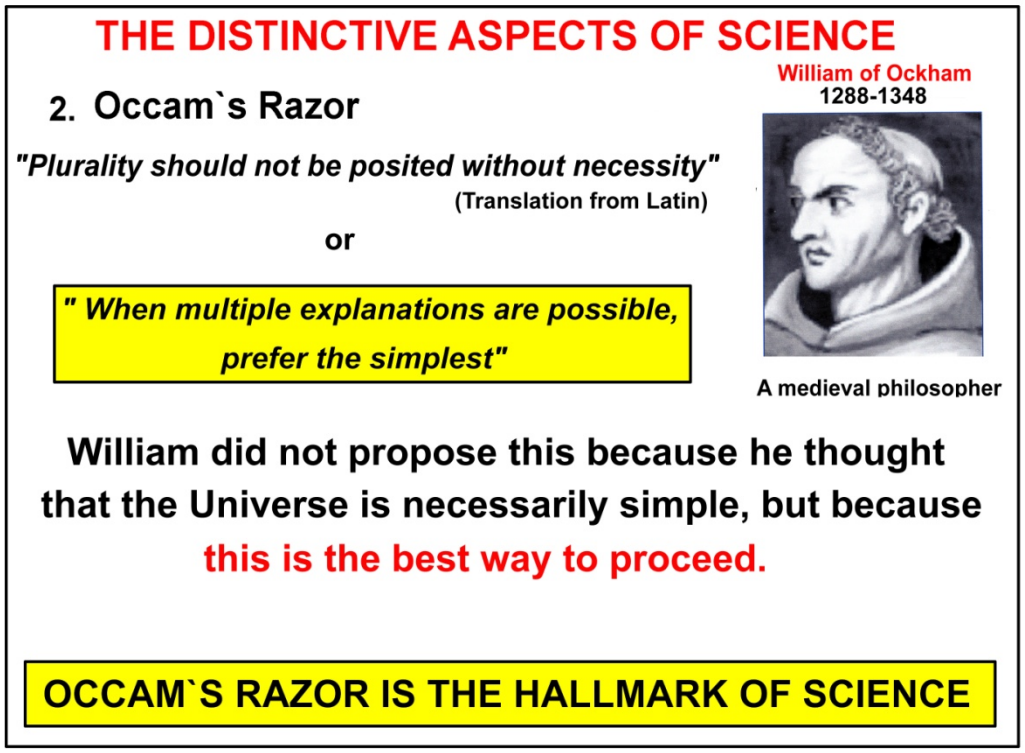

Figure 5

William of Occam was a Franciscan philosopher who came from the village of Ockham (or Occam) in the county of Surrey in the United Kingdom. He tackled the problem that for any given body of evidence you can almost always postulate several,
quite different explanations. William argued that in this situation the best way to proceed is to prefer the simplest explanation that is consistent with all the available evidence – the explanation that makes the least number of assumptions. The word `razor` is used to mean that unnecessary assumptions are shaved away. Occam`s razor is sometimes referred to as the `principle of parsimony`; the word `parsimony` means `economy`. Let me give you an example that actually happened recently.

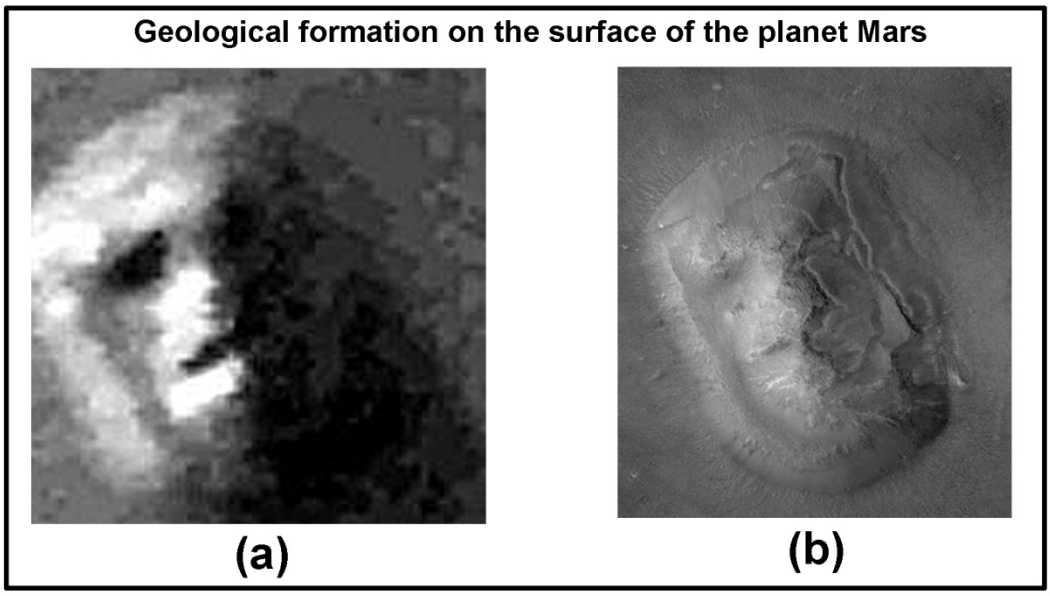

Figure 6

In 1976 the Viking spacecraft took the picture of a rock formation on the Martian surface shown in Figure 6(a). This picture caused a lot of excitement because many people, including some scientists, interpreted it to mean that Martians had carved the image of a human face on the rock. Now this interpretation clearly makes a lot of assumptions – that intelligent creatures exist or have existed on the planet Mars, that they know what humans look like, or even look like humans themselves and that they want to signal to us. A much simpler interpretation, that is one with fewer assumptions, of course is that this is just an accidental effect of the angle of sunlight that happens to remind us of a face. We humans are programmed to recognise faces. Some people see faces in clouds, fires, tea cups and items of pastry!

The picture shown in Figure 6 (b) was taken in 1998 by the Global Surveyor spacecraft when the angle of illumination of the same region was different, and it clearly supports the simpler interpretation. But let`s be honest - the simpler interpretation is also more boring! The reason that conspiracy theories are so popular is that they are more interesting than real life.

Now it is important to grasp that Occam`s razor does not say that you should prefer the simplest hypothesis because it is more likely to be correct – there is no *a priori* reason why Nature should be simple. What Occam`s razor says is that **you should prefer the simplest hypothesis because it is the best way to proceed.** So William is defining a method – an essential part of the scientific method (Fig. 5).

I cannot overemphasise the importance of Occam`s razor to the practice of science. If you abandon this principle, you might as well believe any interpretation of the world that you find comforting and appealing – and many people do. It is probably because of Occam`s razor that the majority of leading scientists today are not supernaturalists, because postulating invisible active agents clearly requires more assumptions than does the naturalistic view that such agents do not exist.

A survey of the incidence of religious belief among leading American scientists was published in the journal *Nature* in 1998, and Figure 7 compares it with similar surveys in 1914 and 1933. The response rate in the 1998 survey of members of the US National Academy of Sciences was about 50%.

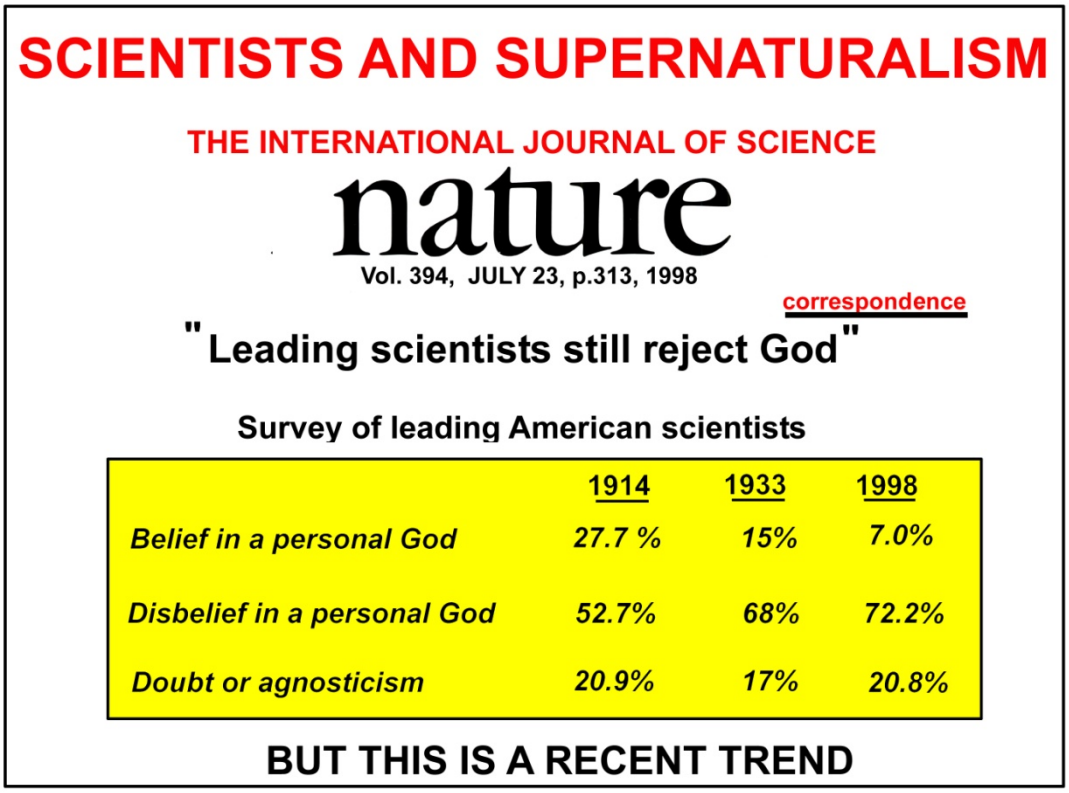

Figure 7

These surveys clearly show a decline of belief in a personal God during that period. A similar unpublished survey was carried out among Fellows of the Royal Society in Britain in 2006 and obtained a similar result – the incidence of supernaturalists is less than 10% among those Fellows who responded to the survey (about 25% of all the Fellows contacted). But interestingly, this is a recent trend, and if we look further back in the history of science, we see a different pattern.

We need first to ask the question - who was the first scientist in the modern sense? What I mean by this is - who is the first person we know about who used the basic experimental methodology that modern scientists use? Figure 8 provides the answer and lists the basic steps in the experimental method.

To be a scientist you have to be curious about the Universe and ask questions about aspects that you do not understand. You have to concentrate on a particular problem that looks to be of a manageable size, and imagine possible explanations. You then devise experiments to test these explanations, and ask whether the natural world behaves in accordance with one or other of your ideas. You usually have to modify your ideas to accommodate the results of the experiments, using Occam`s razor as a guide.

This procedure is not foolproof nor is it guaranteed to give you the correct answers. Occam`s razor can mislead you if, for example, the correct explanation is not among the possible explanations you have imagined. Thus the methodology of science is not a surefire recipe; its successful use requires not only intelligence, but also creativity and imagination, and the honesty to admit mistakes when you make them.

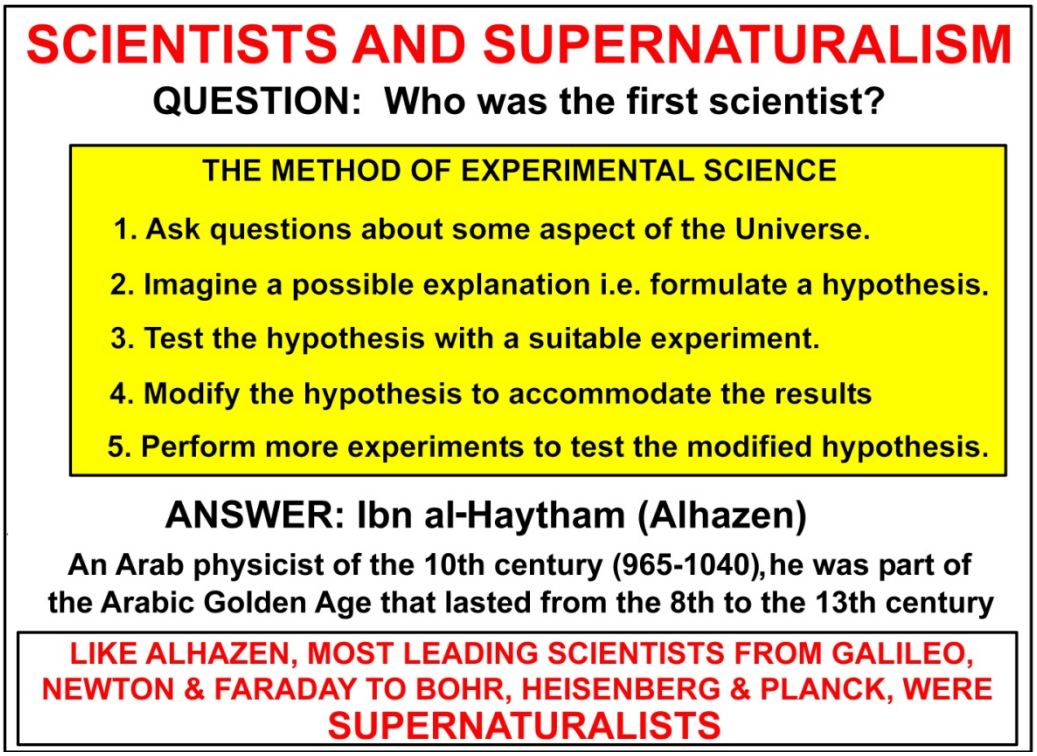

Figure 8

To return to the question as to who was the first experimental scientist that we know about, the answer is surprising. Most people think it was an Ancient Greek philosopher, such as Aristotle or Archimedes. Ancient Greek philosophers based their views in many cases on empirical observations of the world rather than by appeals to authority, and thereby made many advances in understanding, but they were not renowned for formulating hypotheses and then testing them by experiment in the routine way that modern scientists do.

The first recorded scientist, defined as I have described, was an Arab called Ibn al-Haytham, who carried out experiments on many aspects of vision and optics in the 10th century (Fig. 8). This was the middle of a period when in the Arab world there was a tremendous flowering in the arts, literature and science – called the Arabic Golden Age. Some people call it the Islamic Golden Age but many people of different faiths contributed to it and they all wrote in Arabic. It is also surprising to learn that many of the discoveries that we in the West associate with people like Galileo and Newton in the 16th and 17th centuries were in fact initiated in the Arab world, at a time when free enquiry was not encouraged by the religious authorities in Europe.

Now Ibn al-Haytham was a devout Muslim – that is, he was a supernaturalist. He studied science because he considered that by doing this he could better understand the nature of the god that he believed in – he thought that a supernatural agent had created the laws of nature. The same is true of virtually all the leading scientists in the

Western world, such as Galileo and Newton, who lived after al-Haytham, until about the middle of the 20th century. There were a few exceptions – Pierre Laplace, Simeon Poisson, Albert Einstein, Paul Dirac and Marie Curie were naturalists for example. Charles Darwin experienced a decline in his Anglican belief in a benevolent god as he grew older, and in a letter written three years before his death in 1882 wrote "that an agnostic would be a more correct description of my state of mind". Other correspondence suggests that Darwin was inclined to the deist view that an intelligent agent had created the Universe and the laws by which it operates, but thereafter had no interaction with it. This deist view is equivalent in practical terms to being a naturalist because it allows science to function in a naturalistic framework, as well as ruling out miracles and praying for divine intervention. For this reason, deism is the only type of religious belief that is not in conflict with the naturalist approach upon which science depends. Most of the other leading scientists up to about the middle of the 20th century were supernaturalists however.

What can we deduce from these historical facts? Firstly, it is obvious that **believing in the supernatural does not prevent you becoming a leading scientist**. We can also deduce that such people separate the way they think about science from the way they think about religion. When doing science they use Occam`s razor, when doing religion they abandon Occam`s razor, because postulating invisible agents clearly requires more assumptions than not postulating them. These assumptions include the origins, properties, and interests of such agents. These assumptions vary greatly among the different religions – in the monotheistic religions God is good, omniscient and omnipotent (hence the capital G), but this is not the case for some of the gods in many polytheistic religions. So the worst that supernaturalist scientists can be accused of is inconsistency**.**

What about the evidence that, according to polls and surveys, most leading scientists today have no religious beliefs? One can only speculate about the reasons for this. My suggestion is that it is because, at the end of the day, religious explanations are not really explanations – they may be emotionally appealing but they are intellectually unsatisfying**,** because they posit even greater mysteries that the ones you are trying to explain. As the philosopher Anthony Grayling so eloquently puts it "To answer the question of how the universe came into existence by saying `God created it` is not in fact to answer the question, but to explain one mystery by appealing to an even greater mystery – exactly like saying that the universe rests on the back of a turtle, and then ignoring the question of what the turtle rests on".

One interesting problem that some naturalist scientists and philosophers of today are tackling is how to explain the universal persistence of supernatural beliefs - why do they occur, what accounts for their particular features, what purposes do they serve? In recent years, anthropologists studying the huge variety of supernatural beliefs found around the world, and psychologists seeking evolutionary explanations for religious beliefs, have proposed a number of hypotheses (Fig. 9).

There are two general types of explanation offered, but they are not mutually exclusive – elements of both may be correct. The first type assumes that supernatural beliefs have direct survival value for humans and thus are adaptive features. The obvious, common sense purposes listed in Figure 9(a) are certainly found in the world`s major religions and help people cope with suffering, especially illness. Before the real causes of human disease started to be identified some 150 years ago, people often interpreted illness as punishment for flouting the will of a deity, so they would

plead with their deity for relief. Humans are also probably the only species that are aware they are going to die and we all grieve when we lose our loved ones. However, anthropologists such as Pascal Boyer point out that there are many thousands of minor supernatural beliefs where these obvious, common sense explanations do not always apply, so they suppose there must be some deeper underlying reasons for supernatural beliefs related to how the cognitive systems in the human brain interpret the world.

One plausible suggestion is what is called **intentionality,** sometimes called the `theory of mind` (Fig. 9b).

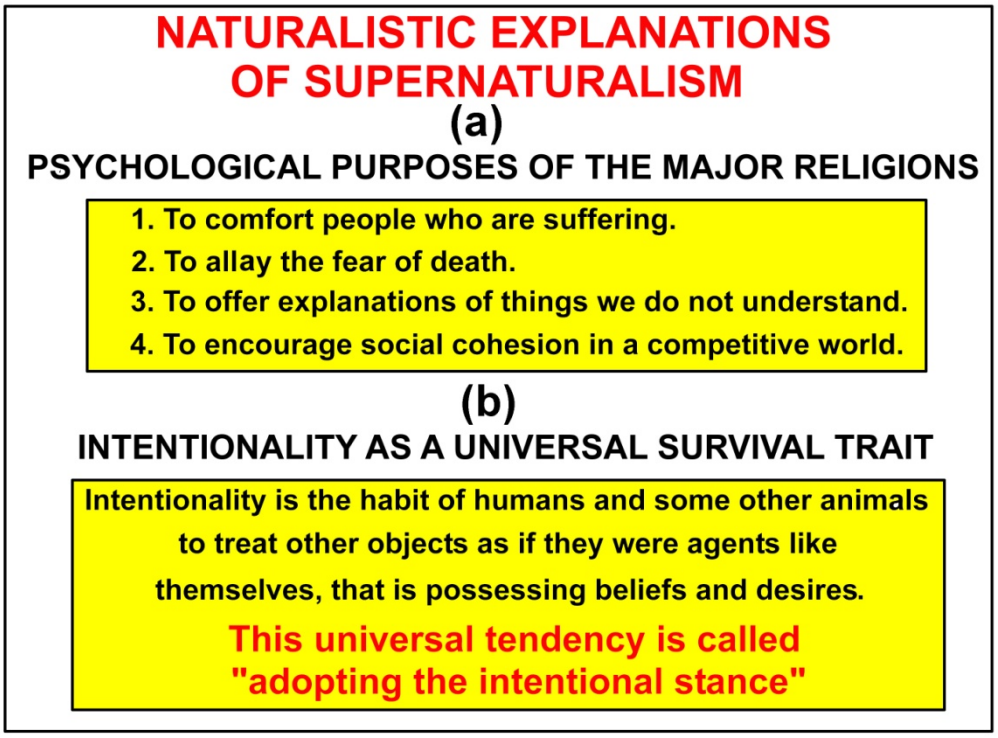

Figure 9

Intentionality is the ability of humans and some other animals to treat other objects and animals as agents like themselves, that is, agents with minds that have desires, beliefs and intentions (Fig. 9b). Each time you have a conversation, you adopt an intentional stance towards the other person - you make assumptions about their desires, beliefs and intentions because you believe the other person is an active agent like yourself. The other person is making similar assumptions about you. The term `adopting the intentional stance` was suggested by the philosopher Daniel Dennett.

Adopting the intentional stance is clearly an important survival tactic for animals, especially for social animals like ourselves. So the suggestion is that our brains are so hard-wired to produce this type of thinking that we extend it to other objects and events that affect us. For example, when a rock falls and injures us, many people tend to assume that this means that there is an active agent making the rock do this - they believe that the rock moves because of some intentionality. Such people commonly
think that the agent is invisible because they cannot see one. In primitive societies today, it is believed that many objects in the environment - trees, rocks, rivers, mountains and so on, are inhabited by invisible spirits that can be influenced by ritual practices. How many among the most rational of us shout at our PCs when they do not do what we want? It is easy to slip

momentarily into responding as though they were active agents. We all sympathize with Basil Fawlty losing his temper with his car when it refuses to start in the BBC comedy series *Fawlty Towers*. This adoption of the intentional stance is also a common experience among survivors of life-threatening accidents - they attribute meaning to their survival in terms of actions by a supernatural agent.

Evidence that this tendency to interpret the world in a supernatural fashion is partly genetically determined comes from the Minnesota twin studies, in which the religiosity of identical twins raised apart in different environments were compared with that of fraternal twins raised apart. The results were interpreted to mean that about 50% of the tendency to be religious is genetically determined. Further studies showed that this tendency becomes more apparent as children approach adulthood.

Given the universality of interpreting the world in an intentional fashion, it is perhaps not surprising that some scientists have also fallen into this trap. For example, the Gaia theory of James Lovelock proposes that the Earth`s biosphere, plus its environment, is a closely coupled, evolving system that has the goal of keeping the climate favourable for life as it exists today. The simpler view, held by most scientists, is that the biosphere is a comprehensible mixture of air, water, soil and organisms, whose behaviour is explicable in terms of different steady states produced by negative feedback effects. There is no sense in which such a system can be said to have a goal.
Similarly, some physicists suggest from the fact that the Universe has properties that allow human life to appear, that this means that its properties were designed with this intention in mind – the so-called strong anthropic principle. It is hard to imagine a finer example of arrogance, as well as ignorance of the mechanisms of evolution, than to assert that humans are the purpose of the Universe, but this example does illustrate the tendency we all have to adopt the intentional stance.

On this intentional hypothesis, the widespread tendency to explain the world in supernatural terms is not itself an adaptive feature of evolution, but a byproduct of parts of the mind that evolved because they aid survival in other ways. It is important to realise that a common feature of evolution is that properties which evolved because they help survival in a particular environment may have important, but quite unrelated, consequences. For example, the evolution of feathers in some dinosaurs was probably connected with the development of warm-bloodedness, but had the unrelated, but important, consequence of permitting the subsequent development of flight.

The universality of the intentional stance does not mean that supernatural beliefs are necessarily correct, only that they originate naturally in the cognitive systems that all humans use to interpret the world. This hypothesis amounts to saying that, while supernaturalism tells us something about what goes on inside the human head, there is currently no convincing evidence that it also tells us what goes on outside the human head. So we have to be alert to avoid being victims of our biology, especially today when we find ourselves living with a stone-age mentality in a space-age world.

I said earlier that there were three distinctive aspects of science. The third is shown in Figure 10. **The provisional nature of scientific knowledge is the aspect most commonly misunderstood by non-scientists**. Often when science is mentioned in the media, the impression is given that scientific knowledge is absolute and certain. This is not the case.

If we ask what science is, it is not a set of data, it is not a set of techniques, it is a set of ideas (Fig.10). These ideas are based on reason applied to data and techniques, but data and techniques do not on their own constitute science - it is the ideas that constitute science. These ideas are based on the best evidence available at the time,
but they are not sacrosanct – they are always open to change to accommodate new data and new ideas. It is this openness to change that explains why science is so successful at understanding the world.

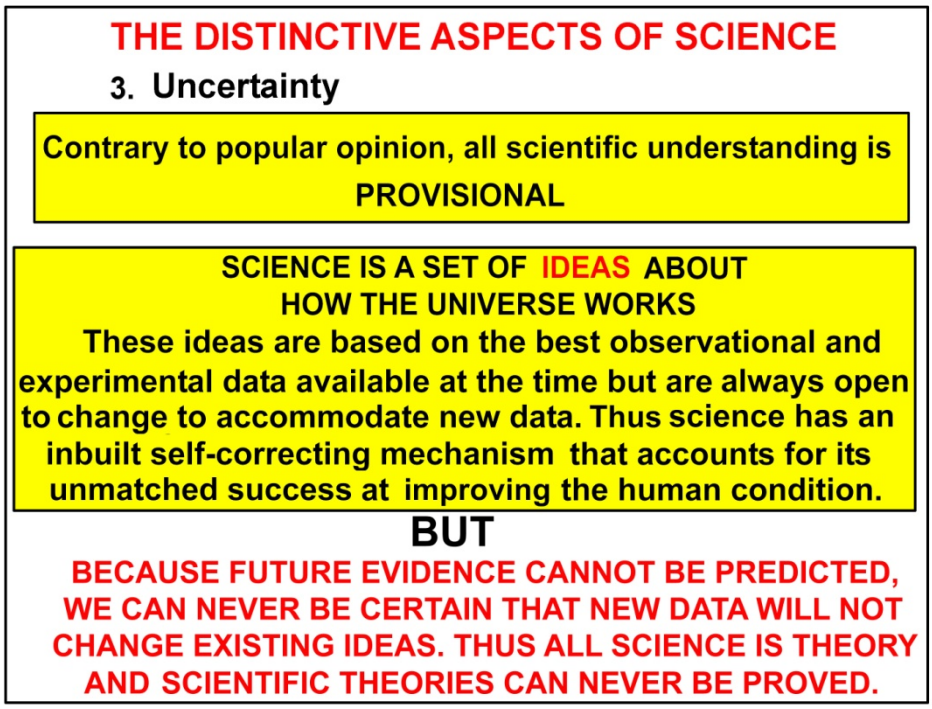

Figure 10

Let me be very clear about this - **science is the most successful human endeavour in history.** Despite all the problems in the world, it is the case that never before in human history have so many people been so well fed, and have had so many opportunities to lead long, healthy and interesting lives. These advances stem from the application of scientific ideas and discoveries. **Science works**, so it may seem surprising that scientific knowledge is not certain in an absolute sense. Why is this?

It is because you cannot predict the future. You can never be certain that even long-held and very successful scientific ideas will not change as a result of future discoveries. Let me give you an example:-

In 1687 Isaac Newton published his master work that marks the beginning of science in the Western world – the *Principia Mathematica.* This was the first book to propose general natural laws in a quantitative fashion. Newton`s laws of motion and his equations that describe gravity are incredibly successful and precise – precise enough to be used to send astronauts to the Moon and to land spacecraft on the planet Mars. Nevertheless, the concepts on which Newton based his laws of motion were shown to be incorrect just over 200 years later by Albert Einstein in 1905. Newton`s concepts with respect to motion are wrong because he supposed that time and space are absolute and independent – this agrees with our common-sense perceptions of time and space. Einstein had the genius to realise that because

experiments show that the velocity of light is constant, irrespective of the velocity of the light source**,** this view must be wrong – time and space are relative to one another, not independent. Experiments show that the faster a clock moves, the slower it ticks and that the faster an object moves, the heavier it becomes. In other words, our common-sense perceptions of time and space are wrong. Newton`s laws of motion work well enough in practice because relativistic effects become significant only at speeds much faster than the ones we normally have to deal with. These effects impact on human affairs only in the design of particle accelerators that would not work unless the relativistic effects were taken into account in their design.

So here we have an example of a very successful scientific theory that was accepted for over 200 years, but whose basic concepts, on which the industrial revolution was partly founded, are now known to be incorrect. **Science is a uniquely successful human activity precisely because it employs this inbuilt self-correcting mechanism.** So certainty is an illusion. Scientific knowledge is not a fixed destination but a moving target. This is why commentators discussing science who use the word `proof` demonstrate that they do not understand how science works. In science, proof is not an option. Disproof on the other hand is an option- if we discovered human fossils in rocks older than the rocks containing dinosaurs, our current ideas about the evolution of mammals would be instantly disproved. Einstein famously said that no amount of experiments could prove him correct, but a single experiment could prove him wrong. So if you crave certainty, you will not find it in science. This is why media interviewers who ask scientists “Are you certain that.....?” are demonstrating their ignorance of how science works.

I should now like to talk about some of the key terms used in science. When I was at university I was taught the importance of defining terms in order to have sensible conversations. So if I ask you to define the term `molar` say or `eukaryote` or `evolution`, I would hope that you rattle off a precise definition in one sentence for each term. Don`t panic, I am not going to ask you to do this now – I want you to realise that this is a good way to learn about science.

Figure 11 lists definitions of three terms used in science – **facts**, **hypotheses** and **theories**. Again, these terms are often misunderstood by nonscientists. Even scientists tend to say `theory` when they really mean `hypothesis`. I talked about theories at the start of this lecture. Let me remind you that theories are coherent conceptual frameworks that unify and make sense of all the available evidence in a given field. Good theories are quantitative and lead to experiments that uncover previously unknown phenomena. All the branches of modern science are founded on theories – in the end science is theory. However Francis Crick, the codiscoverer of the structure of DNA, cautioned that one should beware of theories that explain all the relevant facts, because some of these facts will be wrong – scientists make mistakes!

What about `facts`?

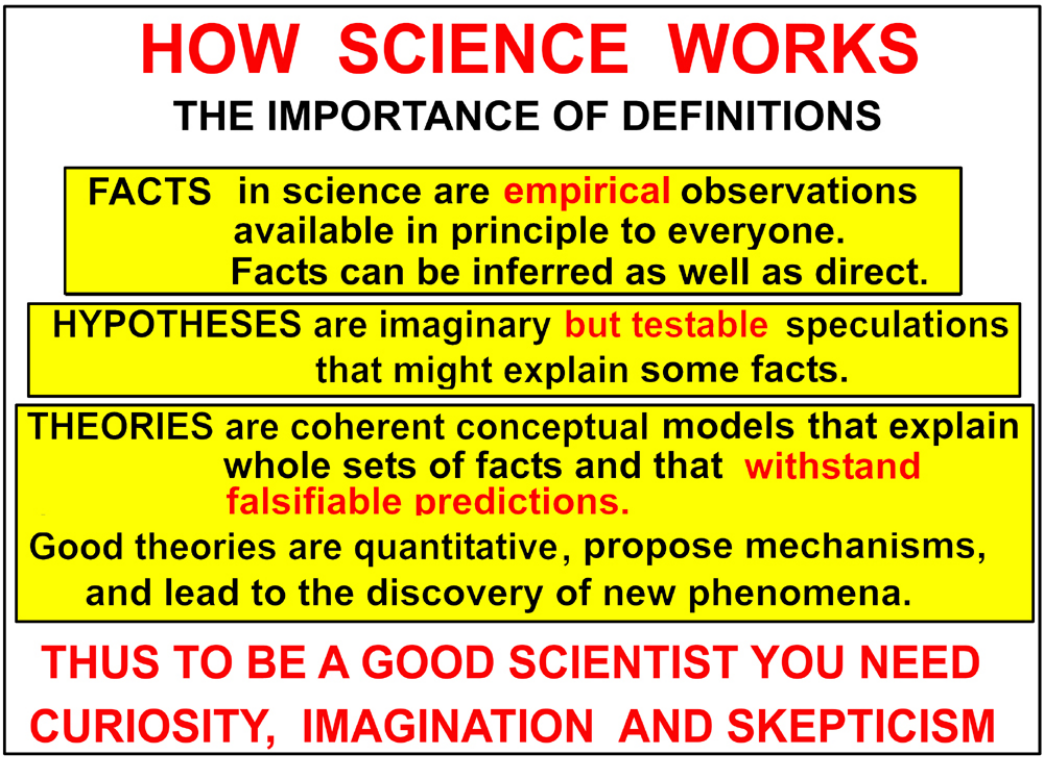

Figure 11

To be considered a fact**,** observations must be empirical, repeatable, and shareable by everyone. The word `empirical` means derived from observation and experiment, not from what someone tells you. So if a person tells you that they had a dream in which God told them to do something, this is not a fact in scientific terms – because this observation is not repeatable by others or shareable directly with them, nor can it be disproved. This does not mean it might not be true, but it does mean that this sort of claim cannot be used in science.

Now it is important to realise that facts do not need to be based on direct observations. Many of them are of course, but facts can be also inferred from indirect observations. For example, no one has seen an electron directly, but the existence of electrons is inferred from so many indirect observations that their existence is regarded as a fact. We shall see later that some aspects of evolution cannot be observed directly because they occur far too slowly to be seen in the human lifetime, but they are inferred from so many indirect observations that they are regarded as facts.

Hypotheses are acts of creative imagination – speculations that might explain some facts. But to be part of science, a hypothesis must be testable, at least in principle. The philosopher Karl Popper summarised this view as follows “Statements constituting a scientific explanation must be capable of empirical test. The criterion of the scientific status of a theory is its falsifiability, or refutability, or testability”. Hypotheses made in a supernaturalist framework are not testable, which is why there is so much conflict between different religions - there is no way of resolving differences between them. For example, in the Christian religion alone, there are between 9000 and 33,000 distinct denominations that are recognised, depending on how they are defined. Each of these denominations claims that its interpretation of the Bible is the correct one.

Science on the other hand advances cumulatively, step-by-step, reaching broad agreement. **Compared with religion, science speaks with one voice.**

That is all I want to say about how science works; Figure 12 provides a summary.

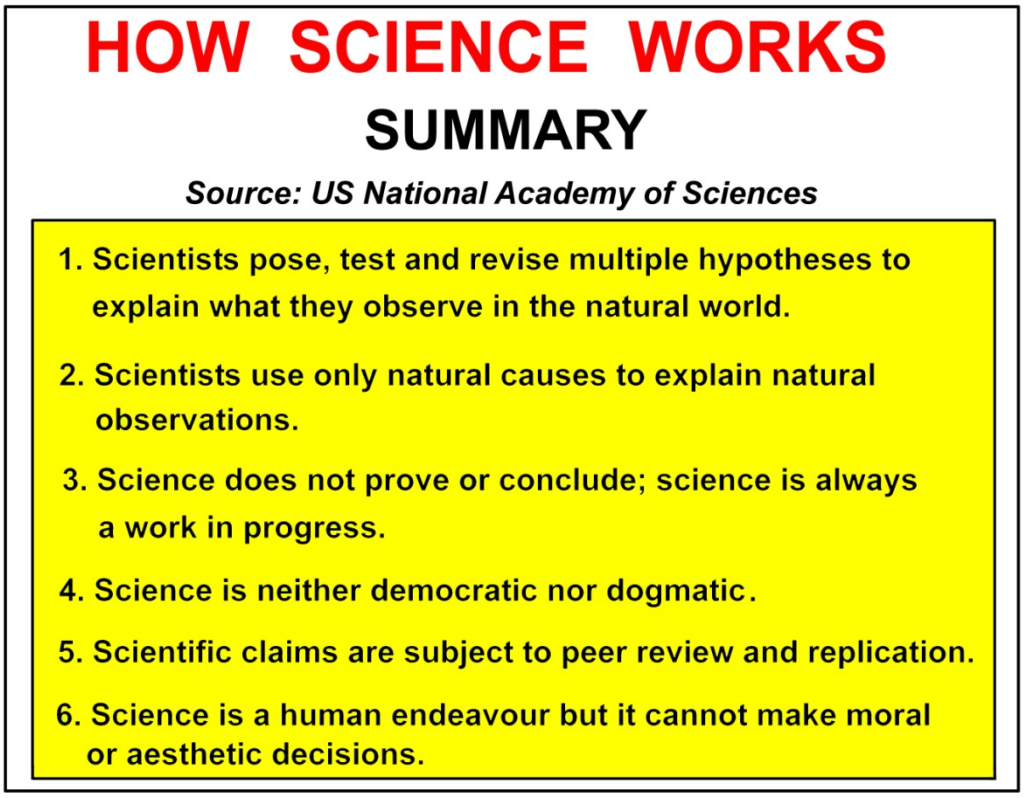

Figure 12

This summary is taken from the web site of the National Academy of Sciences in the United States and lists the main points. I have discussed points 1 to 5, but point 6 is also important. Science tells you how the world works, but it does not tell you how to behave or what to admire - science is morally and aesthetically neutral. The major world religions, on the other hand, do offer instruction in these important areas, but this advice is based on their supernatural interpretations of the world. Thus it is not surprising that different religions take conflicting moral positions on such things as warfare, the status of women, and sexual behaviour.

It is also the case that religious beliefs have inspired and stimulated many forms of art, especially painting, sculpture, architecture and music. Science has not done this to anything like the same extent, but in my personal view, what science is doing is to reveal a Universe whose complexity and beauty surpasses anything imagined by supernaturalists. What science lacks for some, but by no means all, people however, is the same emotional appeal as religion – it presents a view of human life that is bleak and joyless by comparison, because of the absence of any discernable, overall purpose in the Universe. This view conflicts with the purpose-driven, individual lives that we all lead. This relative lack of appeal is probably the main reason why the majority of

people confine their interest in science to its useful applications or dangers, and turn to religion to seek meaning and comfort, especially in times of hardship. As the poet T.S.Eliot wrote, `Human kind cannot bear very much reality`.

The urge to believe in the existence of a personal, all-loving and all-powerful God is very strong in many, but not all, people. The strength of this tendency is shown by the lengths of irrational reasoning that some people will go to in attempting to explain how such a God can permit horrible things to befall innocent people. For example, the argument has been advanced that the Holocaust was permitted by God because he has given humans free will, that is, the ability to make choices between different courses of action. The problem with this argument is that it conflicts with the idea that this God is all-loving, so how can he permit such events, unless he is not all-powerful? This argument also does not explain terrible things that happen, not because of human actions, but because of natural disasters such as earthquakes.

A recent example of this type of thinking was shown by Rowan Williams, the current Archbishop of Canterbury, who was observed to say, when witnessing from close quarters the deliberate destruction of the Twin Towers in New York in 2001, that “God is useless”. He explained that this terrible event had been permitted because God has given us free will. Thus the depth of his need to believe in an all-loving God overrode the simpler explanation of such events provided by the naturalistic viewpoint. On the naturalistic view of the world, such events present no such problem – bad things happen to innocent people because they were unlucky enough to be in the wrong place at the wrong time, while bad behaviour exists because aggression had selective value during the early evolution of humans.

Many people derive their moral values from their religious beliefs. The creationists prominent in the USA reject evolution partly because they fear that acceptance of the evolutionary origin of humans will undermine the basis for morality and lead to social breakdown. But if the naturalistic assumption is correct, these moral values must originate from natural sources. Suggested sources include the survival advantage for social animals like ourselves of treating other humans as we would like to be treated. On this view, morality largely consists of the intentional use of social control for the common good. Some aspects of altruism, defined as regard for others, can be explained on the basis that altruistic behaviour favours the survival of genes that
influence this behaviour. The naturalistic origins of moral behaviour among humans are discussed in the book *The Origins of Virtue* by Matt Ridley (see the Further Reading List).

If you compare the behaviour of humans with that of other animals, it is clear that we have become the dominant species because we can control our environment by means of technology. But an equally important factor is that groups of people choose and conserve those social conventions that improve their own survival, even when these conventions may be disadvantageous to some individuals. Thus the success of the human species depends upon co-operation, even to the extent of putting the interests of the community above that of the individual. This requirement would have been especially true when early humans were evolving over several million years on the African savannah. Which brings me to evolution.

PART III - DARWIN`S THEORY OF EVOLUTION

Evolution is a vast subject, so what I shall do in the space available is to provide in Part III a summary of evolutionary theory, and in Part IV some of the principal evidence in support of this theory. For more detailed information, you may like to look at the books on evolution in the Further Reading List.

The aim of evolutionary theory is to explain the most striking feature of life on Earth –its astonishing diversity, the fact that there are so many different sorts of living organism, each adapted to its particular environment (Fig. 13).

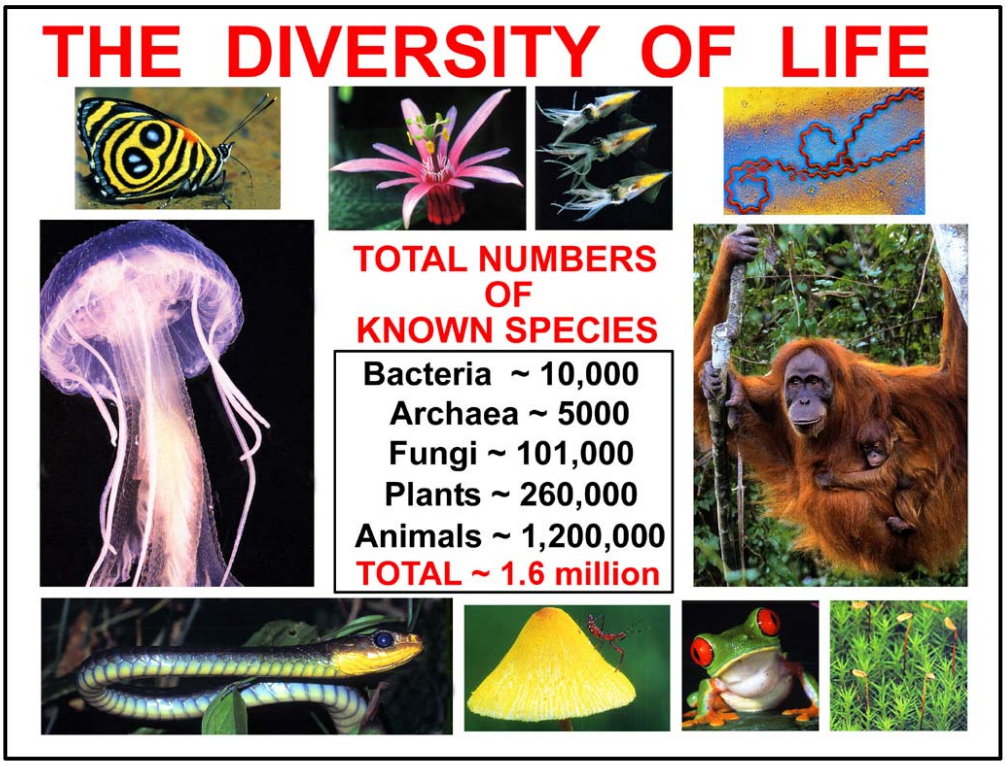

Figure 13

The total number of named species we know about today is between 1.5 and 1.8 million and is increasing steadily, especially for groups such as insects, but estimates of how many more species remain to be described range from 5 million up to 100 million. The numbers of different Bacteria and Archaea especially are thought, from analyses of DNA isolated from different environments, to be between 10 and 100 times greater than those that have been identified so far. The question these large numbers pose is – how can we explain the origin and diversity of all this complexity? Are some or all of this vast number of different organisms related to one another or did they arise separately? How can we answer these questions?

Three distinct hypotheses have been proposed at various times to explain the diversity of life (Fig. 14).

Creationism – this is scientific creationism, not to be confused with religious creationism or creation science or intelligent design – remember that we are working within a naturalistic framework. This hypothesis supposes that each species had a separate origin by some unspecified mechanism and does not change with time, but may become extinct.

Transformism supposes that species have separate origins but can change with time, and may become extinct.

Evolution supposes that all species have a common origin, can change with time and may become extinct.

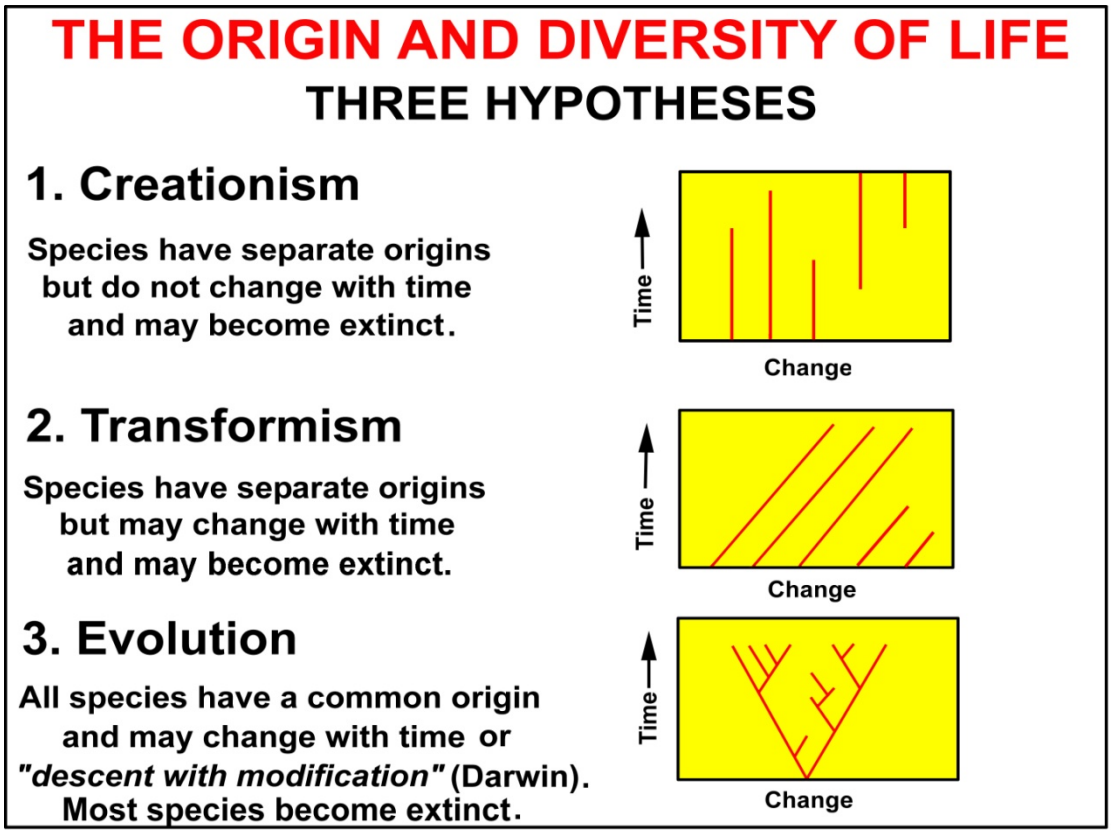

Figure 14

The vertical red lines in Figure 14 indicate that species do not change with time between generations, while red lines sloping to the left or right indicate that generations do change with time. If you compare these three hypotheses in terms of Occam`s razor, you see that evolution is simpler because it supposes only one origin of life, while the other two suppose as many origins as there are species. None of these hypotheses however, explains how life originated nor how the diversity arose.
Explaining the origin of the first living cells is one of the most challenging unsolved problems in biology, but explaining the origin of life`s diversity is one of the intellectual triumphs of science.

Prior to Darwin, most people thought that each species was created separately and persisted unchanged. Religious people thought in addition, that the act of creation was performed by a supernatural entity of some sort, but remember, science works within a naturalistic framework and looks for natural causes of natural events. So the problem is to find a testable explanation of the huge diversity found in the living
world. I will first summarise the evolutionary explanation that was suggested by Charles Darwin.

The 200th anniversary of Darwin`s birth and the 150th anniversary of the publication of his famous book *On the Origin of Species*, occurs in 2009 and these anniversaries are being celebrated around the world. Now Darwin did not invent the idea of evolution. The idea that species may evolve can be traced back as far as the 6th century B.C. to the Greek philosopher Anaximander, who proposed that the first men were generated in the form of fish. This view was not associated with any religious belief, so it represents the first known example of evolutionary thinking in a naturalistic framework. What Darwin did was to propose a particular mechanism, and to amass a large amount of evidence in support of that mechanism – the process he called natural selection. Figure 15 explains this mechanism.

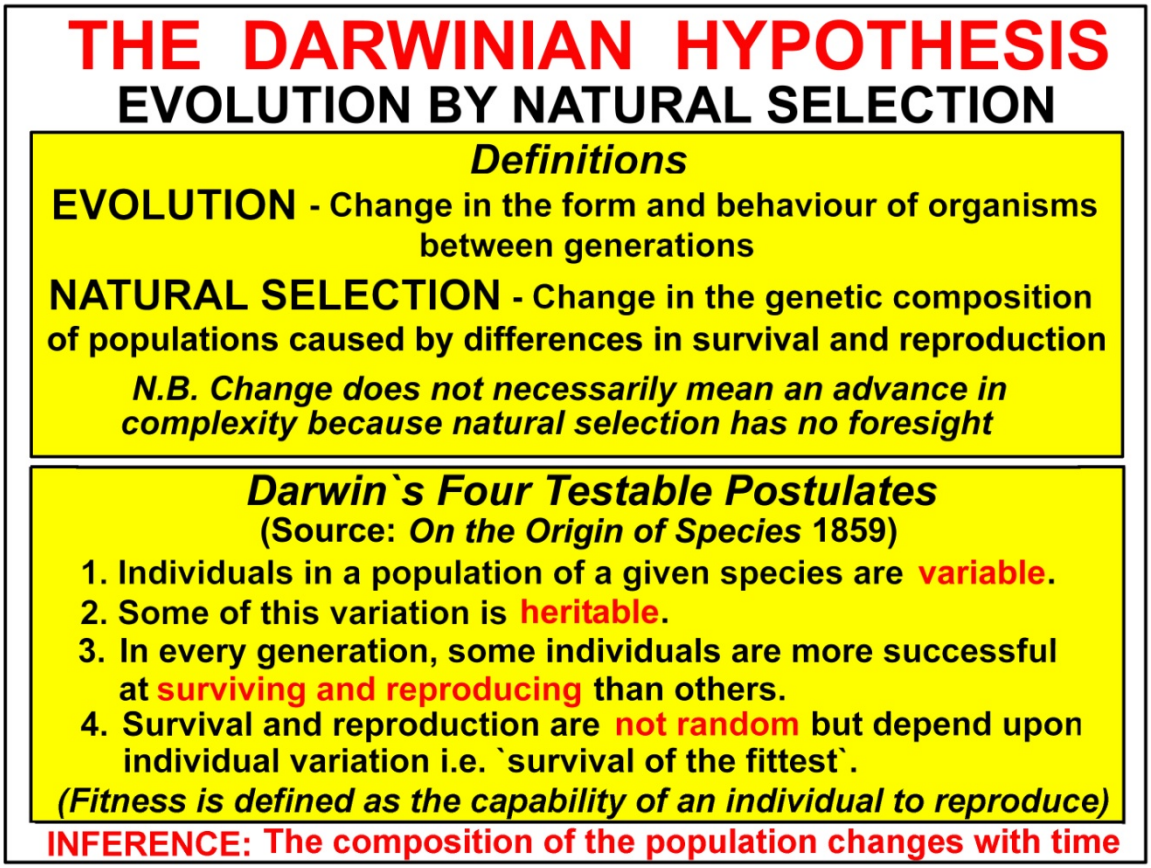

Figure 15

In Figure 15, you will find definitions of the terms `evolution` and `natural selection`. These are modern definitions – the term `genetic` was invented after Darwin`s time. Darwin, remember, knew nothing about genes or the mechanism of heredity. His library does not contain any papers by the father of genetics, Gregor Mendel, who discovered the particulate nature of inheritance at about the same time as Darwin`s book appeared, but who published his work in a little-known journal.

The basic idea that Darwin presented is that, because organisms compete with one another for resources, individuals that are better adapted to their particular circumstances will leave more offspring, and therefore it follows that those better adaptations that are inherited will increase in frequency from one generation to the next. The argument is spelt out in Figure 15 in the form of the four postulates made by Darwin in his

book *On the Origin of Species*. Most of this book is concerned with presenting a large range of observations taken from nature that support these postulates. Unlike Darwin, we know today that inherited adaptations are encoded in genes. It follows that the genetic composition of the population changes with time – this is what we mean by evolution.

Now it is important to understand two particular aspects of this hypothesis. Firstly, it is populations that evolve, not individuals. A population is defined as a collection of interbreeding individuals. Secondly, natural selection responds to pressures produced by the immediate environment. So natural selection is not a random process, but it has no foresight, it has no overall direction. It cannot predict the future – how could it? Any inherited adaptation that promotes an individual leaving more offspring than its competitors will be selected for. This is what we mean by the term `survival of the fittest` proposed by the English philosopher, Herbert Spencer, in 1864 after he had read *On The Origin of Species*. Now the word `fittest` here does not mean the individual who is physically superior, as it does in normal language. Instead it means that people who are better adapted to their environment for whatever reason have a greater chance of leaving more children that those who are less well adapted. We say such people are `fitter` in the evolutionary sense because there are more copies of their genes in the next generation.

Adaptation often involves an increase in complexity and in Victorian times many people thought that evolution is always progressive – after all, it had produced human beings such as themselves who are clearly superior to all other forms of life! But this is a misunderstanding of how evolution works. Complexity evolves only because it improves the fitness of the next generation in the current environment. But if the environment changes, complexity may become a disadvantage, and so natural selection can lead to a reduction in complexity. For example, many parasites adapt to their environment by losing systems they no longer need because their host can replace them. The tapeworm has no gut because it no longer needs one in its present environment living inside the digestive systems of its host, but it evolved from a free-living worm that did have a gut. It is this directionless aspect of evolutionary theory that many people find disagreeable because it offends our innate sense that human beings like us are so wonderful that the process that produced them must be purposeful. This is really an example of human arrogance - we are conceited enough to feel we must be special. Evolutionary theory, in contrast, says that we are just another animal, produced by the same process that has produced all the other animals, as well as the plants and bacteria.

PART IV - THE EVIDENCE FOR EVOLUTION

Now I want to turn to the evidence for evolution. If you ask the average person-in-the-street about this, they will probably mention the fossil record – the remains of organisms of types no longer living on the Earth. But this is incorrect – the fossil record is equally consistent with both scientific creationism and with transformism, which, you will recall, both propose that species had separate origins but can become extinct. All the fossil record shows is that in the past there were organisms that are not around today. So what is the evidence for evolution?

1. Evidence for evolution from DNA sequence data

The most detailed information about the diversity and relatedness of organisms available today is provided by determining the base sequence of all the DNA found in different organisms. The unique DNA sequence of each species is called its genome, and it is the

collection of genes in this genome that contain the information to build and operate that species. Due to advances in sequencing technology, it is now possible to determine the total DNA sequence of say, a new type of bacterium, in 24 hours. In recent years, increasing number of total genome sequences have been determined, mostly for bacteria, but including some plants and animals, including humans, chimpanzees, dogs, fish, worms and flies. These sequences show directly that, for example, we share almost all our genes with chimpanzees, and thus chimpanzees are regarded as our closest relatives. But we also share many of our genes with bacteria and plants – **all organisms are genetically related.** None of these similarities is predicted by hypotheses that organisms have been separately created.

To help you understand how the DNA sequence in the genome specifies the entire organism, Figure 16 reminds you of the basic principles of molecular biology.

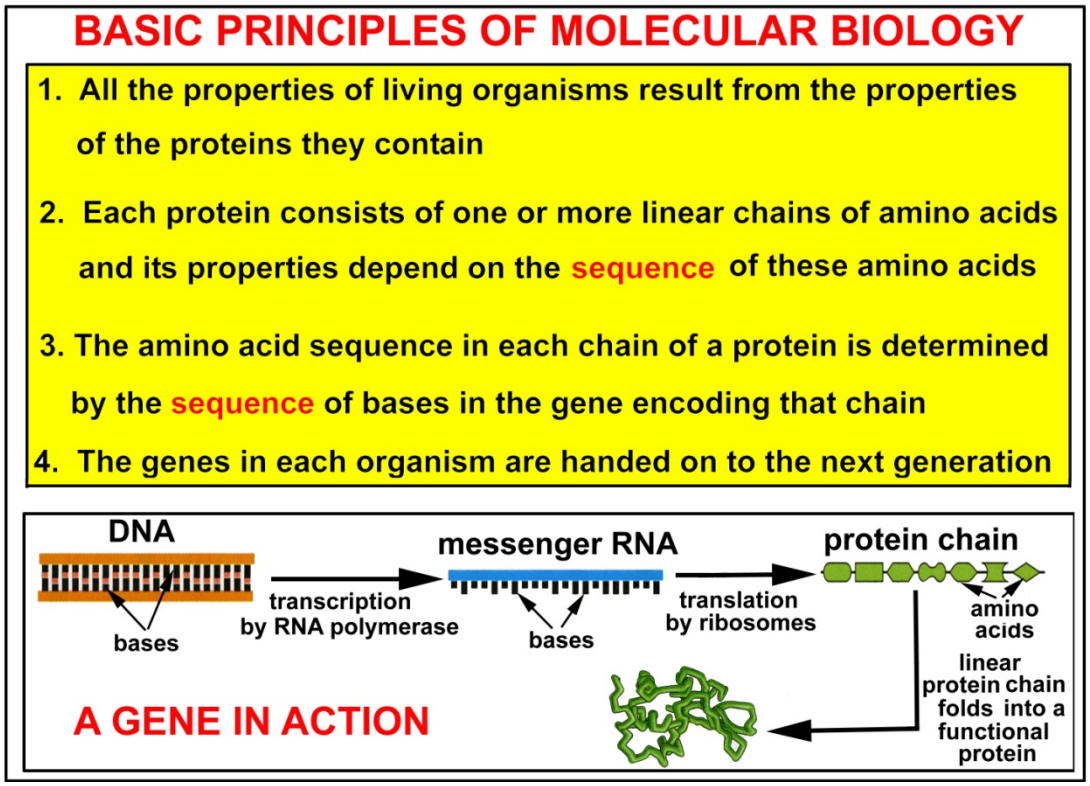

Figure 16

It is easiest to start by talking about the importance of ribosomes. Ribosomes, you will remember, are the structures inside each cell that decode the base sequence information in each molecule of messenger RNA, which is a copy of the base sequence information present in each gene in the DNA. The ribosome decodes this sequence information to synthesize the protein specified by each gene.

By `decode`, we mean that the ribosome is essentially a device for converting the base sequence information in each gene into the amino acid sequence information of the protein encoded by each gene, just as during the Second World war, the scientists at Bletchley Park in England built a machine that was able to decode the secret messages sent out by German military forces. Recall that each gene is defined by its unique sequence of bases, while each protein is defined by its unique sequence of amino acids. Thus ribosomes use the base

sequence in messenger RNA to join amino acids together in the correct order. This process is called translation (Fig. 16).

Why is this decoding absolutely vital for life? It is vital because it is the sequence of amino acids in each linear chain of protein that determines how that chain folds into the compact three-dimensional structure that enables that protein to carry out its specific function. Remember that it is proteins that are the `action molecules` of the organism – that is, the molecules that carry out all the thousands of different functions necessary for life. Genes by comparison, are inert and rather boring – all they do is contain the sequence codes for proteins. You might like to think of this arrangement by analogy with a tape recorder. The tape is like the DNA; it is essential because it contains the information to make the music, but in itself, it is linear, uniform and rather dull. The music produced by decoding the linear information on the tape, on the other hand, is much more complex in structure and much more interesting – in organisms, the proteins are the music.

An example of a gene sequence that is highly conserved in all forms of life is shown in Figure 17. This diagram compares the amino acid sequence of part of a protein involved in controlling protein synthesis by ribosomes in organisms from all three domains of life. This protein is called an elongation factor, because without it the addition of amino acids by the ribosomes to the growing chains of protein stops. Each amino acid (there are twenty different ones in proteins) is represented by a letter e.g. A stands for alanine. You can see that there are several regions where the sequence of amino acids is identical between very different species – from humans to bacteria.

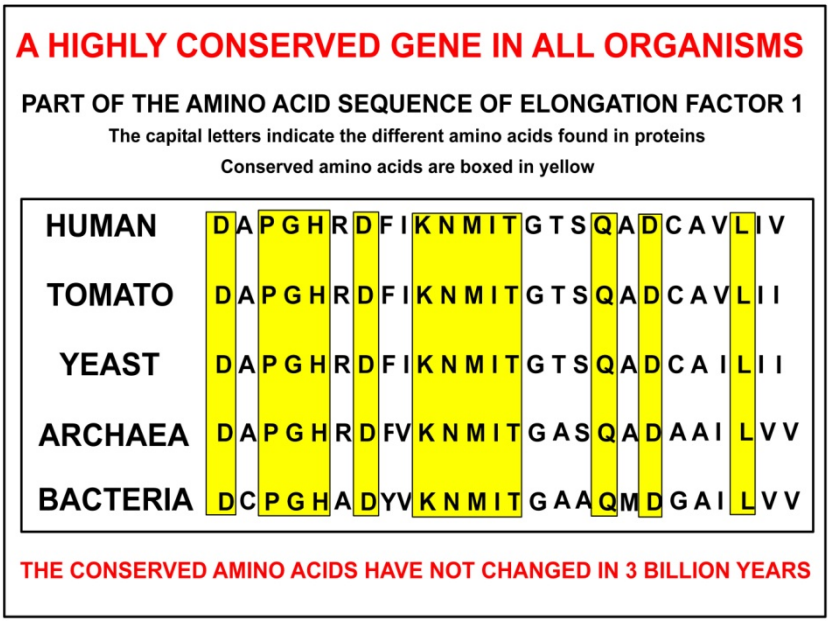

Figure 17

There is fossil evidence that bacteria have been on the Earth for at least 3 billion years, so the interpretation is that these sequences have been conserved over that huge length of time because they are essential for the elongation factor to help the ribosome to carry out its job of making proteins.

Because the ribosome is such a vital component of all cells, its structure is highly conserved in all organisms. This is true for both the protein and the RNA molecules that make up the

ribosome. So it is not surprising that the base sequence of the RNA component of the ribosome is also highly conserved in all organisms - too much variation would run the risk that the ribosomes will not work well enough at making proteins. This constraint means that the sequence of ribosomal RNA changes only very slowly during evolution, and so can be used to determine how the major groups of organisms are related to one another.

Figure 18 shows the three-domain classification scheme that is currently a popular model for describing the relations between the major groups of living organism on the Earth. This model is derived by comparing the base sequence of the genes encoding the small subunit of the RNA component of ribosomes in the different organisms that exist today - these are called extant organisms. The more similar these sequences, the closer together the organisms are placed. This scheme is often described as a family or phylogenetic tree, that is, a diagram that shows how organisms are genetically related to one another. The vertical axis represents time, while the branches indicate that some species gave raise to two new species at some point in time.

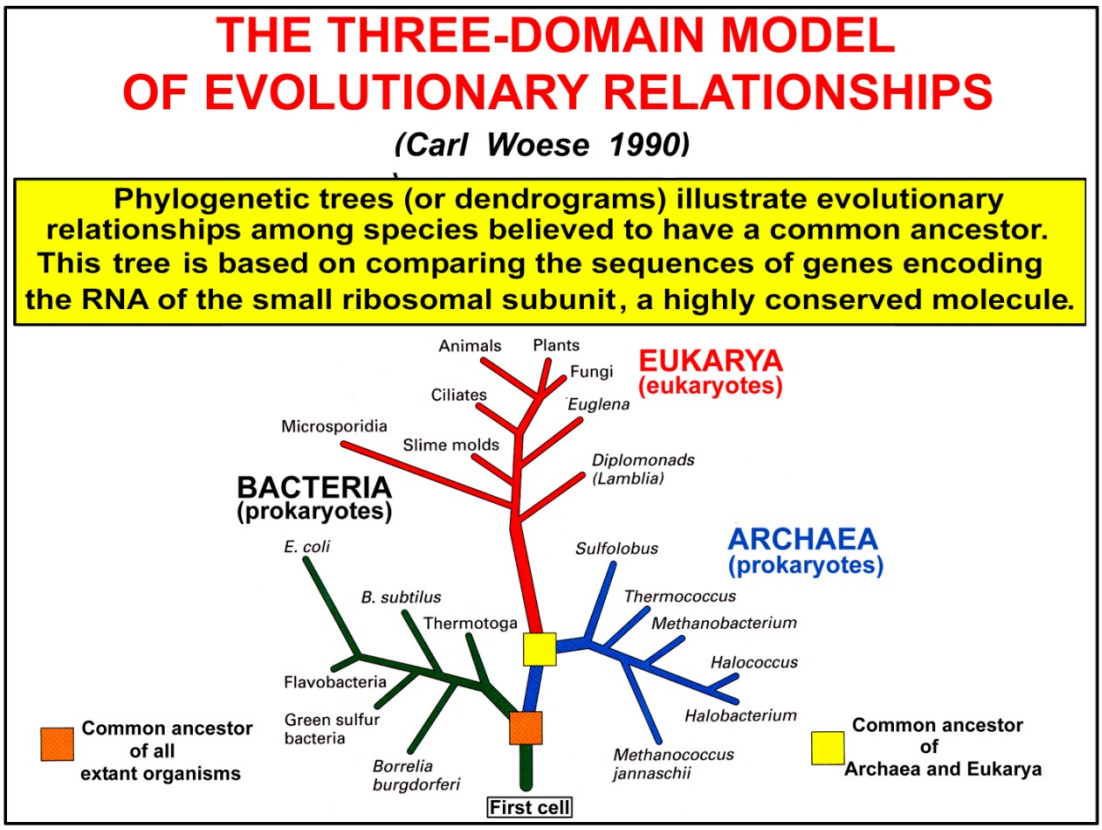

Figure 18

You will note that all the branches in this tree are connected to one another and all converge on the same point at the bottom. So Figure 18 is saying that all organisms are derived from one common ancestor and are related to one another – the basic predictions of Darwin`s evolutionary theory.

Figure 18 contains some terms that are often confused, even by some biologists. The essential point to remember is that the terms `prokaryote` and `eukaryote` describe basic structural differences between two types of cell, while the terms `Archaea`, `Bacteria` and

`Eukarya` describe evolutionary relationships as deduced from DNA sequences. Eukaryotic cells have their DNA separated from the cytoplasm by a nuclear membrane, but prokaryotic cells have their DNA in direct contact with the cytoplasm. This difference affects the relation between transcription and translation. In addition, eukaryotic cells are larger and more complex than prokaryotic cells, and contain a number of internal membrane-bound organelles, such as mitochondria, chloroplasts, endoplasmic reticulum and Golgi bodies, which are not found in prokaryotic cells. Figure 19 illustrates these striking structural differences.

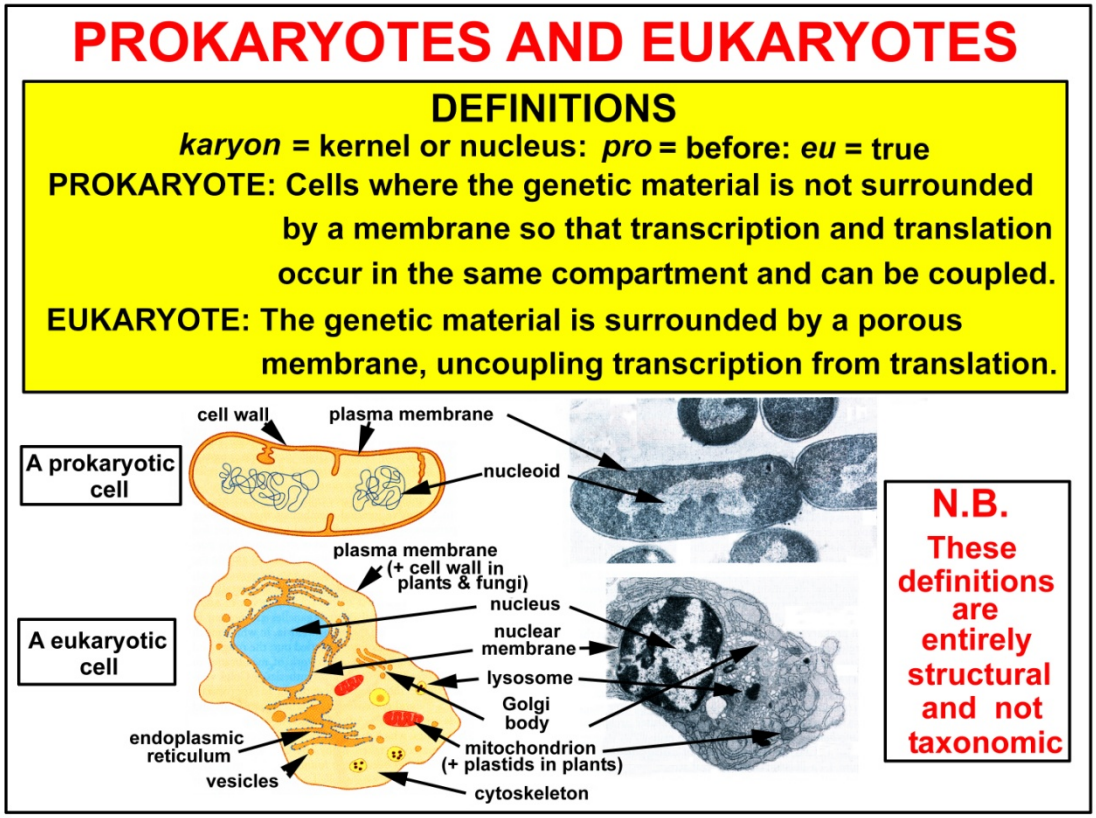

Figure 19

Both the Archaea and the Bacteria are made of prokaryotic cells, while all the Eukarya are made of eukaryotic cells. Confusion has arisen because, while the terms `prokaryote` and ` eukaryote` were first used to describe the main structural difference between the two types of cell, they were then assumed by some biologists to also reflect their evolutionary relationships. But according to the three-domain model presented in Figure 18, the prokaryotic Archaea are more closely related to the eukaryotic Eukarya than they are to the prokaryotic Bacteria.

2. Evidence for evolution from other similarities between different organisms

The second line of evidence is the existence of other similarities besides DNA sequence between different organisms, similarities you would not expect if organisms had independent origins. These similarities occur at all levels, from the anatomical to the molecular. These similarities are sometimes referred to as `homologies` but there is a possible source of confusion with this term because its meaning has changed over time. `Homology` used to

mean the same as `similarity`, but now it means `evolutionarily related`, so to cite homology in the latter sense as evidence for evolution is a circular argument.

Figure 20 compares the forelimbs of seven different tetrapod (four-legged) animals. These animals use these limbs for different purposes – hopping, running, flying, walking and swimming. There is no obvious functional or environmental reason why these forelimbs should all have five digits rather than three or seven, but they do**,** and more amazingly**,** they also share a common pattern of anatomy. This fact impressed Darwin. In his book `*On the Origin of Species*`, he says:-

"What could be more curious than that the hand of man, formed for grasping, that of a mole for digging, the leg of a horse, the paddle of a porpoise and the wing of a bat, should all be constructed in the same pattern and should include similar bones in the same relative positions?"

"Why should similar bones have been created in the formation of a wing and a leg of a bat, used as they are for totally different purposes?"

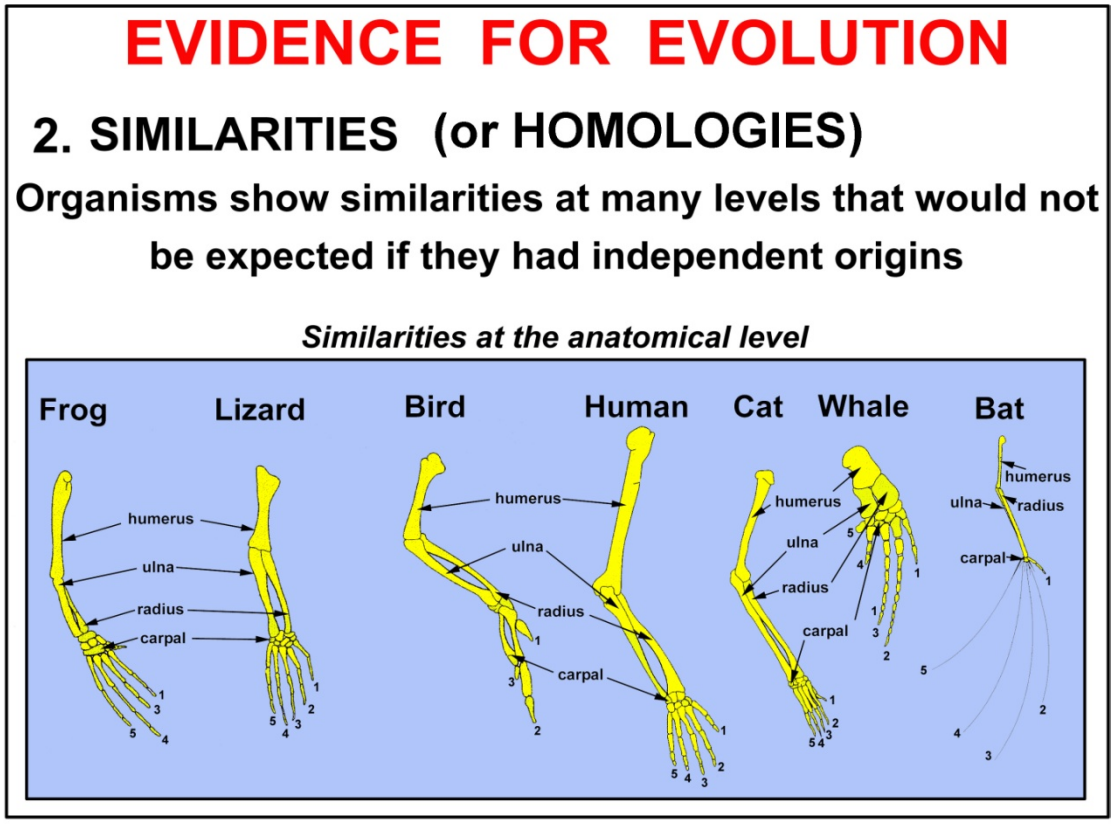

Figure 20

The argument here is that a human designer who was trying to make the best possible wing and the best possible leg would have no need to ensure that the basic components of these two structures were the same. If he did, this would be a serious limitation on his attempt to produce the best design. Evolution by natural selection on the other hand, has no knowledge of the best design – it simply selects from whatever is available at the time for anything that enhances survival in the current environment. Thus the basic structures inside tetrapod forelimbs are similar because they are related, as predicted by evolutionary theory, not because they represent the best design.

Religious people who dislike the idea of natural selection sometimes argue that these similarities might reflect the whim of a supernatural creator. The problem with this type of argument is that it can be used to explain whatever type of structures were found inside these forelimbs, so it has no predictive power. The creator might even prefer to create forelimbs that are not the best design possible. Because there is no way to determine the preferences of a creator, the supernatural explanation lacks the predictive power of the natural explanation. This is an example of my earlier suggestion that the essential difference between science and religion is that the latter lacks a methodology by which its claims can to be tested.

Figure 21 shows some similarities at the molecular level. There is a sense in which the huge diversity of living organisms that is apparent to the naked eye, and which delights us all, is an illusion**,** because this diversity becomes much smaller when we compare organisms at the molecular level. This fact is summarised by the phrase "The Unity of Biochemistry". So the basic metabolic pathways, the energy transduction mechanisms, the signalling systems, and the basic operations of replication, transcription and translation are very similar in all organisms, no matter how different these organisms look to the eye. A few examples from many that can be given, are listed in Figure 21. The continuing success of the discipline of molecular biology is only possible because of this basic similarity between all organisms.

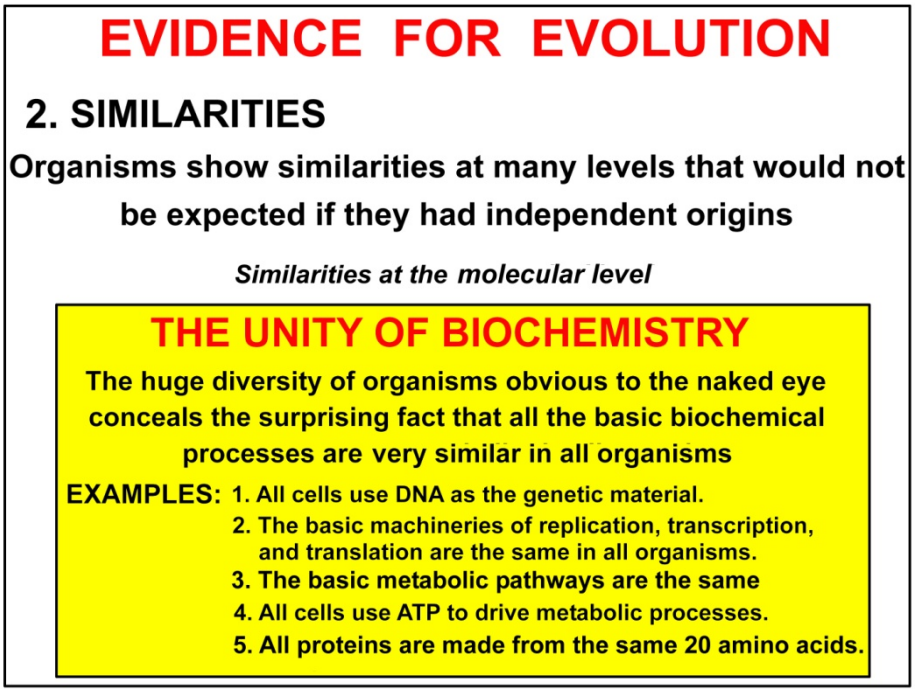

Figure 21

It is the unity of biochemistry that enables genetic engineers to take a gene from one type of organism and get it to work inside a quite different organism. For example, the production of human insulin by both bacteria and yeast has been achieved by isolating the genes for this vital hormone from human cells and inserting them into bacterial and yeast cells. These methods of production have now replaced the original method of isolating insulin from the pancreas of pigs and cows.

3. Evidence for evolution from direct observation

The third and fourth lines of evidence for evolution are that it can be observed for some species, both in the field and experimentally (Fig.22).

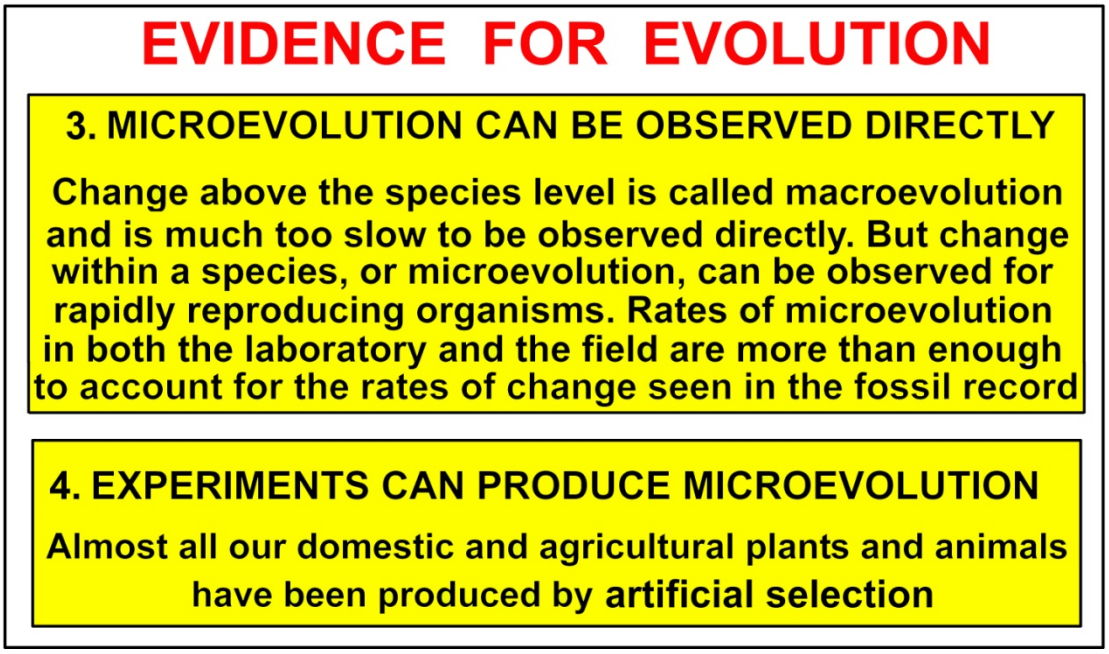

Figure 22

We distinguish two levels of evolution. Microevolution is defined as evolution below the species level, and macroevolution as above the species level, but this distinction is only for convenience - they are part of a continuous spectrum of change across differing time scales and different techniques are used to study them. For some organisms that reproduce rapidly, such as viruses, bacteria and some insects, changes in their genetic composition from generation to generation can be observed directly. This is the case for example with the HIV virus that causes AIDS in humans - the evolution of this virus in an infected person treated with antiviral compounds can be seen in just three weeks.

There are two reasons for the rapid evolution of the HIV virus. Firstly, the invasion of a single white blood cell by a single virus particle results in the production of about 10,000 new virus particles every 24 hours by that cell. Secondly, the mutation rate (the rate of change of the base sequence of the genetic material) is high enough that on average each new particle carries one mutation. A small minority of these mutations cause the virus to become resistant to the antiviral drugs being used. The
result is that the drugs rapidly become less effective with time, making this disease difficult to treat.

4. Evidence for evolution from the domestication of plants and animals

In the first chapter of his famous book, Charles Darwin talked about the evolution of domestic varieties of animals such as dogs and pigeons from wild ancestors. Darwin was especially interested in the way that selective breeding by pigeon fanciers has produced all the varieties of pigeon that they show at exhibitions. All the breeds

favoured by pigeon fanciers have been bred from the wild rock pigeon - Figure 23 shows a few examples. Dogs have been evolving from wolves for at least ten thousand years, and possibly for ten times longer. Selection of favourable traits by humans has produced the 300 or so varieties of dog that we see today. Figure 23 shows just two modern varieties of dog, compared with their remote ancestor.

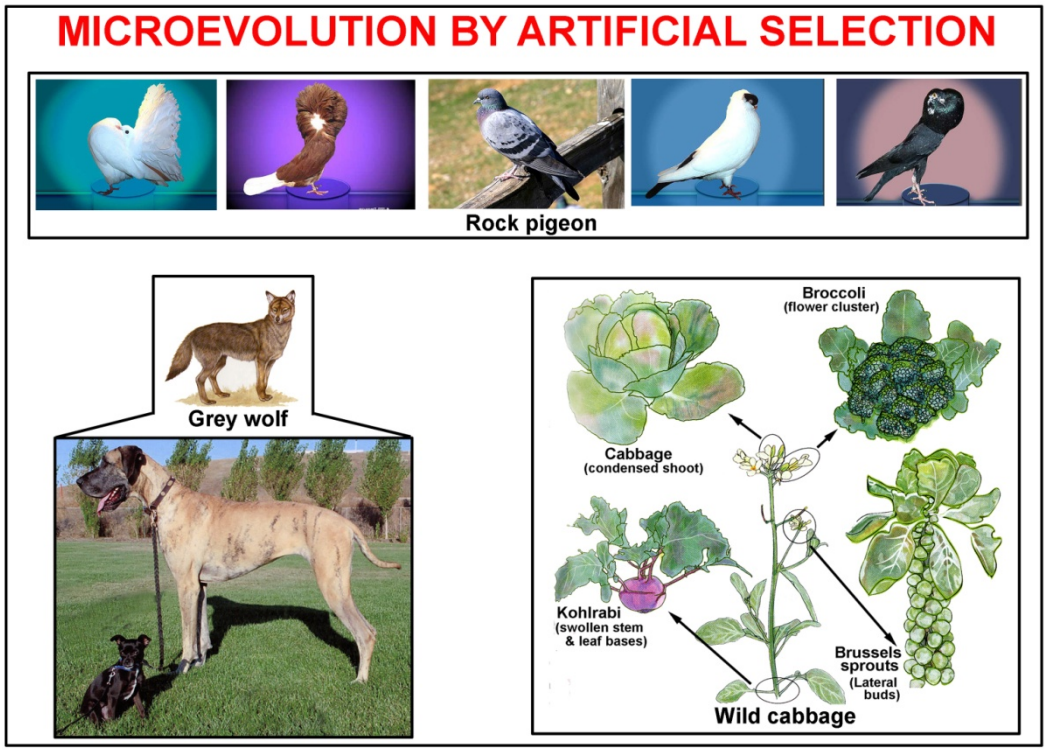

Figure 23

The domestic plants that we all rely upon for food have also been produced by breeders selecting those variants that possess desired characteristics – desired that is by humans, not by adapting to the natural environment. Figure 23 shows the different crop plants that have been bred from the wild cabbage by plant breeders. All these are examples of microevolution. This process produces new varieties, but these varieties are still the same species. So for instance modern dogs can, and do, interbreed with wolves.

5. Evidence for evolution from the fossil record

Unlike microevolution, macroevolution is much too slow to be seen directly but its occurrence is inferred - just as electrons cannot be observed directly but their existence is inferred. Macroevolution is inferred from the fossil record and from the principle of uniformitarianism (Fig. 24). This principle was formulated by the Scottish geologist James Hutton in the late 18th century. He proposed that rock is being continually eroded and washed down into the seas, where it sediments into layers and is compressed back into rock. This sedimentary rock is then uplifted out of the water by earthquakes so that the erosion cycle is repeated. The observed thickness of sedimentary rocks suggested that this process has been continuing for very long periods of time i.e. it was a `uniform` process. This idea led to the generalisation that the continued operation of processes observable today could account for the geology of the planet if prolonged over millions of years.

Figure 24 defines this principle – the idea that the present is the key to the past. This view was very influential in the development of both biology and geology in the 18th and 19th centuries. This principle stems from the naturalistic view that the world is governed by unvarying regularities, and is also an example of Occam`s razor in action, because it is based on the simplest hypothesis - that processes acting now also operated in the past.

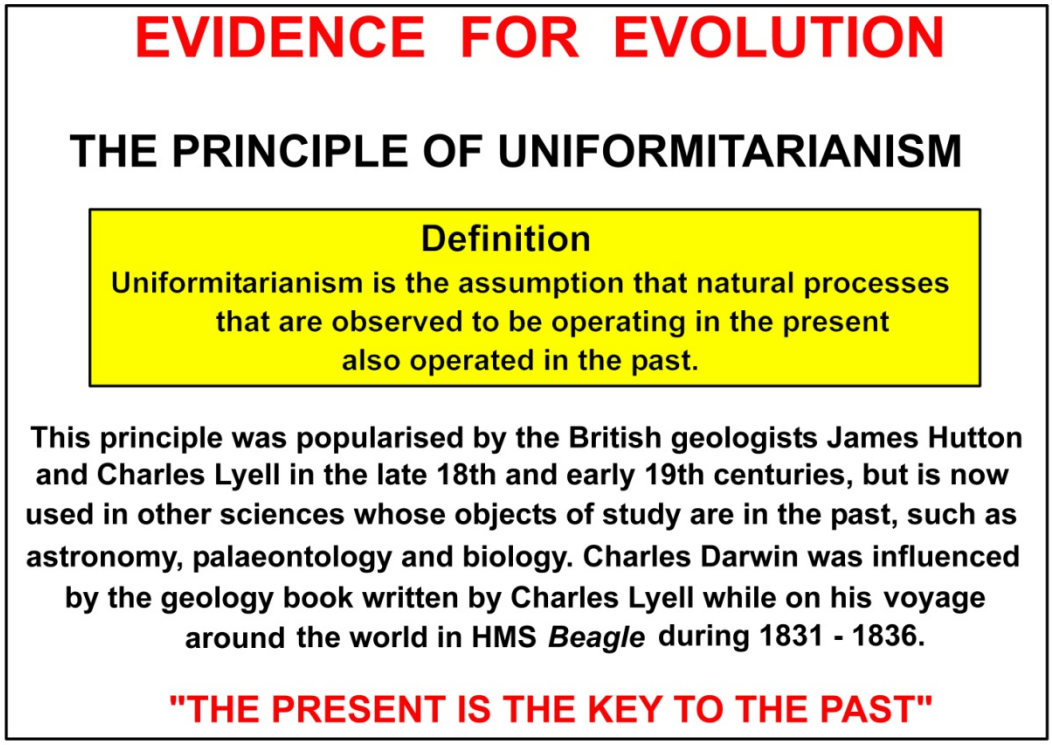

Figure 24

Macroevolution is also inferred from the fossil record. If some species can change into other species over long periods of time, there might to be fossils of transitional forms between them – and there are! Transitional species are defined as those that show a mixture of features from both their ancestors and their descendents. Figure 25 shows some examples of fossils sharing characteristics of both dinosaurs and birds.

On the left of Figure 25 is shown one of the famous *Archaeopteryx* fossils, of which ten specimens are now known, all found in southern Germany. The first was found in 1861, just two years after the publication of *On the Origin of Species*, and the last in 2005. These fossils were all preserved in limestone in Bavaria, and date to the Jurassic period, about 150 million years ago. The word *Archaeopteryx* means `ancient wing`.

These fossils show a mixture of avian and dinosaur traits. They share with dinosaurs, jaws with sharp teeth, three fingers with claws, a long bony tail and an extensible second toe. They share with birds a wishbone, flight feathers and wings. The flight feathers are well developed and asymmetrical, like those of modern birds. *Archaeopteryx* with probably a glider rather than a flapping animal because it lacks a large breastbone required for the anchoring of the powerful muscles necessary for flight, and the anatomy of its shoulder suggests it was unable to lift its wings above its back. Reconstructions of its skull by computer tomography (CT scanning) of the skulls show that the regions of the brain concerned with vision were well developed. The structure of the inner ear closely resembles that of modern birds rather than

that of reptiles. These observations are interpreted to indicate that *Archaeopteryx* had good vision, hearing and balance, but whether it lived as a tree-dwelling glider or evolved flight by running along the ground is the subject of continuing debate.

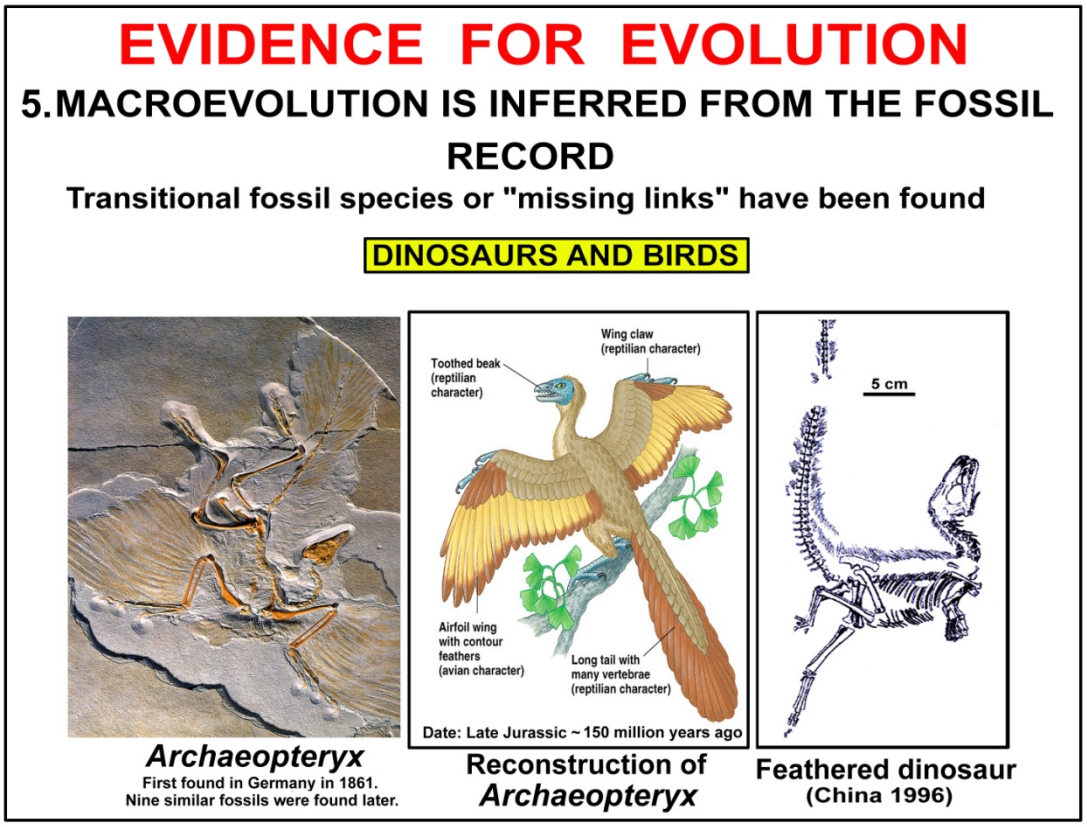

Figure 25

In China in the last 15 years, eight different feathered dinosaur fossils have been discovered (Fig. 25, right hand panel). From their anatomy, these were probably not capable of flapping flight, so their feathers may have evolved to act as insulation as these animals evolved warm-bloodedness, and only later were used for flight. This is a recurring theme in evolution – one thing leads to another. Natural selection is a very powerful opportunistic process – even a slight variation will be selected if it aids survival and reproduction, so traits selected for one purpose can form the basis for the subsequent development of quite different traits.

Figure 26 shows some fossils that bridge the gap between fish and tetrapods - animals with four limbs. The older fossils at the bottom show gill covers, fins and fish tails but no neck, while at the top, the gill covers have gone, the fins are now limbs with digits, there is a neck but the fish tail is still present. In the middle is a fossil called *Tiktaalik,* an Inuit name reflecting that it was found recently in the Canadian Arctic. This find was reported in the journal *Nature*. *Tiktaalik* has fish scales, but no gill covers and the pectoral fins are almost, but not quite, tetrapod limbs – they still have fin rays. These fins would have allowed paddling, but they also have substantial bones that would have enabled *Tiktallik* to prop itself up in shallow water but not to walk.

A remarkable feature of the discovery of *Tiktallik* is that it was not entirely accidental - the fossils hunters who found it were looking for it! By comparing the known fossils shown in Figure 26 that link fish with tetrapods, they formed the hypothesis that the invasion of the land by vertebrate animals took place in a river environment some 375 million years ago. So they looked for fossils in rocks of this age whose geology suggested they had formed in a river delta. Looking for fossils requires unusual amounts of patience and it took five expeditions to Canada before they were successful. This remarkable story is related by Neil Shubin, one of these fossil hunters, in his book *Your Inner Fish.* This is a good example of science in action - you identify a problem with existing knowledge, form a hypothesis about a possible solution and then seek observations or perform experiments to test that hypothesis.

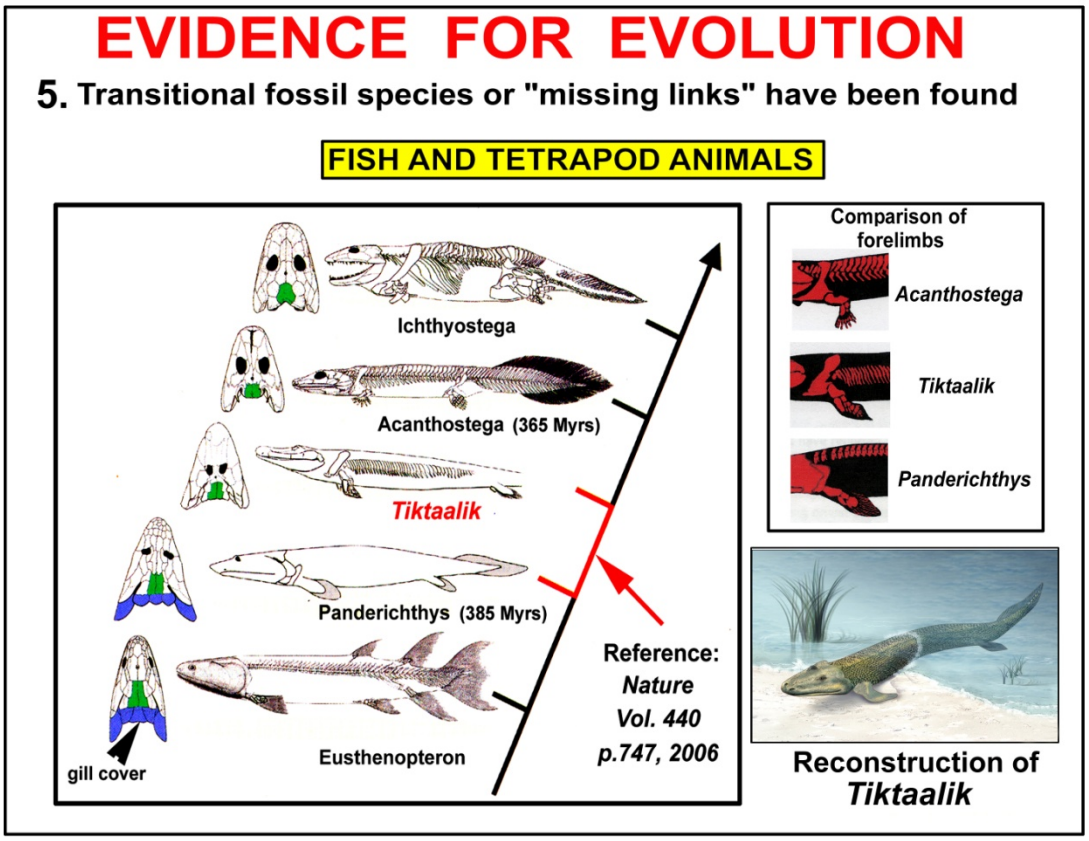

Figure 26

When we call *Tiktaalik* a transitional species, this does not necessarily mean that this species was on the direct line of descent from fish to tetrapods – it could represent an extinct branch on the line of descent between these two groups. But *Tiktaalik* does demonstrate the past existence of a species intermediate in form between fish and tetrapods, as predicted by evolutionary theory. For this reason the term `transitional fossil` is better than the term `missing link`. The value of such transitional fossils is that they show us the order of the evolutionary steps that connect one type of organism, such as fish, with a later type of organism, such as tetrapods. In the same way, *Archaeopteryx* may not be on the direct line of descent of modern birds -
remember that the tree of life is highly branched and most species of life are now extinct!

6. Evidence for evolution from the mutation of DNA

Figure 27 illustrates another line of evidence in support of evolutionary theory – the fact that DNA undergoes mutation**.** Mutation is defined as a change in the base sequence of the

genetic material of the organism. Mutation is the ultimate source of the variation between individuals in a population that was so well documented by Darwin in his book. Remember that Darwin knew nothing about the genetic material or the mechanism of heredity – he had some ideas about how the latter might work, but these were hopelessly wrong.

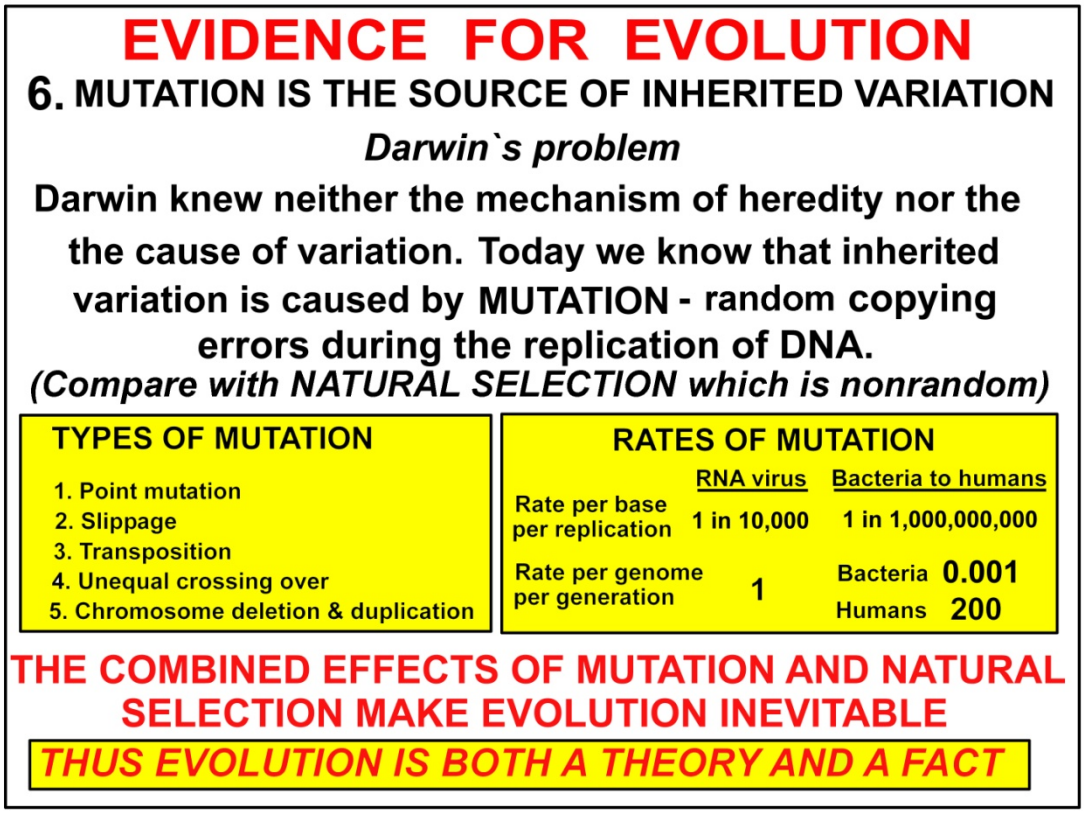

Figure 27

Unlike natural selection, which is a highly nonrandom process, mutation is a chance process – random copying errors that may occur every time DNA is replicated. The term `random` in this context means that the particular mutations that occur are unrelated to their effects on evolutionary fitness. This difference between the properties of natural selection and mutation is another common source of confusion in media debates about evolution.

So remember **- mutation is random, but natural selection is nonrandom.**

There are several different ways in which mutation can occur - these are listed on the left of Figure 27. On the right, are some approximate rates of mutation.

RNA viruses have high rates of mutation because RNA, unlike DNA, is single-stranded and RNA viruses lack editing mechanisms. All cellular organisms contain proteins that are able to detect errors in base-pairing during the replication of DNA and correct them, using the information in the strand of DNA being copied. But RNA viruses lack such editing mechanisms, which is why the AIDS virus evolves so quickly - I mentioned earlier that you can observe the AIDS virus evolving within a single human individual in a few weeks. The appearance of the MRSA superbug in hospitals is another example of evolution in action – the selection here is created by our use of antibiotics.

Rates of mutation are expressed in several ways. The rate per base per replication is very low in everything except viruses. For example, every time a human cell divides about six new mutations arise on average, that is, six bases out of a total of six billion bases are changed. This seems a very small change, but when you consider the number of cell divisions required to make the gametes of an adult human, it turns out that the average person will accumulate in their gametes during their reproductive lifetime around 200 mutations. Most mutations turn out to be neutral in their effect, either because they occur in regions of the DNA that do not code for proteins or because they do not change the amino acid sequence. But a minority of mutations are harmful. For example, about 1 in 25,000 people are born with a single mutation in a gene that encodes a protein involved in the action of growth hormone. The result is the condition called achondroplasia, in which the limb bones fail to elongate normally so that the affected person has short stature. In most case the parents do not have this condition so it is the result of a new mutation, inherited exclusively from the father. In about 98% of cases, the mutation is a single base change that results in the replacement of one amino acid by a different amino acid in the protein that binds to the growth hormone.

On the other hand, a minority of mutations are positive in their effects - they increase evolutionary fitness. An example of a positive mutation that has been selected for recently in human history is a mutation that occurred in the gene encoding the enzyme lactase. This enzyme is required so that babies can digest the sugar lactose that they receive in their mother`s milk. After weaning, the production of this enzymes ceases, as babies prepare for an adult diet. Several thousand years ago, a mutation occurred in a human that allowed him or her to continue to digest lactose in dairy products into adulthood. From the ethnic distribution of this trait, it is likely that this mutation occurred in a European who lived in an area where animals such as cows and goats had been domesticated and thus where a supply of milk was available to adults. This mutation spread throughout Northern Europe by positive natural selection because it conferred survival and reproductive advantages on those who carried it. Today this mutation occurs in 95-98% of Europeans, but in only 20-50 of Hispanics and 5% of Asians. Adult people who lack this mutation suffer from the condition called `lactose intolerance` because the inability to digest lactose results in bloating and cramping.

It is the few mutations that have positive effects that provide the variation whose selection drives the evolutionary process. So we come to the surprising realisation that the diversity of life is created by mistakes – errors made when DNA is copied. If mutations did not occur, evolution would not be possible. Evolution is the result of a series of successful mistakes.

So the conclusion that biologists have reached is that, because both mutation and natural selection are observable facts**,** evolution is inevitable. **Thus evolution is both a theory and a fact.** But evolution is more than just another scientific theory because it challenges those views that suggest humans are basically different from other animals and so can escape the laws of nature. It is this aspect of evolution that makes it so unattractive to many people. But rejecting evolution means that we reject the best means we have found so far to understand ourselves and our place in the world.

ACKNOWLEDGMENTS

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I am especially grateful to Konstantinos Thalassinos for creating the website.

Image of Charles Darwin on page 1 by kind permission of the Darwin Heirlooms Trust: Copyright English Heritage Photo Library.

Figures 14, 20 and 27 in this essay are based on Figures 3.1, 3.6 and Table 2.2 respectively, in the book *Evolution* by Mark Ridley (see reference 8). Figure 18 is modified from Figure 1.5 in *Molecular Cell Biology* by H. Lodish, A.Berk, S.L. Zipursky, P. Matsudaira, D. Baltimore and J. Darnell, 4th edition, Freeman & Co.

FURTHER READING

1. Wikipedia articles provide useful non-peer reviewed introductory discussions of: *Naturalism (Philosophy)/Scientific Method/History of Science/Origin of Religion/Evolutionary Psychology of Religion.*

2. *Methodological Naturalism and Philosophical Naturalism: Clarifying the Connection*: Barbara Forrest.
www.infidels.org/library/modern/barbara_forrest/naturalism.html
This article discusses the philosophical basis of naturalism.

3. *How Science Works*: David Goodstein.
www.cs.wisc.edu/~dluu/data/papers
A useful discussion about the criteria that distinguish the practice of science.

4. *Religion Explained: The human instincts that fashion gods, spirits and ancestors.* Pascal Boyer. Published by Vintage, 2001. ISBN 0 099 282763.
This book discusses the evidence for the intentionality argument for the origin of religious beliefs.

5. *In Gods We Trust: The evolutionary landscape of religion.* Scott Attran. Published by Oxford University Press 2002. ISBN-1*3 978-0-19-517803-6.*
An anthropologist`s view of the naturalistic origins of religious beliefs.

6. Evolution: Nicholas H. Barton, Derek E.G. Briggs, Jonathan A. Eisen, David B. Goldstein and Nipam H. Patel. Published by Cold Spring Harbor Laboratory Press, 2007. ISBN 978-0-87969-684-9

7. *Evolutionary Analysis*: Scott Freeman and Jon C. Herron. Published by Pearson Education, Inc. 2007. 4th edition. ISBN 0-13-239789-7.

8. *Evolution:* Mark Ridley. Published by Blackwell Publishing 2004, 3rd edition. ISBN 1-4051-0345-0.

9. *Understanding Evolution: History, Theory, Evidence and Implications.* Geoff Price 2006. www.rationalrevolution.net/articles/ - scroll down to `Understanding Evolution: History, Theory, Evidence, Implications`.
   This is a comprehensive account of the historical relations between science and religion in the context of evolution.

10. *The Demon-Haunted World: Science as a Candle in the Dark***.** Carl Sagan. Published by Headline Book Publishing 1996. ISBN 0 7472 5156 8.
    This book contains a personal plea for the need to use scientific thinking to safeguard democratic institutions and to combat the growth of irrationality in advanced societies.

11. *Breaking the Spell: Religion as a Natural Phenomenon.* Daniel C. Dennett. Published by Allen Lane 2006. ISBN-13 978-0-713-99789-7.
    This book argues that religious beliefs originate from the cognitive systems that have evolved in the human brain.

12. *How We Believe; The Search for God in an Age of Science.* Michael Shermer. Published by W.H Freeman and Company 2000. ISBN 0-7167-4161-x.
    This book addresses the question as to why people believe in God, as determined from surveys, and examines the validity of the different reasons they give.

13. *The Making of The Fittest: A DNA and the Ultimate Forensic Record of Evolution.* Sean B. Carroll. Published by Quercus 2006. ISBN 978 1 84724 4765.
    This book is a very readable account for the non-specialist of the evidence for evolution that resides in the sequences of DNA molecules.

GENERAL WEBSITES

1. www.darwin-online.org.uk
   This website contains all the publications of Charles Darwin.

2. http://www.darwinproject.ac.uk
   This website contains all the correspondence of Charles Darwin.

2 http://evolution.berkeley.edu
   An introduction to evolutionary theory from the University of California at Berkeley.

SUGGESTIONS FOR DISCUSSION TOPICS

1. What sort of empirical observation would persuade you that Darwin`s theory of evolution is false?

2. Can you think of any ways of explaining the world other than naturalism and supernaturalism? Can you test any of these alternative explanations?

3. Discuss the four postulates that Darwin made in order for natural selection to operate (see Figure 15). What would be the effect on a population if postulates 1, 2 and 3 are correct, but postulate 4 is incorrect? Could natural selection operate if

postulates 1, 3 and 4 are correct, but postulate 2 is not?

4. What is your view of those religious scientists who alternate between naturalistic and supernaturalistic explanations of the world? Does consistency of behaviour matter?

5. Discuss why mutation is random, but natural selection is nonrandom.

6. Conduct a survey of your classmates about what they believe about the nature of the world, and why they believe it. Then conduct another survey of what they think other people believe and why they believe it. Compare the surveys with each other.

7. Can you think of any empirical observation you could make or experiment you could conduct that would persuade you that supernatural agent(s) exist? Are you aware of any such observations or experiments?

8. Assume for the sake of argument that evolution is the invention of a supernatural agent, rather than a natural process. From your knowledge of how evolution works, what might you deduce about the character of that agent?

9. Compare the different lines of evidence for evolution outlined in Part IV. Which do you regard as the strongest evidence and which the weakest? Can you think of any other ways in which the theory of evolution could be tested?

10. Suppose that mutation is not random, but directed to create useful adaptations. From your knowledge of how the genetic code is used to make proteins, how might you explain such a hypothetical process of directed mutation, without invoking supernatural agents?

11. Some religious scientists argue that the `laws of nature` have been created by a supernatural agent, while atheistic scientists point out that natural laws, by definition, have only natural causes. Which of these positions makes more sense to you? Explain why.

12. Suppose that no evidence has been found to support the idea of evolution. Given that both mutation and natural selection are observable facts, how might you explain this absence?