Alles Introductory Biology Lectures

An Introduction to Science and Biology for Non-Majors

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(Painting of Columbia Mammoths by Mark Marcuson)

"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time."

—T. S. Eliot
Little Gidding

Introduction

The organization of this course has been driven by the goal of providing non-majors with a coherent picture of modern biological knowledge. To accomplish this goal it's necessary that each student gains an appreciation of the nature of science and is introduced to the integrated view of our world that modern science has produced. To facilitate this the course is divided into four parts.

Part One: The Nature of Science

There are three elements in defining science: 1) the values of science, 2) science as a profession, and 3) the product of science—scientific knowledge. Using this definition, the goal of Part One is to introduce the fundamental nature of the scientific enterprise.

Major Topics

- Defining Science
- The Epistemic Values of Science
- The Origin of Modern Science
- Science as a Profession

Part Two: The Conceptual Framework of Biology

The goal of Part Two is to introduce the conceptual framework of modern biology. Evolution and historical systems provide the conceptual framework or paradigm for understanding modern biology. But a basic understanding and appreciation of molecular biology is also necessary before we can begin to integrate all of biological knowledge.

Major Topics

- Cosmological Evolution
- Natural Levels of Organization in the Physical World
- Biological Evolution
- Life as a Chemical Function—Biochemistry & Genetics
- The Modern Synthesis—Darwin and Mendel

Part Three: The Integration of Biological Knowledge

The purpose of Part Three is to show how biological knowledge can be integrated into a coherent picture of life on Earth. Because life on Earth is an effectively closed historical system, we must understand that biology is an historical science. One result of this is that a chronological narrative of the history of life provides for the integration of all biological knowledge.

Major Topics

- Geologic Time
- The Origin of our Solar System
- The Origin of Life
- Photosynthesis
- Aerobic Respiration
- Endosymbiosis & Eukaryotic Cells
- The Classification of Life

Sexual Reproduction

Multicellularity

Adaptive Radiations & Mass Extinctions

The Cambrian Explosion

Vertebrate Evolution

Human Evolution

Part Four: Biology and Society

Part Four attempts to show how modern biological knowledge directly affects the important social, ethical issues of our times.

Major Topics

Science & Ethics

Human Population Growth

The Sixth Extinction

Why do Science?

General University Requirements (GURs)

Western Washington University

The General University Requirements embody the belief that liberal education—education in breadth—is as important for informed and effective participation in contemporary life as specialized education. Graduates of Western must be prepared for a complex, rapidly changing world. Students must be skilled communicators, able to critically analyze and use information, able to recognize and address the complex issues of the modern world, and able to become informed and effective citizens.

General University Requirements engage first-year students immediately in the intellectual life of the University and helps them connect their disciplinary expertise to wider academic and cultural contexts. Western graduates complete not only a formal major in an academic or professional field, they also devote a significant part of their study to courses that are part of their GURs. Through the GURs, it is believed that students will lead fuller and more interesting lives, perceive and understand more of the world around and within them, and become engaged citizens of the world.

"Bodily exercise, when compulsory, does no harm to the body; but knowledge which is acquired under compulsion obtains no hold on the mind."

—Plato (427BC-347BC) The Republic, Book VII.

Science Education as Reporting

Science

What is it?

And what does it say about our world?

The Science Instructor as Reporter

What is the proper role of an instructor in a science course for non-majors? In public secondary schools few science instructors have advanced or even undergraduate degrees in science. What, then, is the role they should play in a science classroom? To remain credible their role should be that of a reporter, reporting to their students the current state of scientific knowledge. The state of our scientific knowledge is readily available to most instructors in the form of current college level textbooks for science majors. On the other hand, because they do not have expert knowledge, it is not credible for public secondary school instructors to make judgments about what is, and what is not, a part of current scientific knowledge. They simply are not in a position to judge.

Conversely, by definition students are not in a position to judge what is current scientific knowledge. It is difficult, then, to understand why there is contention in our public secondary schools about teaching science. Students may not believe what they are taught for whatever reasons, but that does not change the obligation of instructors to provide accurate information about modern science.

This is also true for non-majors science courses at the college level. Science is too specialized for any college instructor, whether they are a working scientist or not, to be able to make judgments about content in areas where they do not have expert knowledge. In this sense, it is true that scientific knowledge is what the scientific community says it is. No one other than the collective community of working scientists is in a position to determine what is our current scientific knowledge of the natural world. In the end, the integrity of a science instructor can be measured by how accurately they report to their students what the scientific community says about our world.

Part One: The Nature of Science

Defining Science

What is science?

What is it that makes science different?

And different from what?

Is there a scientific method?

And if so, a method for doing what?

What does the general public think about science? Is it good or bad?

Why does our society support science?

Could we do without science?

If not, what do we get by doing science?

Why do science?

• **Note:** All indicators point to widespread support for government funding of basic research. In July of 2009 the Pew Research Center released their survey of public opinion on science and scientists entitled: *Public Praises Science; Scientists Fault Public, Media*. The survey found that 84% of Americans feels that science's effect on society was mostly positive, and 60% of the public feels that government investment in research is essential for scientific progress.

The complete survey is available online at:
http://people-press.org/report/528/

Defining Science

1) As a set of rules for how to look at the world

—Epistemic Values

2) As a very human activity with all of the attendant failings

—Science as a Profession

3) As the product of the activity of science

—Scientific Knowledge

A Legal Definition of Science

Judge William R. Overton 1982:

McLean versus the Arkansas Board of Education

“A descriptive definition was said to be that science is what is ‘accepted by the scientific community’ and is ‘what scientists do.’ The obvious implication of this description is that, in a free society, knowledge does not require the imprimatur [approval] of legislation in order to become science."

This ruling was upheld by the Supreme Court in 1987.

Note: A corollary to this ruling is that what qualifies as scientific knowledge is not decided by political majority vote, either at the level of local or state school boards, or by state or federal legislation.

Part One: The Nature of Science

The Epistemic Values of Science

Introduction

In trying to answer the question, "What is it that makes science different?", we must examine the values of science as a human endeavor. The first step in doing so is to understand the relationship between worldviews and values.

Worldviews, Values, and Decision-making

A worldview is our mental model of external reality. It consists of theories about the processes that operate in the external world or how the world works; theories as to the state of external reality or how the world is; theories of self-identity that are derived from our mental model of the world; and a set of values derived from our self-identity that assigns priorities in decision-making.

From these elements we build an image of how the world came to be and our place in that world. This image of our personal identity determines what we consider of importance in determining our behavior—our values.

Griffiths gives this picture of what a worldview is and does. "Our view of the universe is built up slowly from input acquired since the beginning of consciousness. This viewpoint represents our identity as individuals. It drives our attitudes and our actions and, as such, determines the kind of people we are and ultimately the kind of society we have."—Griffiths, 1991

The Cultural Transmission of Worldviews

Are worldviews passed from generation to generation?

If they are, then is the particular worldview that an individual has just an accident of birth?

Primary and Secondary Socialization

The problem with primary and secondary socialization is that they entail the uncritical acceptance of beliefs. The problem isn't so much what you receive in the way of beliefs; it's that you didn't have a choice in whether or not to accept them.

> "Our parents' teachings are naturally subject to review as a result of subsequent cultural influences. There is, however, a mechanism that renders some areas of parental teaching particularly effective: humans' greater sensitivity to certain influences during the early years of life. There are critical periods in psychological development during which cultural influences leave indelible traces..." "This mechanism, known as **imprinting**, is especially strong in animals."
> —Cavalli-Sforza, 1995, 210

Self-Autonomy

Our worldviews determine our values, which, in turn, determine how we choose between different courses of action—our decision-making. It is, therefore, extremely important that we analyze our personal worldviews in the light of what we learn about the world as adults. In doing so we achieve self-autonomy.

To be a scientist requires self-autonomy.

Science and Epistemic Values

“Against the background presumption that our aim is to understand the world of experience, a world of unbroken regularity, these values are tools or standards that we cherish, since they are presumed to promote the truth-like character of science, its character as the most secure knowledge available to us of the world we seek to understand. Hence, an epistemic value is one we have reason to believe will, if pursued, help toward the attainment of such knowledge.”—Ruse, 1996, 9

“We want knowledge that is reliable, public, and universal, based upon unambiguous, reproducible experience that is (or can be) common to all of us—in a word, knowledge that is scientific.”—Raymo, 1998, 23

Terms and Definitions to Know

- **Epistemology**—the systematic investigation of the origin, nature, methods, and limits of human knowledge. It attempts to answer the question, how does the human mind perceive and know what is outside itself?

- **Descriptive**—that about a phenomena that can be proven or verified by experience or experiment; descriptive statements are empirical observations subject to scientific verification.

- **Descriptive Epistemology**—empirical observations on how we actually view the world.

- **Prescriptive**—that which gives direction or rules; prescriptive statements are statements of what we should do to achieve specific goals.

- **Prescriptive Epistemology**—rules for how we should view the world that are based upon more fundamental epistemological assumptions.

- **Epistemic Values**—are prescriptive epistemological values that serve in achieving a specific goal. In science that goal is to produce reliable knowledge of the natural, physical world.

The Epistemic Values of Science—A Short List

1) Only those claims to knowledge where the underlying physical causes of a phenomenon have been shown can be accepted by science. This requirement that the cause and effect mechanism that produces a phenomenon must be demonstrated is called **skepticism**. Methodological skepticism requires that all underlying assumptions of a claim to knowledge be identified and their validity questioned. The philosopher David Hume, in his *Treatise on Human Nature* (1740), is credited with being the first to show the importance of skepticism in epistemology.

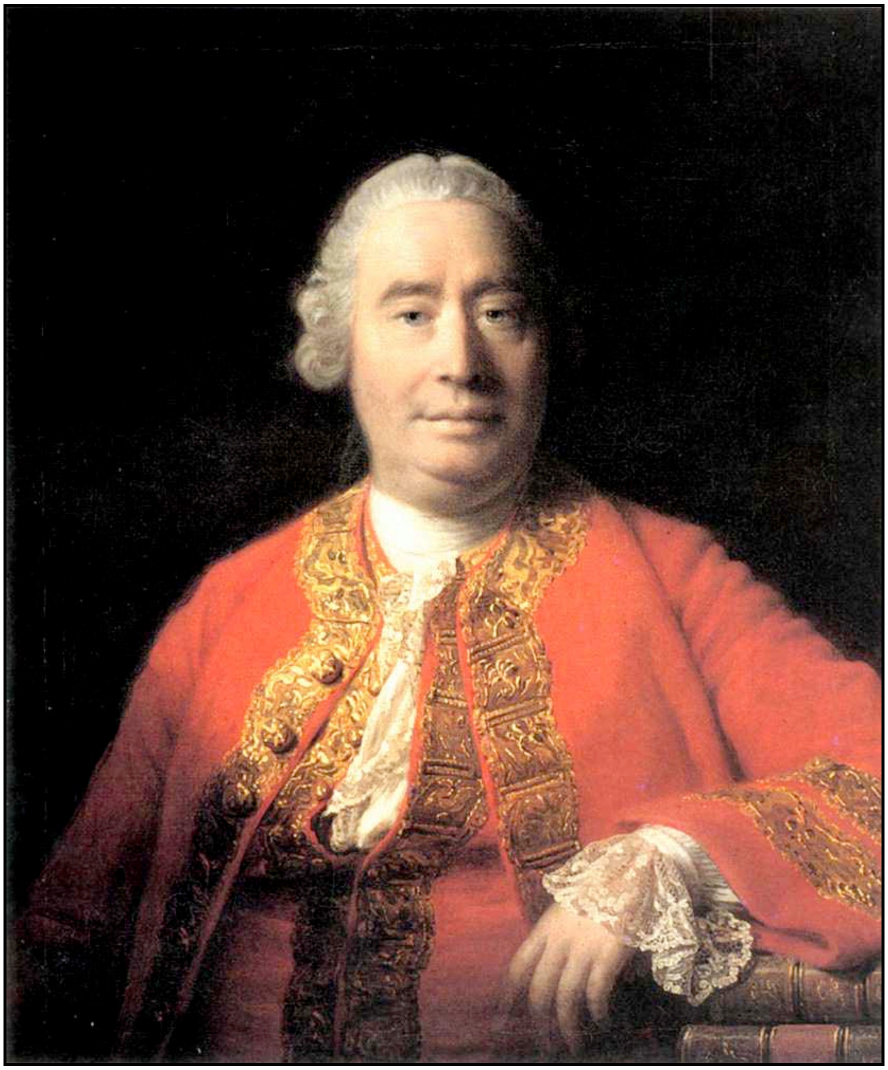
2) Only knowledge claims based upon **physical evidence** can be a part of science. The corollary of this is that all knowledge claims based upon authority alone must be rejected. Personal beliefs do not support claims to knowledge in science. This reliance on physical evidence is closely tied to the rejection of the "scholastic tradition" of accepting the word of authority as absolute truth, which began in the Renaissance and continued on through the Reformation with the rejection of the authority of the Catholic Church.

3) **Prediction** by itself is insufficient to support knowledge claims. Correlation by itself fails to link cause to effect. What is needed is an understanding of the mechanism by which a given phenomenon is produced. This is reflected in science by the value placed on skepticism. But if prediction is combined with a **coherence** to the sum of our reliable knowledge of the physical world, successful prediction in science does support knowledge claims.

4) **Coherence** is the logical connections between the elements of a set of concepts and facts; the degree of coherence that a set of concepts and facts has is a measure of its internal, logical consistency. In science all concepts and scientific facts must cohere to all other scientific facts and concepts; they must be both internally and externally, logically consistent.

5) **Consilience**, as a property of scientific theories, increases the reliability of scientific claims to knowledge. The degree that a scientific theory has consilience is a measure of its ability to explain and unify many separate and seemingly unrelated areas of scientific study. Consilience presupposes the unity of knowledge that follows from the assumptions of realism. That is, if there is only one real world, then all true knowledge will be coherent and contribute to understanding that world. The term consilience was first used by William Whewell in 1840.

• **Point:** Science is set apart from other human endeavors by the epistemic values it accepts.



David Hume (1711-1776)

Hume, an eighteenth century Scottish philosopher and historian, is consider by many to be the greatest philosopher to have written in the English language.

For more on David Hume and the history and philosophy of science go to: http://fire.biol.wwu.edu/trent/alles/Gallery.pdf

Part One: The Nature of Science

The Origin of Modern Science

Introduction

It is difficult to understand how profound a revolution that the origin of modern science was unless we understand how dramatic a change it represents from the medieval worldview. The following essays are included, therefore, to provide a picture of the medieval view of reality.

Essay—The Medieval Worldview and Augustine the Bishop of Hippo

"After the fall of the city of Rome to the barbarians in A.D. 410, it seemed to the rest of the Roman empire that darkness and death were inevitable. Augustine, the Christian Bishop of the north African Roman province of Carthage, was deeply affected by the fall of Rome. His reaction to the pessimism of the times was to offer a way of escape. Augustine was influenced by Plato's philosophy which drew a distinction between reality and appearances as well as between opinion and knowledge. The everyday world of the senses was worthless because it was only a shadow of reality, a product of opinion. True knowledge lay in the mind and consisted of the pure, ideal forms [this is Platonic essentialism]. By implication, everything in the daily life of the Platonist Christian was a shadow of the truth. The miseries and trials he had to suffer were transient, as was all else in the world. The human body itself was a shadow. Only the soul was real, escaping its temporary and irrelevant prison of flesh at death to return to heaven, the ideal world, from which it had originally come.

Augustine combined these views with the teachings of the Scriptures in a book called *The City of God*. This work, which offered a complete set of rules for living and an integrated structure for Christian society, was to influence Christian thinking for a thousand years. Augustine offered escape to a spiritual life in the monasteries. If the world was not worth study, deserting it for a life of contemplation could only be for the good. Belief was more important than earthly knowledge. *Credo ut intelligam* (understanding comes only through belief) was the creed which would see the monasteries through the Dark Ages that lay ahead."—Burke, 1985, 20

Essay—Life in Medieval Europe

"Contemporary references reveal the people of the time to have been excitable, easily led to tears or rage, volatile in mood. Their games and pastimes were simple and repetitive, like nursery rhymes. They were attracted to garish colors. Their gestures were exaggerated. In all but the most personal of relationships they were arbitrarily cruel. They enjoyed watching animals fight and draw blood.

Much of their life was led in a kind of perpetual present: their knowledge of the past was limited to memories of personal experience, and they had little interest in the future. Time as we know it had no meaning. They ate and slept when they felt like it and spent long hours on simple, mindless tasks without appearing to suffer boredom.

The medieval adult was in no way less intelligent than his modern counterpart, however. He merely lived in a different world, which made different demands on him. His was a world without facts. Indeed, the modern concept of a fact would have been an incomprehensible one.

Medieval people relied for day to day information solely on what they themselves, or someone they knew, had observed or experienced in the world immediately around them. Their lives were regular, repetitive and unchanging.

There was almost no part of this life-without-fact that could be other than local. Virtually no information reached the vast majority of people from the world outside the villages in which they lived. When all information was passed by word of mouth, rumor ruled. Everything other than personal experience was the subject of hearsay, a word which carried little of the pejorative sense it does today. What medieval man called 'fact' we would call opinion, and there were few people who traveled enough to know the difference. The average daily journey was seven miles, which was the distance most riders could cover and be sure of return before dark."
—Burke, 1985, 91-92

Essay—Scholasticism

One of the central epistemic prescriptions of science is that only knowledge claims based upon physical evidence can be supported. Its obvious corollary is that all knowledge claims based upon authority alone must be rejected. This is the rejection of the medieval "scholastic tradition" of accepting the word of authority as absolute truth.

The scholastic tradition or scholasticism was "the system of theological and philosophical teaching predominant in the Middle Ages, based chiefly upon the authority of the church fathers." (Webster's, 1989). The first significant figure to challenge that tradition was Pierre Abelard (1079-1142), French scholastic philosopher, teacher, and theologian. His love affair with Heloise is one of the famous romances of history.

In his work *Sic et Non* (For and Against), Abelard was the first to apply the dialectic use of logic to the Holy Scriptures. "Until the time of Abelard a statement by an accepted authority had sufficed for proof. Abelard showed that these authorities were contradictory. Though he claimed that his attack on authority aimed only at finding the truth, the Church did not approve. When he said, 'By doubting we come to enquiry; by enquiring we perceive the truth,' Rome heard the voice of a revolutionary. Abelard laid down four basic rules for argument and investigation:

> Use systematic doubt and question everything.
>
> Learn the difference between statements of rational proof and those merely of persuasion.
>
> Be precise in the use of words, and expect precision from others.
>
> Watch for error, even in Holy Scripture.

Statements like these were quite extraordinary in the twelfth century. Objectivity, detachment and unprejudiced, unemotional ratiocination were rare to the medieval mind, steeped as it was in mystery and dogma."
—Burke, 1985, 44-45

Today the scholastic tradition lives on in both the humanities and theistic religions. The following example is from Pope John Paul's 13th Encyclical, Chapter III *Intellego ut Credam*, Section 33:

"Such a truth [absolute truth] ... is attained not only by way of reason but also through trusting acquiescence to other persons who can guarantee the authenticity and certainty of the truth itself."—Stanley, 1998

Peter Abelard (1079-1142)

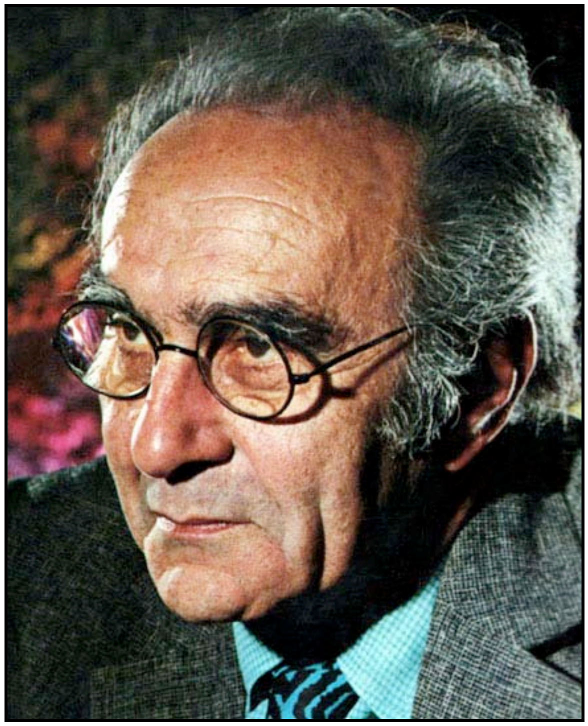
Abelard was one of the great intellectuals of the 12th century, with special importance in the field of logic. His advanced use of logic is best demonstrated by his book *Sic et Non*. But he is perhaps as famous today for his love affair with Heloise (1101-1164) and its disastrous consequences.

- **When did modern science originate?**
- **Where did modern science originate?**
- **Why did it happen?**

On the Origin of Modern Science

The origin of modern science can be established by locating when the shift toward the epistemological values of modern science began. This shift in values has been defined most clearly by the late Jacob Bronowski.

> "I hold that the scientific revolution from 1500 onward was an essential part of the Renaissance, ..."
>
> "Since that time we have been in the unique position of trying to form a single picture of the whole of nature including man. That is a new enterprise; it differs from the preceding enterprises in that it's not magical, by which I mean that it does not suppose the existence of two logics, a natural logic and a supernatural logic."
>
> "If one had to put a date to this, [the origin of modern science] one would say that roughly speaking between 1500 and the publication of Porta's book in 1558, which was called *Natural Magic*, the turning point took place."—Bronowski, 1978



Jacob Bronowski (1908-1974)

Bronowski was a Polish-born, British mathematician and man of letters who eloquently presented the case for the humanistic aspects of science. From 1964 until his death Bronowski was a resident fellow of the Salk Institute of Biological Sciences (San Diego, Calif.). His last major project was the authorship and narration of the BBC television series *The Ascent of Man* (1973), a luminous account of science, art, and philosophy in human history.

Pietro Pomponazzi (1462–1525)

“It is possible to justify any experience by natural causes and natural causes only. There is no reason that could ever compel us to make any perception depend on demonic powers. There is no point in introducing supernatural agents. It is ridiculous as well as frivolous to abandon the evidence of natural reason and to search for things that are neither probable nor rational.”—Pomponazzi of Padua from his book *Of Incantations* (1520)

Note: In sixteenth century Europe statements like this could get you in trouble—a lot of trouble.

Giordano Bruno (1548-1600)

By the year 1582, it’s easy to get an impression of the reputation which Bruno had created in the minds of the church authorities of southern Europe. He had written of an infinite universe which had left no room for the greater infinite conception of God. For he could not conceive that God and nature could be separate and distinct entities as taught by the Church. Inevitably, charges of heresy were made against him. He was imprisoned by the Inquisition for eight years as his trial dragged on. When he was finally sentenced as a heretic for his beliefs, Bruno answered the sentence of death by fire with the words: “Perhaps you, my judges, pronounce this sentence against me with greater fear than I receive it.”

On February 17, 1600, he was taken to the Piazza Campo dei Fiori in Rome, tied naked to an iron stake, and burned alive by the Catholic Church.

Galileo Galilei (1564-1642)

In 1633, Galileo was condemned to house arrest by the Catholic Church for his book *The Dialogue on the Two Chief Systems of the World*. He remained under arrest until his death in 1642. His book was placed on the Index of Prohibited Books and remained there until 1835. Finally, in 1992, the Catholic Church formally apologized for its treatment of Galileo.

Peeling the Chinese Onion:

Why Science originated in Europe and not China (Diamond, 1998)

"In no society, Eastern or Western, Chinese, Roman, medieval, or contemporary, have science and rational speculation long survived the imposition of absolute dogma—religious or social."—Bronowski, 1977, 253

Europe is a peninsula of peninsulas broken up by mountains and water. Because of this no single country or ruler has been able to conquer all of Europe.

Most of classical China was a vast open plain created by the lower basins of the Yellow and Yangtze rivers that stretches north to south from modern Beijing to Shanghai. Partly because of this, China for most of its history had a strong central government.

Science and the Reformation

The beginning of the Reformation in 1517, is marked by Martin Luther nailing his Ninety-Five Theses to the door of the Wittenberg Church in Saxony, signaling his rejection of the authority of the Catholic Church. The Reformation, like the Renaissance, was born in the fold of small independent states such as Saxony. Indeed, without them, it could not have survived.

Like the humanists, the Reformers were opposed to life in the monastery and were thoroughly committed to life in the world. The culture roughly described as humanist which gave rise to much of our modern world including modern science, and the Reformation, arose as the authority of the Catholic church ebbed. Both movements were movements of emancipation, drawing their inspiration and their legitimacy from an earlier period. In their recasting of values, and their attempt to shape new views of man, the humanists and Reformers were akin, but their visions of life and of human capacity and their sources of authority were quite different.

• **Note:** Henry VIII rejected the authority of the Pope and founded the Church of England in 1534.

Time Line for the Epistemic Values of Science

1130—Pierre Abelard writes the book *Sic et Non*

1520—Pomponazzi of Padua writes *Of Incantations*

1620—Francis Bacon writes "we cannot command nature except by obeying her"

1662—the founding of the Royal Society in England with their motto (roughly translated from Latin) "Take nobody's word for it; see for yourself"

1740—David Hume on skepticism in *Treatise on Human Nature*

1840—the work of William Whewell on the *Consilience of Inductive Sciences*

• **Note:** The shift in epistemic values that produced modern science occurred first and more than 300 years before science became a profession.

Survival Value & Control

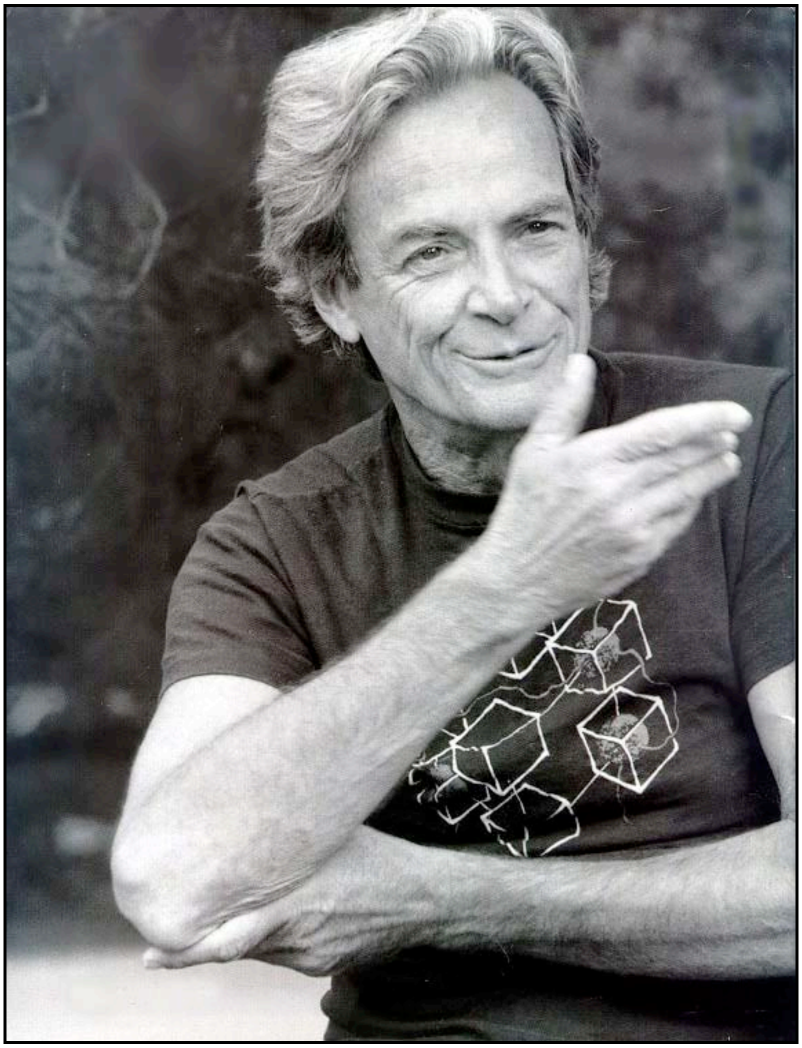
In answer to the question, "What do we get by doing science?", we have the following.

For science to exist we must want to know; we must really want to know. We must be willing to give up all our preconceived notions and beliefs and **let nature be the final arbitrator of truth**. The tradeoff is that there is tremendous survival value in having reliable knowledge about our world. With it comes control over nature and for the first time in human history we are no longer at the mercy of an indifferent universe.

• **Point:** The goal of science as a human endeavor is the production of reliable knowledge about the natural, physical world. This goal, in turn, through a spontaneous process of trial and error in the history of science, has determined the modern epistemic values of science.

Part One: The Nature of Science

Science as a Profession



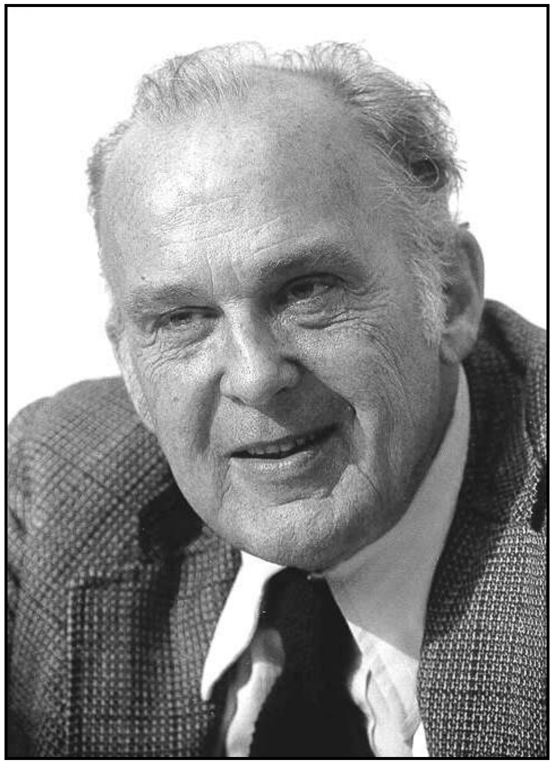
"Science is a long history of learning how not to fool ourselves."

Richard Feynman (1918-1988)

Science as a Profession

"The known is finite, the unknown infinite: intellectually we stand on an islet in the midst of an illimitable ocean of inexplicability [a limitless sea of ignorance]. Our business in every generation is to reclaim a little more land, to add something to the extent and solidity of our possessions."

—from Thomas Henry Huxley written in 1887



“Donald T. Campbell, one of the most respected philosophers of science of this century, had a vision of science in which flawed, venal people together yield the noblest of products. His hypothetical realism [his philosophy] is addressed to those with faith that science edges towards truth, and shows us how—via variation and selective retention, and competition among the cooperators—ego-involved, over-committed, and under-informed mortals could bring this about.”—Heyes, 1997

• What is the history of professional science?

• How is it organized today?

• How does it operate to produce reliable knowledge?

The Organization of Modern Science

• The University Connection—Academic Science

Institutes —The NIH, Salk, Max Planck

Societies—AAAS, NAS

Journals—*Nature, Science*

The Reward System

(research / publish—peer reviewed journals / grants / promotions / prizes)

Science as a Self-Correcting System

(You are rewarded for finding mistakes as much
as you are for making new discoveries.)

• The Corporate Connection—Corporate Science

The Rise of Biotechnology

Fundamental as opposed to Directed or Applied Research

• How can we define who is a professional academic scientist?

“By statured scientists I mean those who collect and analyze the data, build the theoretical models, interpret the results, and publish articles vetted [peer reviewed] for professional journals by other experts, often including their rivals.”

E. O. Wilson in *Consilience: The Unity of Knowledge* (1998)

Professional Science can be divided as follows:

• **Academic and Institutional Science**—consists of those scientists working in public and private institutions such as universities and institutes where the major funding for research is public monies. Publishing results in peer reviewed journals is a central goal of this research.

• **Corporate or Industrial Science**—consists of those scientists working for private companies or corporations where funding is provided by private investment. Publishing results is not a goal of this research.

Both Academic and Corporate Science can then be divided into:

- **Fundamental or Pure Research** is driven by the goal of discovering new knowledge without regard to the direction the research might take.

- **Directed Fundamental Research** has a predetermined goal that only can be achieve by the discovery of new knowledge. The cure of specific diseases such as cancer is an example of such research.

- **Applied Research** takes existing scientific knowledge and applies it to develop new technological applications. The development of computer software produces no new scientific knowledge and yet is central to developing new applications of our existing scientific knowledge of electronic computing. Applied research is done by both professional scientists and engineers.

Excerpt from

The Demon-Haunted World: Science As a Candle in the Dark

by Carl Sagan (1996)

“Science may be hard to understand. It may challenge cherished beliefs. In the hands of politicians or industrialists, it may lead to weapons of mass destruction and grave threats to the environment.

But one thing you have to say about science: It delivers the goods. If you want to know when the next eclipse of the Sun will be, you might try magicians and mystics, but you’ll do much better with scientists. They can tell you within a fraction of a second when an eclipse will happen decades or centuries in the future, how long it’ll last and where on Earth you should be standing to get a good look. If you want to know the sex of your unborn child, you can consult astrologers or plumb-bob danglers all you want, but they’ll be right, on average, only one time in two. If you want real accuracy, try science.

What is the secret of its success? Partly, it’s this: There is a built-in error-correcting machinery. There are no forbidden questions in science, no matters too sensitive or delicate to be probed, no sacred truths. There is an openness to new ideas combined with the most rigorous, skeptical scrutiny of all ideas, a sifting of the wheat from the chaff. Arguments from authority are worthless. It makes no difference how smart, august or beloved you are. You must prove your case in the face of determined, expert criticism. Diversity and debate between contending views are valued.

Scientific findings and theories are routinely subjected to a gauntlet of criticism—oral defenses of doctoral theses, debates at scientific meetings, university colloquia punctuated by withering questions, anonymous reviews of papers submitted to scientific journals, refutations and rebuttals. There is a reward structure built into science for finding errors: The more basic and fundamental the error exposed, and the more widely accepted it was, the greater is the reward.

This may sound messy and disorderly. In a way, it is. Science is far from perfect. It's just the most successful method known, by far, to understand the world. The discipline of science is hard; scientists, being human, don't always follow the methods of science themselves. Like other people, they don't especially enjoy having their favorite ideas challenged. But they recognize it as the cost of getting to the truth. And the truth—rather than the confirmation of their preconceptions—is what they're after.

Wherever possible, scientists experiment. They do not trust what is intuitively obvious. That the Earth is flat was once obvious. That heavier bodies fall faster was once obvious. That blood-sucking leeches cure disease was once obvious. That some people are naturally and by divine decree slaves was once obvious. That the Earth is at the center of the Universe was once obvious. The truth may be puzzling or counterintuitive; it may contradict deeply held prejudices. But, as the history of both science and politics has amply demonstrated, preferring comfortable error to the hard truth is, sooner or later, disastrous."

• How old is professional science?

The creation of a profession from 1662 to 1869

Time Line for Science as a Profession

Mid 1600s—founding of the Royal Society in England and the Academie des Sciences in Paris

1665—first issue of the scientific journal the *Philosophical Transactions* of the Royal Society

Early 1800s—"France despite and because of the Revolution, was the first and most vigorous country in offering opportunities for professional scientists, in any sense that we know them today." (Ruse 1996)

1833—William Whewell in England coins the term "scientist"

1869—founding of the scientific journal *Nature* by T.H. Huxley and friends

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• Point: Scientists are "ego-involved, over-committed, and under-informed mortals", but science works because the profession imposes the epistemic values of science on individual scientists.

T. H. Huxley was the first to forge the connection between professional scientists and public education, i.e. with the training of science teachers and the link to training doctors. Huxley was also an example of the new breed of scientists who relied solely on their income earned as a professional scientist. Darwin, in contrast, was independently wealthy and did all of his research without having a professional position.

“At the time that the *Origin of Species* was published, Britain was a country desperately in need of reform, as revealed by the horrors of the Crimean War and the Indian Mutiny. Huxley and others worked hard to bring about change, trying to move public perceptions into the 20th century. They reformed education, the civil service, the military, and much else. Huxley’s own work was in higher education, and he succeeded best in the areas of physiology and morphology. He realized that to improve and professionalize these fields as areas of teaching and research, he needed clients (a must in all system building). Huxley sold physiology to the medical profession, just then desperate to change from killing to curing. Huxley’s offer of a supply of students, ready for specialized medical training, with a solid background in modern physiology was gratefully received. Morphology, Huxley sold to the teaching profession, on the grounds that hands-on empirical study was much better training for modern life than the outmoded classics. Huxley himself sat on the new London School Board and started teacher training courses. His most famous student was the novelist H. G. Wells.”—Desmond, 1997

Terms and Definitions to Know

• **Scientific Fact**—a piece of empirically verifiable information presented as having objective reality about the physical world.

• **Scientific Hypothesis**—a guess about processes in the physical world consistent with current scientific knowledge.

• **Scientific Law**—a precise mathematical relationship between physical parameters that is believed to hold true in all circumstances. Some examples are Einstein's $E = mc^2$, Newton's 2nd Law of motion $F = ma$ and the Law of Universal Gravitation $F = G \bullet m1\ m2/r^2$.

• **Scientific Theory**—provides understanding of dynamic processes in nature. Scientific theories must cohere to the sum of scientific knowledge and provide empirically verifiable predictions. "In science, theories do not turn into facts through the accumulation of evidence. Rather, theories are the end points of science." (NAS, 1998)

• **Scientific Paradigm**—a universally explanatory theoretical structure that provides unity to a field of scientific study. Examples are plate tectonics in geology, general relativity and quantum mechanics in physics, and evolution by natural selection in biology. Consilience, the ability of a scientific theory to explain a wide range of phenomena, is a central characteristic of scientific paradigms.

Essay—Theory, Hypothesis, and Fact

Science seeks to understand the steps in the dynamic processes that produce what we see in nature. But once we have achieved an understanding of a given process, and once we have repeatedly verified that our explanation is correct, what do we call this explanation? The term "theory" is used in science to describe such an understanding of a given process. And, indeed, the first definition of "theory" in Webster's reads, "a coherent group of general propositions used as principles of explanation for a class of phenomena."

The term, however, is also burdened with a generic meaning. Webster's second definition of "theory" is, "a proposed explanation whose status is still conjectural, in contrast to well-established propositions that are regarded as reporting matters of actual fact." In science this meaning is given to the term hypothesis.

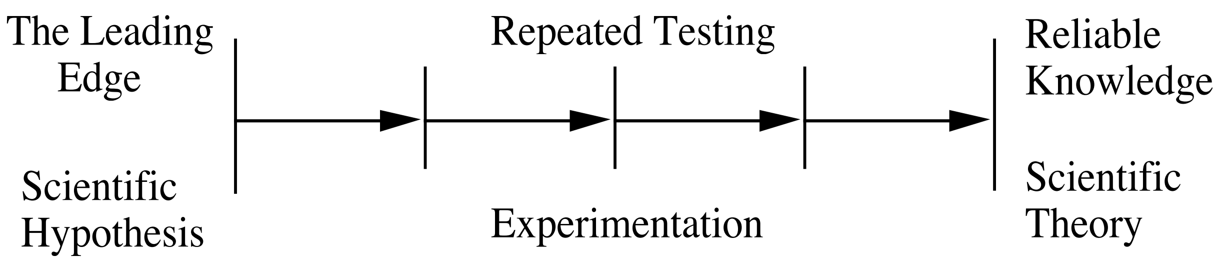
"Hypothesis ... a proposition, or set of propositions, set forth as an explanation for the occurrence of some specified group of phenomena, asserted merely as a provisional conjecture to guide investigation (working hypothesis) or accepted as highly probable in the light of established facts."

The term "fact" as used above is used to express that something is true: "fact ... that which actually exists; reality; truth." But this use of the term "fact" is itself misleading. Are scientific theories just a collection of facts, or are they how a process actually exists; in reality; in truth? It is crucially important to understand that "truth" is defined by the epistemology that an individual or group accepts.

In science the term “truth” is problematic. If the issue is whether science can produce absolute truths, it must be understood that absolute truths require absolute knowledge to prove their validity. In an epistemology that is restricted to physical evidence, such as the epistemology of science, absolute knowledge is not possible as it would require that we were aware of all the phenomena in the universe. This would require a knowledge of all places in the universe throughout all of time—clearly an impossibility. Therefore, without absolute knowledge, all scientific knowledge claims must remain tentative. Scientific knowledge, however, because of the epistemic values of science, remains the most reliable knowledge we have of the physical world.

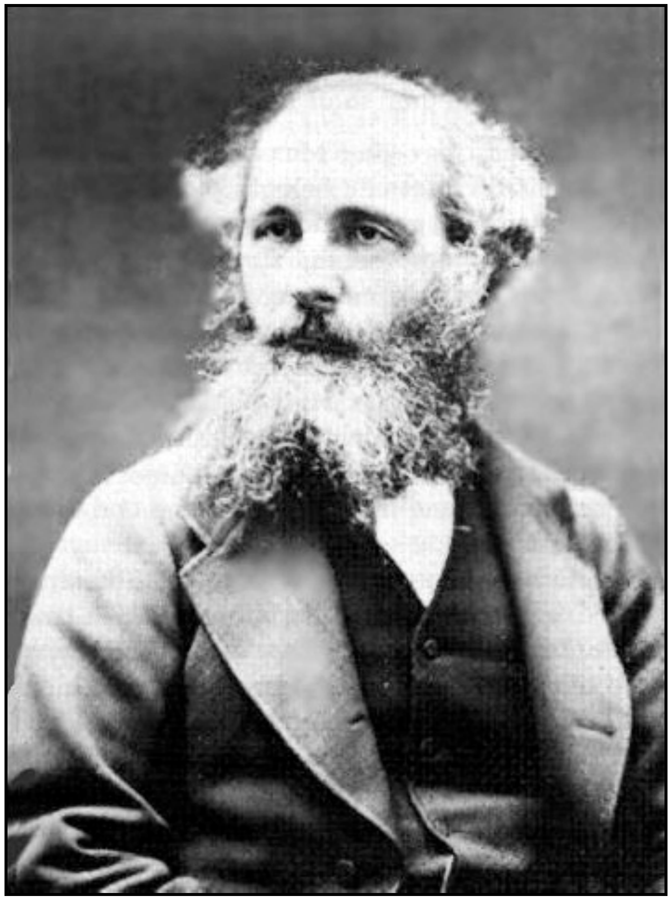
(All definitions used are from *Webster’s Encyclopedic Unabridged Dictionary of the English Language*, 1989.)

• **How does science produce reliable knowledge?**



“Theories are the crown of science, for in them our understanding of the world is expressed. The function of theories is to explain.”

—Harré, 1986, 168



James Clerk Maxwell (1831-1879)

Maxwell, who was born in Edinburgh, Scotland, is generally regarded as one of the greatest physicists the world has ever known. Einstein felt that Maxwell's work produced the most profound change in our concept of physical reality since Newton. One of Maxwell's many achievements was to unite electricity and magnetism into the concept of the electro-magnetic field.

Maxwell's equations describing the properties of electro-magnetic fields have been repeatedly tested in our modern world by the design and construction of every electronic device made since the nineteenth century. Scientist, being pragmatic, have long understood that at some point any further questioning of Maxwell's equations is a useless waste of time, and, today, treat them as a true description of physical reality.

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http://www-groups.dcs.st-and.ac.uk/~history/Mathematicians/Maxwell.html

Is there a “scientific method”?

Reductionism versus Holism?

Reductionism and holism are methods used in science to investigate a phenomenon of interest. To compare the two think of a clock. To understand a clock you have two fundamental choices. You can take it apart to examine its parts and from them try to reason how the clock works, or you can look at the whole thing to see what it does. Reductionism is to take a phenomenon of interest apart to see what it is made of; holism is to view a phenomenon of interest as a whole and see how it functions. The central question, however, is can you use one method without the other?

• **Point: There is no single scientific method.** “Science can be a process in which practically anything goes—from middle-of-the-night hunches to mathematical formulations driven by classical aesthetics—so long as the results accurately describe and predict phenomena in the real world.” (Tyson, 1998). We must recognize that developing hypotheses is a creative act as much as art or music. Creative thought can occur in almost any fashion, and it is only after a hypothesis is formed that the rigorous process of experimentation and testing can begin. The creative act must come first in science just as it must in the arts.

The Unity of Science

Science may be the only spontaneously forming, unified human endeavor in all of human history. It is truly an international community with a common language composed of mathematics, a common literature, and a common nomenclature including standardized metrics; in biology, species names; in chemistry, the periodic table of elements; etc..

Why is this so? Because there is only one physical world out there, thus everyone is studying the same thing using the same rules. And why the same rules—because they work. These rules are the epistemic values of science. If your goal is to understand the natural world, and there is only one natural world, then you must develop a methodology that allows you to “accurately describe and predict phenomena in the real world”. The epistemic values of science are what they are because they do just that.

• **Note:** Scientific knowledge, once produced, exists apart from how it was produced. As Bronowski puts it: "But of course, the facts discovered must not be confused with the activity that discovers them." (Bronowski, 1977).

We have now completed the first two elements in defining science, epistemic values and science as a profession, and now turn to the third element, the product of the scientific endeavor—scientific knowledge.

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