Characteristics of Science

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Understanding Scientists and their Work

What is science? How does science work? What are scientists like? Most people have given little thought to these sorts of questions, yet often possess surprisingly entrenched misconceptions of each. These strongly held opinions are often formed from everyday media portrayals of science and scientists found in movies, television programs, commercials and advertisements, and popular literature. School science classes from elementary school through college also send persistent messages regarding what science and scientists are like and how science is done. Unfortunately, both the media and school science often inaccurately portray what authentic science and scientists are like. Thus, the impressions many people hold are likely mistaken in many important ways.

You may be wondering why understanding the characteristics of science is important and worthy of your attention. These misunderstandings are associated with several unfortunate consequences:

- Very bright students, particularly women and those from underrepresented groups, often do not pursue science careers because they wrongly see science as a field devoid of social interaction, creativity, and personal expression.
- Difficulty in deeply understanding important science concepts has been linked to misunderstandings of what science attempts to do and how it goes about understanding the natural world.
- Poor social decision-making by citizens and policy-makers regarding matters involving science are linked to misunderstanding how science is done and how knowledge becomes well established.

The benefits of accurately understanding the characteristics of science include a more scientifically literate society, a public that is more supportive of science, a more informed use of scientific knowledge, and a reduced flight of capable students out of science career tracks.

In order to help you better understand the characteristics of science, in this course you will read several short stories that accurately reflect how scientific knowledge was developed and came to be accepted. Comments and questions are embedded in these stories to draw your attention to accurate ideas regarding the characteristics of science. However, your prior ideas regarding what science is, how science is done, and what scientists are like may easily cause you to miss important lessons about the characteristics of science. To help you get the most out of the stories and accurately interpret what they are illustrating about science, the following overview is intended to assist you in recognizing misconceptions regarding the characteristics of science that you may possess.

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Referring to and keeping these characteristics of science in mind when reading the stories that are assigned will help you better understand what science and scientists are like, and how doing science is more interesting than you may have previously thought.

Science Is Not the Same as Technology

Many people know that while football is related to the game of rugby, the two are not the same. And American football and Australian football are just two kinds of football. This same sort of confusion occurs regarding different kinds of science and their relation to technology. Figure 1 will help illustrate two different forms of science and how they interact with each other and technology.

While science and technology do impact each other, basic science is not directly concerned with practical societal outcomes. Instead, basic science focuses on

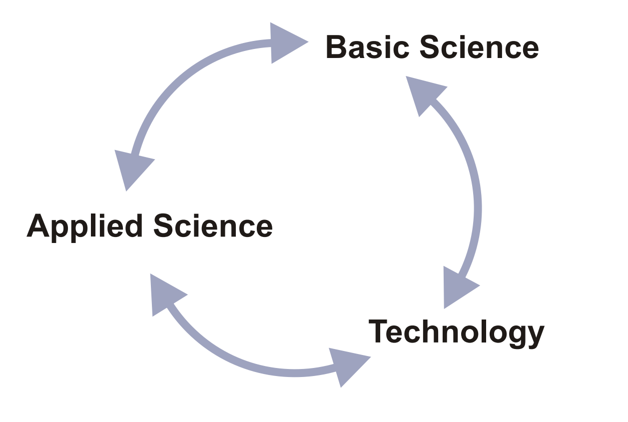

Figure 1. Interactions between Basic Science, Applied Science, and Technology

understanding the natural world for its own sake – akin to playing a game for the love of sport. Scientists conducting basic science often do not even consider what societal use may come from their work. However, basic research is responsible for most of the fundamental breakthroughs in our understanding of the natural world. And knowledge that comes from basic research often has unanticipated practical outcomes. For instance, James Watson's *The Double Helix* made clear that scientists working to determine the structure of DNA gave little thought to how the knowledge might be applied, and they certainly could not have foreseen the multiple applications in medicine that exist today. And when Thomas Brock went to Yellowstone to study organisms that live in hot springs at temperatures where most life cannot exist, he could not foresee that decades later his work would provide the foundation for a process that generates millions of dollars in revenue and is an essential aid to the biotechnology industry.

Of course, much scientific research *is* done because of the likely benefit it may have in helping address a societal problem. This sort of science is referred to as applied research. While the product of basic and applied science is knowledge about the natural world, technology can be thought of as more tangible products and processes useful in everyday life, industry, and the military. While technology uses knowledge developed by basic and applied science, it also produces products that promote scientific research. And the knowledge produced by either basic or applied science impact each other as well. If any of the three were missing, the other two would significantly suffer.

In practice, disentangling science from technology, and basic science from applied science, is sometimes difficult, but this entanglement illustrates how interdependent the three are. What is important is that you come to see the complex relationships between the three and understand that all are valuable endeavors worthy of funding.

Scientists Will Employ Whatever Methods They Find Useful for Understanding the Natural World

Perhaps the most pervasive misconception regarding the characteristics of science is that scientists follow a step-by-step scientific method when conducting research. While scientists do reason through problems, the variety of methods they use result from a number of factors – the kind of phenomena being explored, the specific problem at hand, existing scientific knowledge and thinking, available resources, serendipitous events, and the investigator's preferences, imagination and creativity. This is why the physicist and Nobel Laureate, Percy Bridgman, once claimed that "the scientific method, insofar as it is a method, is nothing more than doing one's damnedest with one's mind, no holds barred". Scientists tend to use whatever methods and approaches that will shed insight onto a research problem. For instance, many well-established science ideas did not come about from experiments. Experiments are often useful in science, but they have limits. Some of the most fundamental ideas in science were not developed or established through conducting experiments, but by other means such as observation, model building, and other approaches. In some fields of science, conducting experiments or having an experimental control is not even possible. Even in scientific disciplines where experiments are prevalent, the notion of a rigid scientific method simply does not reflect what actual scientists do.

Doing Science Well Requires Imagination and Creativity

Nobel Laureate Peter Medawar argued that although scientific papers are written in a manner to best communicate and persuade readers of the logic behind the reported work, the format implies to non-scientists that researchers actually follow a step-by-step method. Left out of scientific papers are the hunches, dead ends, creative insights, extensive discussions, and other occurrences that make clear science is a human process. Thus, what does appear in scientific papers implies that scientists follow a step-by-step scientific method. Conveying a definite structure to scientific methodology wrongly leads students to think that experiments are the only route to understanding the natural world, that imagination and creativity play little if any role in research, that the success of science is due to a purely logical step-by-step method, and that this method separates science from other disciplines.

Actual research is far messier and demands imagination and creativity to generate ideas never before considered. Einstein once remarked that imagination is more important than knowledge for that is where novelty arises. He claimed that his ideas regarding relativity emerged from his imagining what riding on a beam of light would be like. John Dewey once said that "Every great advance in science has issued from a new audacity of imagination." As you read the stories, look for how imagination and creativity are the engine of scientific advance and indispensable for its success.

The Generation and Acceptance of Scientific Knowledge Often Takes Much Time

The media and science textbooks often give the impression that credible scientific ideas were generated and accepted rather quickly. But typically much time passes as questions are conceived, ideas are put forward, debated, modified, become credible, and are eventually accepted by the scientific community. A variety of reasons account for the length of time required for scientific questions to be confidently answered.

Sometimes asking the precise question that will lead to productive research can be very challenging and much time may pass pursuing unproductive questions. Moreover, unlike most school laboratory experiences, scientists conducting authentic research do not have a set of instructions to follow in pursuing their questions. And the data that is collected do not tell scientists what to think. Rather, scientists must determine what data are significant, what data to ignore, and generate ideas that will make sense of the data. Once generated, ideas must be persuasive to the community of scientists who do research in that area.

Importantly, scientists do not vote on what the natural world is like. The well-known vote among astronomers in 2006 to reclassify Pluto as a dwarf planet was not to determine whether an object existed or how it behaved. Rather, it was a vote on how to classify the object. Consider how absurd and problematic voting on what the natural world is like would be! All in favor of gravitation say “Yay”, all opposed say “nay”? Motion passes 57% to 43%? How would the dividing line between passage and failure be determined?

In authentic science, ideas emerge and are accepted over much time as scientists are persuaded that an idea is valid. As further research evidence and reasoning supports such ideas, they become so widely accepted by the researchers in the relevant field of research that, as the paleontologist Stephen J. Gould put it, withholding provisional consent would be perverse. New researchers are educated in the latest way of thinking and eventually that way of thinking is accepted as the way nature is.

However, remember that scientists have no higher authority to seek out and ensure whether they are asking the most productive questions, are pursuing them appropriately, have correctly analyzed their data, and whether or not they have reached correct conclusions. Figuring all this out is what makes doing science so interesting and challenging. As Einstein noted, if all these decisions were straightforward and quick, “it wouldn't be called research, would it?”

Science Has a Subjective Aspect

Because science is a human endeavor, subjectivity or preconceived notions cannot be eliminated. The knowledge scientists bring to their research influences what questions they ask, how they go about pursuing answers to those questions, what data is deemed relevant and irrelevant, and what kinds of answers are plausible. Knowledge, as well as being a product of investigations, is also a tool for making further observations and deriving new knowledge. What scientists think and see is necessarily influenced by the previous thinking they bring to bear on their research.

A more realistic view of how scientists and the scientific community work to check, but not eliminate subjectivity, includes an understanding of private science, public science, and their interactions. Private science refers to the inspiration, intuition, imagination and creative leaps that individual scientists make. Private science can also refer to the dynamics of research teams. The processes and ideas born in these close-knit situations can easily result in unwarranted conclusions and unexamined biases, but the process of publicly sharing ideas with the larger community of scientists acts to constrain subjectivity as methodologies and biases are examined and modified by the views of other scientists. Public science tempers, without eliminating, the subjective tendencies of private science.

Well-Established Science Knowledge is Durable, but Always Open to Revision

Knowledge about the natural world is not discovered like finding your lost car keys. Much effort, imagination, creativity and time is required to generate credible ideas and for those ideas to be accepted by the scientific community. Many people wrongly think of well-established scientific knowledge as proven truth, but this misses the important point that scientists can never know if they have the absolute truth of the matter (remember, they have no higher authority who can confirm their ideas). Science teachers often perpetuate this view by using words like “prove” and “true” without making clear to students what those words mean in a science context. Many arguments can be made against the notion of absolute truth in science, but Einstein and Infeld provide an easily understood analogy:

> In our endeavor to understand reality we are somewhat like a man trying to understand the mechanism of a closed watch. If he is ingenious he may form some picture of a mechanism which could be responsible for all the things he observes, but he may never be quite sure his picture is the only one which could explain his observations. He will never be able to compare his picture with the real mechanism and he cannot even imagine the possibility or the meaning of such a comparison.

Because the “watch” can never be opened, asking whether our ideas concerning the natural world are absolutely true is to ask an unanswerable question.

However unlikely, even the most cherished and well-established scientific knowledge could, in principle, be revised or replaced. That scientific knowledge is open to revision is one of the great strengths of science as a way of knowing. That even well-established scientific knowledge is not proven truth and thus potentially open to revision should not result in a loss of confidence in that knowledge. Well-established scientific knowledge is so well supported that withholding provisional consent would be ridiculous. And the many technologies responsible for lengthening our lives and easing everyday difficulties are built upon that well-established scientific knowledge. While we have good reason to place great confidence in well-established science ideas, all science knowledge is created by human beings and is thus always open to revision with new evidence and thinking.

Well-Established Science Ideas Are Not Easily Abandoned

That well-established scientific knowledge is potentially open to revision does not mean such knowledge is easily changed – and for good reason! Unsolved puzzles and seemingly refuting evidence do not always result in rejection of an idea. Widely encompassing scientific ideas are always faced with anomalies – phenomena that are poorly accounted for or perhaps even contradict an idea. The reasons for this are varied and detailed, but the crux of the matter is that comprehensive ideas are not discarded simply because some pieces do not fit. Many historical examples can be found where contradictory data did not result in abandonment of ideas that we today accept as good science.

When well-established science knowledge is faced by apparently refuting evidence, the far greater likelihood is that the problem lies with the seemingly disconfirming instance or instances. For example, in the nineteenth century, scientists noted that observations of Uranus' orbit departed significantly from that predicted by Newton's gravitational law. While some scientists at the time speculated that the law of gravity might not apply at the distance of Uranus, most scientists, noting the enormous success of the Newtonian framework in other affairs, rightfully expected the anomaly to be accounted for without abandoning or modifying Newton's law. In 1835, years after the anomaly in Uranus' orbit was first recognized, the return of Halley's Comet sparked the idea that celestial bodies beyond Uranus might exert a force on the planet large enough to explain the planet's orbital discrepancy. This confidence, rather than seeing the anomaly as falsifying a well-supported idea, was crucial in the prediction and discovery of Neptune in 1846. This and other stories illustrate that apparently disconfirming evidence can, in time, usually be explained in terms of previously well-established knowledge. However, at other times, well-established prior ideas have, however reluctantly, been modified or abandoned.

Hypotheses, Laws and Theories are Different, Yet Related Kinds of Knowledge

The words "theory," "law," and "hypothesis" are frequently used in science classes, yet their appropriate meaning and relationship is rarely conveyed to students. Outside of science, the word "theory" is often interpreted as a "guess" or "speculation." And many people wrongly think that hypotheses become theories and then laws as the certainty of the idea increases. However, while laws and theories are related to one another in complex ways, one *never* becomes the other. Laws are generalizations or universal relationships that express the way that the natural world behaves under specific conditions. Scientific theories predict and explain laws, and provide a kind of road map for further research. Not only are laws not a higher form of scientific knowledge, but an understanding of laws is incomplete without a theory to explain them. Consider, for example, that we have a law of gravity, but no well-established theory that explains precisely how bodies are attracted to one another.

The scientific community's confidence in ideas concerning the natural world can range from speculative, gaining support, well supported, to near certain (but not proven truth!). Ideas that are speculative or are gaining support, but are not yet well-established are often referred to as "hypotheses." Note that "hypothesis" can mean a guess or a well-informed speculation, and these two meanings might refer to a particular instance (an observation), a universal relationship (law), or an explanatory framework (theory). Hence, the word "hypothesis" has at least six different meanings. Speculative explanatory frameworks (theories) may, over time, become well established, but they are still theories. Speculative invariable relationships (laws) may also become well established, but they remain laws. Scientific theories and laws are different kinds of knowledge with different purposes. Thus, as evidence for a theory grows, it becomes better established, but it remains a theory.

Science Provides Natural Explanations for Phenomena

Scientific knowledge must, in principle, be testable. This means that obtaining conceivable evidence for or against a claim must be possible. Because science limits itself to testable ideas, explanations deferring to supernatural forces are not used in science. This stance is referred to as "methodological naturalism". Most of us adopt this stance in our everyday lives, even though we might believe in a supernatural being. Imagine that your car mechanic tells you your car won't start because it is possessed by an evil spirit; most of us would demand a second opinion! Importantly, because science limits itself to naturalistic evidence and explanation, it is incapable of addressing questions regarding the supernatural – science simply must ignore these kinds of questions. You might think of science and religion like playing two different games – different means are used to reach each game's respective goals.

Science sets out to understand the natural world in ways that human beings can comprehend and then manipulate through technology. This approach to explaining natural phenomena without reference to the supernatural has undeniably been successful and has provided scientific explanations for phenomena that in the past were attributed solely to supernatural intervention. Future efforts will undoubtedly result in even more powerful explanations that make no reference to the supernatural.

The scientific community's demand for empirical evidence and naturalistic explanations, in part, account for its success at establishing reliable knowledge about the world. However, these demands also set up boundaries that preclude it from investigating or making claims about what matters most to people. For instance, matters of spirituality, morality, and the meaning of life are not amendable to scientific investigation. One commentator wrote that "The fact that science cannot find any purpose to the universe does not mean there is not one. We are free to construct parables for our moral edification…".

Importantly, science does not and cannot deny the existence of the supernatural. In their personal lives, many scientists have a deep faith in a God, but when they do science they work to understand our world and the universe in naturalistic terms, the same as with researchers who look for a non-supernatural cause for disease. Explanations using supernatural events and/or deities are beyond nature and, thus, beyond the realm of science. The word "supernatural" means beyond nature. Science deals with the natural world and, consequently, *scientific* explanations must be based in natural expressions with no reference to the supernatural. Science and religion are like two different games with different rules and goals.

Doing Science is a Social and Collaborative Process

A scientist once said that if science really worked like the media and school science often portray, no one would be a scientist. One of the most common misconceptions of science and scientists is that of the solitary and introverted investigator working in a drab laboratory. Of course, at times a scientist may find her or himself working alone, but that's the case in most any career. But most often scientists work with others in all sorts of settings – in nature doing field research, in the laboratory, and in the meetings common to all careers. Scientists must work together and do so in all aspects of research. Solving problems is more productive and enjoyable when collaborating with others, and most scientific problems are far too complex, time consuming, and demanding of resources to work alone.

1. What ideas about the characteristics of science surprised you?

2. What new insight about science and scientists did you learn from this reading?

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