Chapter 3. Words Of Science

The first step in the scientific [testing] process is always trying to prove ourselves wrong. I have an idea, I discuss it with my colleagues, and we try to destroy it. The better the idea sounds, the harder we try to destroy it. — Chris Lee, physicist

Scientific Observations

You may have heard (or thought) that “The main goal of science is to collect facts or learn the truth.” Wrong! The main goal of science is to understand nature, not to collect or produce facts. “Truth” will be discussed later. Understanding nature means finding the best explanations for how nature works. But before we can do that, what must we do? Right! Observe nature! To get answers, scientists must observe carefully and critically, gather facts, and look for patterns to help find explanations. But it’s those explanations that are the real goal of science, not the facts or observations. Surprise!

Just what are observations? And what are explanations? Some of the words used in science do not mean the same as they do in everyday life. In science, most words have very precise meanings. For example, in everyday language, “facts” are details about anything real and permanent. “Observation” means something that you see, or it could be an opinion you have about something. But in science, those words have different meanings.

Scientific Observation, Data, And Fact

Observation: Any information received directly or indirectly through the senses: by seeing, hearing, tasting, smelling, and/or touching.

Data: All of the observations that were made and recorded during a particular study.

Fact: An observation that appears the same to all critical observers. It is therefore is assumed to be real. Surprise!

Fact assumed to be real?

Why is “fact” defined this way? Well, you already know that our senses can play tricks on us. Haven’t you watched a magician do tricks—make something disappear, or appear, out of thin air? You know those are illusions intended to fool you. Maybe your teacher will show the class some neat tricks or optical illusions, if you ask nicely! For example, see Figure 3.1 (below). If your class hasn’t done the Perception lab ("Perception is not always reality"), and figured out why a T-illusion is an illusion, ask your teacher about it. If the class doesn’t do this, maybe you can form a team to do it as a special investigation.
Shift and turn your head a bit from side to side. Describe what happens. How can something seem to move when it really doesn’t? Or does it?

**Natural Illusions:**

You’ve also seen how nature can fool you, too. Remember how the Sun seems to move across the sky, from east to west during the day? Then it disappears below the western horizon, and somehow travels under us to rise the next morning in the east? And doesn’t the Earth really seem like it’s flat and just standing still? Well, those are natural illusions. It’s hard to believe, but we’re actually standing on a ball-shaped Earth that’s spinning fast. In fact, our Earth makes one complete spin in 24 hours, while the Sun stays in about the same place. Astronauts in space can actually see that (see Figure 1.1).

Near our equator, everything is moving about 1600 km (1000 miles) per hour! The "moving-Sun" illusion is like being on a merry-go-round and watching a friend on the ground come into view, then disappear behind you as you continue around. However, in that analogy, we do feel the air rushing past. And we can also stand on the ground to watch the merry-go-round go ‘round. But on our “merry-go-Earth” we don’t feel that wind, and the Sun does seem to move around us. Wow!

In addition, the Earth also travels about 940 million km (583 million miles) in one year in its orbit around the Sun. How fast (in km/hr, or mi/hr) is Earth travelling in that orbit? Now add that to our speed moving around this spinning Earth. Wow-Wow! Why aren’t we blown away? Can you think of any other natural illusions? Be sure to share them with your class.
Figure 3.2: This shows another natural illusion: The Big Moon Illusion. Have you ever seen a full moon in the evening eastern sky? Didn’t it look bigger than when you saw it overhead later in the evening? Why is that? Some say it’s the way our brain views the shape of the sky. The sky seems to be a flattened dome, with the overhead nearby and the horizon far away. It makes sense: Birds flying overhead are closer than birds on the horizon. When the moon is near the horizon, your brain, trained by watching birds, miscalculates the moon’s true distance and size. How could we test this idea? (Ask your teacher for the article by Kaufman and Kaufman, 1999, in the Teacher References). And, what's wrong with this diagram? (Hint: does the "true sky" line mean that there really is a dome above us? What does the "true sky" line actually mean?)

Science is a powerful tool:

Obviously, our senses are not always reliable. And our brain does play tricks on us. What we think we see and remember is not always real. Many studies have shown that eyewitnesses to crimes are often wrong. As a result, the testimonies of eyewitnesses in court are not as reliable as we once thought. In fact, we are finding that many people have been wrongly convicted, and sent to jail based on eyewitness testimony. And we are now seeing more and more prisoners having their convictions reversed and are being released from jail. This is because new and better evidence of their innocence (like DNA evidence) has been found. This is one way that the power of science is helping people.

Remember that anything science calls a "fact" must have been critically observed by many people. This tends to cancel out the differences in what people think they’ve seen or heard. And that tends to leave us with what was actually being observed. After critical testing, this becomes the most reliable basis for a fact in science. As you can see, science is a powerful tool, using certain rules and techniques to expose the reality behind illusions.

Scientists use other powerful tools to help them observe what they can’t observe directly with their senses. This includes the very small, the very distant, the very fast, the very slow, and the very old. They can also measure those dimensions precisely. And that enables them to use precise mathematical descriptions of their observations. What tools or techniques do scientists use to observe and measure those five examples? Discuss them with your team and your class.
Can a scientific fact change?

We are always getting better tools for observing. As a result, we have found that some previous “facts” are not really what we thought they were. But science is self-correcting. For example, we once thought humans had 48 chromosomes in each cell. Several scientists had counted them carefully and reported this in science journals. But with better equipment and techniques, we found later there were really only 46 chromosomes. Scientific facts don’t change very often, but they can change. Surprise! We sometimes say scientific facts are very durable because they are not likely to change.

Scientific Explanations

Observations and facts are directly tied to our senses. On the other hand, explanations are formed in the mind. We can say that explanations are what we think or infer from the observations. Our brain thinks about our observations, and tries to make sense of them. We may wonder how those observations came to be the way they are, and how they relate to each other. In science, explanations must be based on scientific observations and scientific facts. But, it’s the answers, or explanations, formed in the brain, that are the main goal of science.

Do you remember doing the Mystery Boxes lab? Did you notice that you were coming up with possible explanations (or answers) without realizing it? Our brain often works that way. While observing (tilting the box different ways, feeling, listening), you got some idea as to what was probably inside the box. You hardly noticed that you moved directly on to testing those ideas. You did that by tilting the box certain ways, and listening or feeling for predicted movements (observations). By tilting different ways, you were testing for different answers. (Does it seem to roll, or slide, one way, but not the other?) Finally, you selected the answer that seemed to fit all your tests best. In science, we make a point of stating the tentative explanation. Do you know what a possible, tentative explanation is called?

In science, some answers are better than others:

Better answers just work better, and have survived lots of testing. We say they’re more durable. If we don’t have much evidence for an answer, it would be called a possible answer. We could say it’s more tentative or uncertain. The level of acceptance for an answer can be anywhere between tentative and durable. As an explanation survives more testing and is used widely, our level of confidence gets higher. We have words to describe explanations at different levels of confidence. These are words like hypothesis, model, law, and theory.

How do they rank?

A scientific theory generally explains a number of facts. It uses laws and hypotheses that have been well-tested by many scientists. Therefore, scientific theories hold the highest level of acceptance. They are the most reliable, most durable, and most useful explanations in science. Surprise! (How does this contrast with the way “theory” is used in everyday language?) Theories are the most useful because they raise new questions and open the doors to further research and deeper understanding.
Natural laws rank about as high as theories. But they tend to be more precise. A natural law usually describes how key parts of a natural process relate to each other. Such a description is often shown as a mathematical formula.

Scientific hypotheses start off with the lowest level of acceptance. But they can become stronger as they are used and survive repeated testing. If they don’t survive, they may be changed, or rejected. A scientific model is a more general word often used instead of hypothesis, law or theory.

Scientific Explanations

Theory: In science, a well supported explanation of a broad feature of the natural world; it can include facts, laws, models, inferences and tested hypotheses.

Law: A descriptive statement about how some feature of the natural world behaves under certain conditions, often shown by a mathematical formula.

Model: A description, diagram or structure that shows how parts of an explanation might be connected or related to each other.

Hypothesis: A possible explanation or relationship of certain facts about the natural world, based on observation. It must be testable.

By the way, you may have heard that a hypothesis can become a theory that can then become a law. This is typically not true. A scientific theory is a well-supported explanation of a broad natural feature. It usually includes hypotheses, laws, observations, and facts. Surprise!

See Appendix SA-3.1: Examples of some hypotheses, major theories and laws.

Also, see Appendix SA-3.2 Some Old Theories Replaced.

Hypothesis Practice:

The word hypothesis is often misused. Many have misused it to mean the test of an explanation, or the predicted results of that test, or both! So we need to spend some time working with those concepts. You will be asked to study Appendix SA-3.3: Hypothesis EXPLAINED. This will clarify the differences between a hypothesis, a test, and a prediction. Your teacher may also hand out some practice sheets to help you with those terms. Be sure to discuss with your team why acceptable examples are acceptable. And discuss why unacceptable examples are not acceptable.
**Do This #3.1: Build a Concept Map or Mind Map** showing how these “Words of Science” relate to each other: fact, law, theory, and hypothesis. Think about how they are related to each other. You should now be able to build a concept map. This is a diagram that arranges those four words so they can be connected with arrow lines pointing from one term to another. Each arrow line should have a short label saying how one word relates to the other. To do this, first print the terms laws, hypotheses, facts, and theories on little strips of paper, or Post-its®. Move them around on your notebook page. Put the words for highest acceptance near the top. Then connect them all with labeled arrows saying how they relate to each other. When you and your partner(s) agree on a final arrangement, copy it to a sheet of paper and add your names. Be prepared to discuss and defend your map with your partners, and then with the class (in other words, be prepared to explain to others why you arranged them as you did). Doing this, by the way, is an example of scientific argumentation!

When you finish, give some thought about where you think “observations” should go. Then consider where “questions” or “problems” should go. Show your placements of these terms by writing them on strips of paper and putting them in place. Then add labeled connecting arrows. Discuss and defend those additions with your team, making changes that seem to improve this arrangement.

**Do This #3.2: Priority of Terms:** Let’s further test your full understanding about those original four terms (laws, hypotheses, facts, and theories). How do you think scientists would rank them for usefulness? Arrange them in a column (one word above the other). Put the most important (most useful) term on top, and the least important on the bottom. Place the remaining terms in order between them. Compare your sequence with others in your team. Be critical. Discuss these, and rearrange if you change your views. What is the evidence for your choice? Be careful, you might be surprised! It may not be what you thought at first! When each team shares and defends its “best” sequence, try to clarify your understanding of each term. Ask questions where you’re not sure. The most important term is also the most useful. When the class has settled on a final sequence, consider where “observation” would best fit. Explain why. Discuss this. (What's this “discussion” process called?)

**More About Tentativeness & Uncertainty:**

Explanations are clearly products of our minds, and can change with new information. But scientists know this and expect change. This can be surprising to those who think that science produces only certainties and facts. Surprise! Actually, one of the strengths of science is its uncertainty. It’s a strength because science is open to change when new facts are found that support new explanations. What people often miss, though, is that there are degrees of uncertainty in scientific answers. As we learn more about the natural world, even our theories get better. In other words, our understanding of the natural world gets better.
Figure 3.3: Remember the Checks Lab? When you “found new evidence” in the Checks Lab (new checks), you probably had to change your earlier explanation. This new explanation (or story line) had to include the information from those new checks. That’s exactly how science works. Did you also notice that the Checks Lab is not an experimental process? It’s an example of how “historical science” works. It’s the same process used in forensic science, to help solve crimes. Did you do the Crime Scene lab, The Great Fossil Find, or the Laetoli Puzzle? They all use good science to answer questions about past events, and they’re not experimental. Lots of good scientific investigations are done without experiments.

All scientific answers are said to be “tentative,” but new ones are far more tentative than older ones that are still around. “Tentative” means that we’re not absolutely certain about the answer. Hypotheses are, by definition, “tentative” (surprise!), so we are clearly unsure about them. But as a hypothesis is used and tested, and works, we get more confident about it. Sooner or later, it may be combined with other hypotheses and facts and become part of a broad theory. Scientific theories are well supported by many studies over time, and they work. They combine the most useful and successful explanations we have about a major process of nature. And they are the most durable, too. Therefore, we often treat theories as if they were very close to reality. Surprise! This is not certainty, but very close to it, and is usually treated as such for all practical purposes. Like observed facts, even scientific theories can change, but major change is unlikely. See Appendix SA-3.2 Some Old Theories Replaced. So now we have better theories than what we had before.

A good example of a theory is the atomic theory. This is the idea that all matter is made of atoms. It also includes details about atomic structure and how that knowledge has changed over time.

Atomic Structure:

Not too long ago, scientists wondered what an atom looked like. So they used a variety of clever investigations to give them clues. From those early studies, they figured out that an atom has a heavy but very tiny central nucleus. And whizzing throughout the atom were tiny particles they called “electrons.” See Figure 3.4A.
Later, scientists found evidence suggesting that the electrons had no fixed orbiting paths. In fact, they showed that you could never tell exactly where an electron was. You could only say that they were more likely to be in certain areas, and less likely in others. Imagine each of several electrons to be a tiny black dot, and you took a time-exposure photo. All you’d see would be a blur of blackness with fuzzy edges. This is called an “electron cloud” (see Figure 3.4B). The cloud is darkest where the electrons are most likely to be.

The nucleus turned out to be a tight cluster of proton and neutron particles. It’s so tiny that if it were drawn to scale, you really couldn’t see it in these diagrams. The total volume of the atom is mostly empty space with tiny electrons zipping throughout. The size ratio of the nucleus to the entire atom is about 1 to 100,000. If this atom were enlarged to the size of a football stadium, its nucleus would be the size of a grain of sand! And the atoms of all elements are roughly similar in size.

Later studies suggested that the electrons have different energy levels. Still later, they were shown to be more likely in different shaped “cloud” regions, called "orbitals" (see Figure 1.2 in Chapter1). And the protons and neutrons are actually made of quarks. But these are really just more details. They answer different questions about the atom, all figured out from many clever studies. Those details help to apply our knowledge about the atoms to new practical uses. New studies in the future may give us even deeper details. But those details are not likely to change this general picture. From all of this, we have high confidence in the general structure of an atom. It’s always subject to change so it is technically uncertain. But the general structure is widely accepted and treated as if it is close to reality. We can say that it’s a durable concept. And it is useful.
Change is a Strength of Science:

As discussed earlier, there are different levels of relative uncertainty in science. Scientists can (and often do) disagree with the work of other scientists. They actually argue with each other about their claims. This is called scientific argumentation (see Chapter 2). It’s a very special kind of arguing. What they insist on is that every scientific claim made by a scientist must be backed by material evidence. This is one way that errors in methods or conclusions are discovered. In fact, it can be said that uncertainty (or degrees of ignorance) is one of the driving forces of science. If new data don’t fit the current understanding, scientists may change those ideas and try new tests. This openness to change gives us confidence that we are getting ever closer to the realities of the natural world. This means that scientific knowledge is always getting better. And we are getting less ignorant! The scientific knowledge of today is far more reliable, and useful, than it was even ten years ago. Surprise! Other “ways of knowing” are not nearly as open to change. This is one of the reasons that science has been such a powerful and useful tool for understanding nature.

A Word About “Models”:

Sometimes you hear about scientists testing a particular “model” in much the same way that they would test a “theory” or “hypothesis.” A scientific model may refer to a description, diagram or structure that shows how we think the parts of an explanation are related. When a model is tested (challenged) and shown not to work, we say it is weakened, so it may be changed or rejected. If the model does work, we say it has been strengthened or supported.

The words “hypothesis” or “theory” give a better idea about how well an idea is accepted. Using “model” is not as clear about that; it gives us no idea how tested the idea might be. In general, however, a model may not be as well established as a theory. It depends on how the word is being used. In any case, where we might be tempted to use “theory” for its everyday usage, “model” would be much better. That way, “theory” is reserved just for those scientifically well-established understandings.

A Word (or Two) About “Truth”:

You may hear claims that science is supposed to be searching for truth, as if “truth” meant “fact” or “reality.” However, “truth” can mean different things to different people. “Truth” to many is what has been said or written by a highly regarded authority. This is sometimes called “revealed truth.” This “truth” may be real and comforting to supporters of that authority, but it doesn’t follow the rules of science. The success and usefulness of science are based on critical observations and tested explanations, not authority. Clearly, those “truths” based on authority have different sources and follow different rules. This can be confusing. Therefore, it’s probably best to avoid saying that science seeks “truth.” Surprise! Then what is science seeking? (See Chapter 1).

Try replacing “truth” with “reality.” Reality is what the real world actually is, not what we think it is or what it seems to be. We may never “know” that reality with absolute certainty. But in science, we try to come as close to that reality as we can. At the same time, we humbly recognize the flaws in our senses and reasoning abilities. Therefore, scientific knowledge is probably just a close approximation of reality. But if it works in its applications to real-world issues, then it’s probably close enough.
Problems With Words: Their Use and Misuse:

Even when you read your science text or other science books, you will discover that these words of science are not always used in the ways described here. This is especially true when you hear other people talk about science, even scientists or science teachers. For example, you might have learned that a “hypothesis” was just “an educated guess.” Is that all it is, really? From certain clues, you could guess what’s for dinner, but is that a hypothesis? What’s missing? You may have heard a scientist being interviewed on TV say “I’ve got a theory about the cause of that disease.” Saying it in this casual way suggests that it’s just an idea, not really an established scientific theory. So, why do we hear these things? If you’re curious, read Appendix SA-3.4 for More Problems with the Words of Science.

What’s Next?

Hopefully, the key words of science make more sense now. But how can we really trust science? Sometimes a recommended medicine is found not to work. It might even be dangerous for some people. We may also read that an earlier scientific explanation has been replaced with a new explanation about something. Or we see that some scientist has committed fraud. How can we depend on science? How can we tell when we see poor science, or when we see reliable science? The next chapter will give you some clues.

Self Check C:

Without looking back, answer these 12 items briefly in your notebook. Then re-read the section, and make appropriate changes or additions (*TPS = be ready to discuss in class):

1. What is the main goal of science?
2. Use a diagram to show how these terms are related to each other: fact, theory, law, model, observation, hypothesis.*
3. What do scientific theories, laws, hypotheses and models all have in common?*
4. Why is a scientific explanation not really a scientific fact?*
5. Can facts change? If so, when? (Continue to next page.)*
6. What’s wrong with the idea that a theory is a mature hypothesis?*
7. What’s wrong with saying that science seeks the truth?*
8. Why is "uncertainty" a strength of science?*
9. Give 2 reasons why scientific theories are the most useful and successful explanations.*
10. Give 1 example of a strong theory that was replaced with a new, better theory.
11. List three (or more) ideas or words in this chapter that were hard to understand.
12. List three things in this chapter that were surprises to you.

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