

What Is Argumentation and Why Does It Matter in the Teaching of Science?

Why Argumentation Is Central to Science

Many people think that most scientific ideas are common sense. This is a mistake. A moment's thought makes you realize that many of the concepts we teach in science sound crazy or unbelievable. Take, for instance, the idea that day and night are caused by a spinning Earth. Why should anyone believe this when it seems patently obvious that it is the *Sun* that moves, rising in the East and setting in the West? Moreover, if you think about it, it is approximately 25,000 miles around the Equator and, if the Earth rotates once every 24 hours, this means that the speed at the Equator is over 1,000 miles per hour. Surely, we would be flung off? Finally, if the Earth were spinning that fast, then surely, when we jumped up, we would not land in the same spot. Looked at this way, the canonical explanation for day and night—something that is taught in elementary schools—seems crazy. Surely, then, to convince anybody that the standard scientific explanation is correct, we have to produce the evidence to justify such claims. In short, we have to put forward an evidence-based *argument*. Somewhat surprisingly, most people are hard pushed to identify the two pieces of empirical evidence that do support the scientific explanation—Foucault's pendulum¹ and a photograph of the night sky taken by a camera with the shutter left open and pointed at the pole star.²

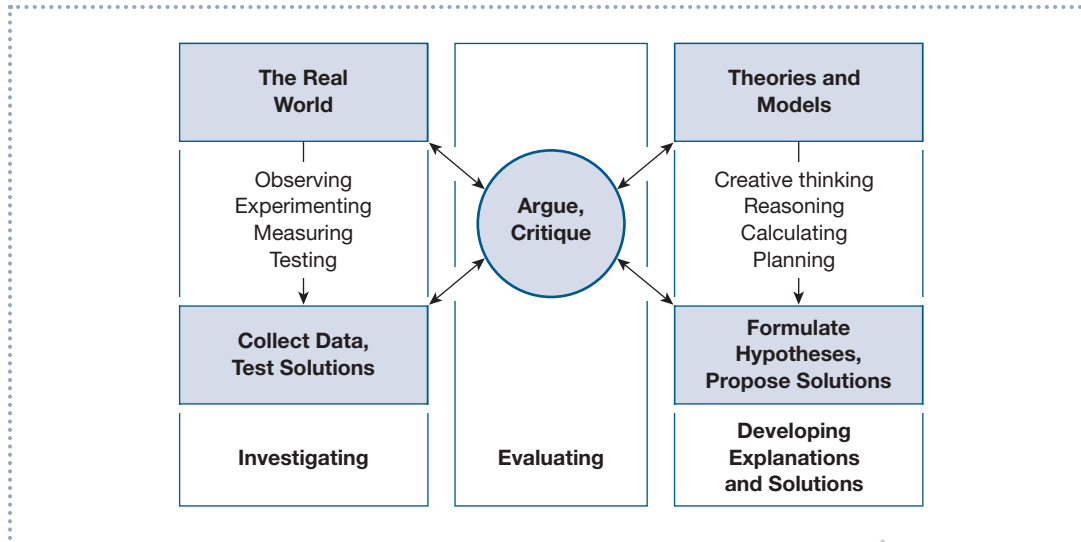
Lest you think that this is one special example, there are many more. Take the idea that the continents once were one. Why should you believe that? What force is capable of moving mountains, let alone continents? Indeed, this idea was summarily dismissed when first put forward by Alfred Wegener in 1915 for this reason. Or the idea that you look like your parents because every cell in your body carries a chemically coded message about how to reproduce you, or the idea that diseases are caused by tiny living microorganisms that are invisible to the naked eye, or the idea that we live at the bottom of a sea of air whose pressure is equivalent to 10 m of seawater, or the idea that most of the atom is empty space—that is, if you think of the nucleus as being about the size of a tennis ball, the nearest electron will be three quarters of a mile away. We have only come to believe all of these ideas because scientists have made arguments from evidence that ultimately have proven to be better than other ideas. It is this idea that is captured in Figure 1.1, which comes from the *Framework for K–12 Science Education* (National Research Council, 2012b).

What this figure says is that, in any science, three spheres of activity interact. On the left, there is an investigation space. Here scientists do things like make observations, collect data, and build instruments to test their ideas. On the right, there is space where they invent ideas and hypotheses

1 Foucault's pendulum is a long pendulum with a large heavy mass at the bottom supported on a frictionless pivot. During the course of the day, the plane of the swing appears to move by anywhere up to 360 degrees when there is no force acting on it. Foucault realized that it was not the pendulum that was moving but the earth beneath it.

2 Such photographs show a set of circular trails with all the stars appearing to be going round the pole star. There are two explanations: (a) all the stars are going around the pole star, or (b) the ground on which the camera is placed is turning. In science, we apply Occam's razor—commonly known as the KISS principle—and go for the simplest explanation that it is the Earth that is moving.

FIGURE 1.1 A Model of the Sciences



Source: Osborne (2011).

about the way the material world behaves. These ideas depend on creative and imaginative thinking and often use models. These models enable predictions. It is these ideas that are the real achievement of science. For instance, think of a famous scientist. Our guess would be that the overwhelming majority of you would think of somebody who is famous for a new idea—Einstein, Darwin, Hawking, Wegener, Maxwell, Copernicus, or Bohr—rather than somebody who is famous for an experiment. What this shows is that you get your name in lights in science for devising a new idea or theory or that it is theories that are “the crowning glory of science” (Harré, 1984).

Fundamentally, science is about building new ideas. Experiments are simply the means of testing the ideas. Deciding on which ideas are best, however, requires argument—arguments about whether the ideas are supported by the evidence, arguments about the nature of the experimental tests and their validity, or arguments about the interpretation of the data. Arguments are thus central to what it means to do science. For this reason, the history of science can be seen as history of vision, argument, and error (Allchin, 2012; Crombie, 1994). And, just like any other group, science and scientists learn from their mistakes.

What is the difference then between argument and *argumentation*, you might ask? Argumentation is a process of considering arguments and counterarguments. We can give you an argument for why day and night are caused by a spinning Earth and you could give us a counterargument as to why they are not. If we were to do this, we would be arguing, as you would be criticizing our idea using counterarguments and engaging in the process of argumentation that could also be called *critique*.

Learning to Argue Is Learning to Think?

Argumentation is necessary in science as there are always multiple explanations that compete. In particular, in teaching science, the scientific explanation often has to compete with students' pre-existing but flawed ideas. Deciding on the best explanation is a matter of argument and a choice that is justified by how well any given explanation fits with the data—in essence, how coherent the explanation is with observations. This means that argument is a core feature of science. Whether it is new theories, novel ways of collecting data, or fresh interpretations of old data, argumentation is the means that scientists use to make their case for new ideas (Latour & Woolgar, 1986), and in response, other scientists attempt to identify weaknesses and limitations (Popper, 1963). Peer review is the formal mechanism for conducting this process within the scientific community. Over time, ideas

that survive critical examination are accepted. In this way—through argumentation and critique—science maintains its objectivity (Longino, 1990). It is not a case of anything goes—any idea has to fit with the evidence, and everybody has to be convinced that it does.

Thus, critique is not some peripheral feature of science, but rather, it is core to its practice. Without critique, the construction of reliable knowledge would be impossible. Likewise, in learning science, developing an understanding of scientific ideas requires both construction and critique (Ford, 2008). Or, to put it another way, when you are learning science, knowing why the wrong idea is wrong matters as much as knowing why the right idea is right. However, students will only begin to see how central argument is to science, and to developing the critical disposition that is the hallmark of the scientist, if they are provided with regular opportunities to engage in constructing arguments from evidence. Moreover, if students are not occasionally offered some windows into how the knowledge that we are asking them to believe came to be, then school science cannot defend itself against the accusation that it is simply a “miscellany of facts” to be learnt dogmatically. And, a set of facts in science is no more of substance than a pile of stones is a house. Indeed, without any attempt to explain how we know what we know, school science education finds it hard to defend itself against the accusation that what it offers is no better than the religious dogma the masses were expected to believe before the Enlightenment. Some would go further, arguing that to ask students to believe ideas without justifying why they should be believed is morally questionable (Norris, 1997).

These are the reasons why arguing from evidence is one of the eight practices in the Next Generation Science Standards (NGSS). As argued in the *Framework for K–12 Science Education* (National Research Council, 2012b), the basis of the NGSS standards, the science is not “not just a body of knowledge that reflects current understanding of the world; it is also a set of practices used to establish, extend, and refine that knowledge” (p. 26). Teaching students to be scientifically literate requires us to give them the opportunity to experience what these practices are and how scientists think.

The traditional approach to science education does not commonly do this (Newton, Driver, & Osborne, 1999; Weiss, Pasley, Sean Smith, Banilower, & Heck, 2003), and very little material in textbooks approaches ideas in this manner (Penney, Norris, Phillips, & Clark, 2003). This book is an attempt to remedy that deficiency. What you will find in this book are 24 activities spread across the science topics that are taught in middle schools. Each of these is designed to take 30 to 60 minutes of classroom time. You will find concrete guidance about how to use these activities, and to start with, it is probably best to follow the activity as suggested. At the end of the book, we summarize the standard strategies that can be used to support argument in the classroom.

The major point to be made at the moment is that “argument” often carries a negative connotation for many young people. For that reason, it is important to start with strategies that *separate the idea from the person*, such as discussion of instances, a concept cartoon, an argument line, or four corners. It might also be better to say that you are asking your students to “discuss” or “debate” ideas. However, fundamentally, what you are asking your students to do is to think critically and to learn that reason and understanding are the product of difference, not fond consensus. Or, to put it another way, that learning to think is learning to argue.

Why So Much Emphasis on Argument?

You may have noticed that the word *argument* seems to feature in the talk not just about science but also about mathematics and language arts. For instance, in the Common Core Mathematics Standards, one of the mathematical practices is that students are expected to “construct viable arguments and critique the reasoning of others” (Common Core State Standards Initiative, 2010) while in the Common Core Standards for Language Arts—notably not just for English language but also history, social studies, and science—students are expected at Grade 6 to be able to “trace and evaluate the argument and specific claims in a text.” By Grade 9/10, the Common Core in

Language Arts requires the ability to evaluate arguments as well (i.e., “Delineate and evaluate the argument and specific claims in a text”). Why, then, so much emphasis on argument?

First, it does not take much to realize that people have ever-increasing expectations of education. As well as students who know a lot, society wants education to develop higher order competencies—often called 21st-century skills—of critique, evaluation, and synthesis (“Coming to an Office,” 2014; Gilbert, 2005; National Research Council, 2012a). Clearly, students are not going to develop this kind of competence if they are not given the opportunity to practice these kinds of cognitive processes. Increasingly, we are living in world where jobs requiring low-level skills are being replaced by machines. As information is so readily accessible, this is no longer a prized individual attribute. Rather, in a world where there is an oversupply of information, it is now the ability to make sense of information that is the scarce resource. Making sense of information requires the ability to distinguish good information from the bad both at the personal level and in work. At the personal level, we are confronted by issues of environmental degradation, whether to vaccinate our children, or whether to exercise. At work, there is a plethora of information competing for our attention about how to be more productive and effective. Distinguishing the good from the bad, the wheat from the chaff, so to speak, requires us to engage in argumentation and critique.

What Are the Elements of an Argument?

There is a language for talking about the elements of an argument. This language comes from the conception of an argument first put forward by Stephen Toulmin in 1958 (Toulmin, 1958). Toulmin suggested that everyday arguments or informal arguments (as opposed to logical deductive arguments) consisted of

- a **claim** about the world,
- some **evidence** to support that claim, and
- a **reason** that explained why or how the data supported the claim.

This concept of an argument is shown diagrammatically in Figure 1.2.

Argumentation happens when people decide to criticize either the evidence or the reason. They can do this by advancing a rebuttal. This is essentially a counterargument explaining why either the reason or the evidence is flawed. Alternatively, they might choose to suggest that the argument has a qualifier—that is, that it is only true for certain instances. This is represented by Figure 1.3.

An example of an actual argument using these terms is shown in Figure 1.4.

In talking about argument with students, though, we have learnt that the word *claim* can be confusing as students think of claims in English or history class as a right or entitlement. In contrast to literary and historical claims, scientific claims are statements or assertions about the *natural world*. Scientific claims include what happens in nature and what causes natural phenomena to occur. Hence, in this book, we tend to talk about a claim as what somebody might be “arguing for” or is trying to “justify.”

FIGURE 1.2 Elements of an Argument

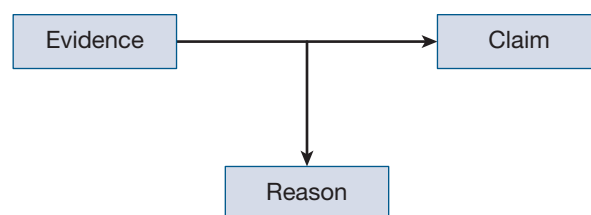
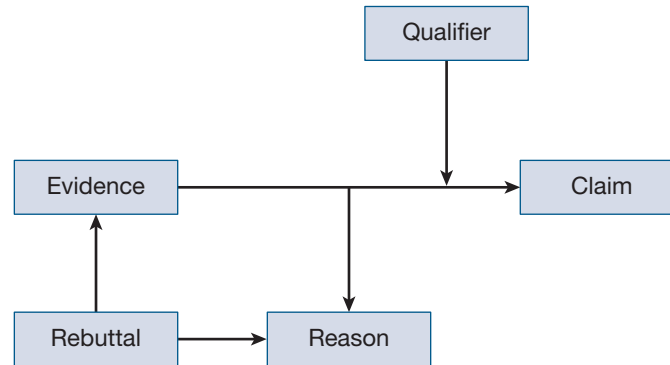
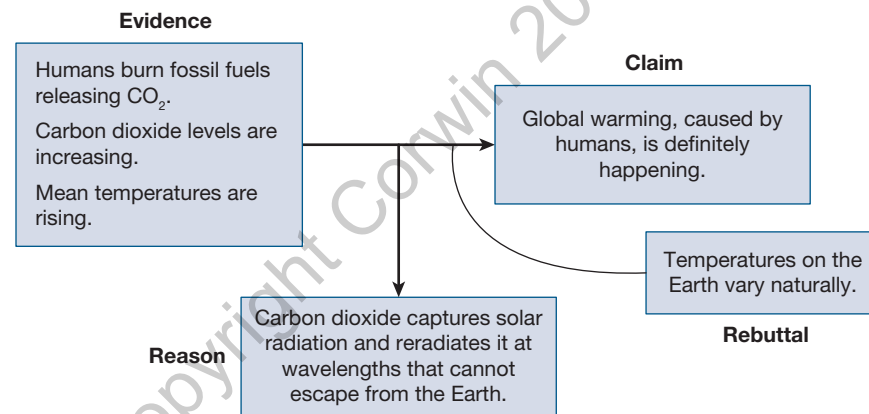


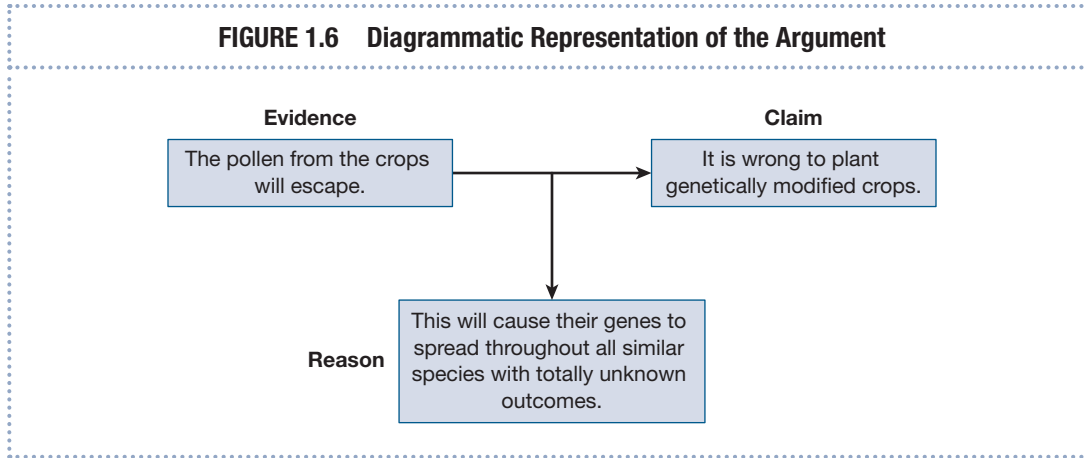
FIGURE 1.3 Elements of an Argumentation**FIGURE 1.4 Example of an Actual Argument Using the Toulmin Framework**

At this point, you might ask what the difference is between “data” and “evidence.” In short, “data” become “evidence” when they are used in an argument. More or less anything can be data, but they are only evidence when we choose to use them in an argument. So while all evidence consists of data, not all data are evidence. In the examples above, specific data have been selected and are being used as evidence.

Figure 1.5 presents an example of another scientific argument. See if you can identify the separate elements of the argument.

FIGURE 1.5 Example of a Scientific Argument

It is wrong to plant genetically modified crops. The pollen from the crops will escape. This will cause their genes to spread throughout all similar species with totally unknown outcomes.

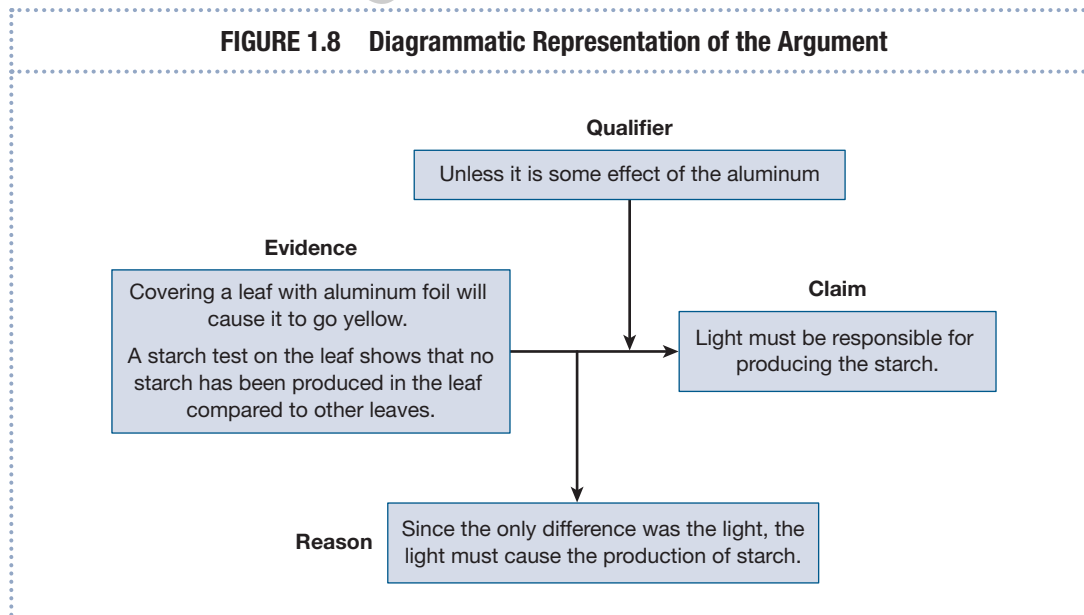
FIGURE 1.6 Diagrammatic Representation of the Argument

Our answer would be that “it is wrong to plant genetically modified crops” would be the claim. “The pollen from the crops will escape” is the evidence as that is essentially a fact. In that sense, data are not just restricted to numbers but can also be facts. Finally, the last sentence, “This will cause their genes to spread throughout all similar species with totally unknown outcomes,” is the reason (see Figure 1.6).

Figure 1.7 presents another example. See what you think are the elements of an argument in this example.

FIGURE 1.7 Second Example of a Scientific Argument

Covering a leaf with aluminum foil will cause it to go yellow. A starch test on the leaf shows that no starch has been produced in the leaf compared to other leaves. Light must be responsible for producing the starch unless it is some effect of the aluminum.

FIGURE 1.8 Diagrammatic Representation of the Argument

In this example, the evidence is the first sentence (“covering a leaf with aluminum foil will cause it to go yellow”) and second sentence (“a starch test on the leaf shows that no starch has been produced in the leaf compared to other leaves”). There is then a claim that “light must be responsible for producing the starch,” followed by a qualifier “unless it is some effect of the aluminum.” There is really no reason in this example other than the tacit inference that because the only difference was the light, the light must cause the production of starch (see Figure 1.8). Sometimes arguments are incomplete (see Figure 1.9).

FIGURE 1.9 Third Example of a Scientific Argument

We see objects because light enters the eye; as we cannot see in the dark, vision must be caused by light entering the eye rather than rays leaving the eye.

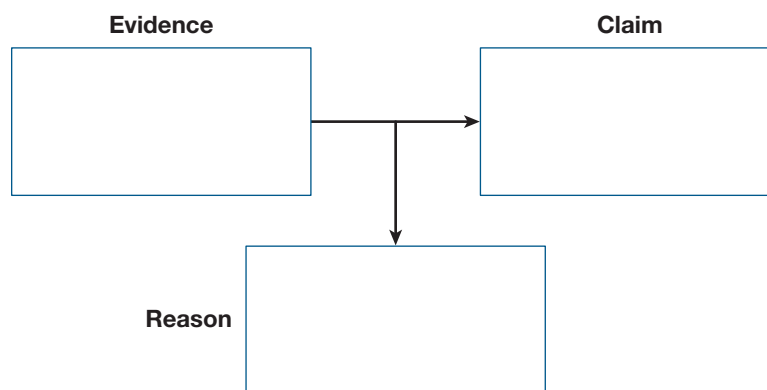
In this third example, the claim is that “we see objects because light enters the eye” and later that “vision must be caused by light entering the eye rather than rays leaving the eye.” Many students have a concept that vision is an active process and something that is directed by the eye. The evidence is that “we cannot see in the dark.” What this argument lacks is a good reason relating the claim to the evidence of the form that, if vision were a process where something came out of the eye, then we would be able to see in the dark. As we cannot, it must occur because light enters the eye. If there is no light, therefore, we cannot see. Try sketching a diagrammatic representation of this argument for yourself.

Now try and apply this mode of thinking to some of the things that we commonly teach in science. For instance, what arguments would you give to convince a dubious student that

- Living matter is made of cells.
- Matter is made of atoms and molecules.
- Plants take in carbon dioxide and give out oxygen during photosynthesis.
- Matter is conserved in a chemical reaction.
- Energy is conserved.
- Lithium, sodium, and potassium are similar elements.
- We live at the bottom of a sea of air.
- Seasons are caused by the tilt of the Earth’s axis.

Try mapping out the argument for any one of these claims about the world using Figure 1.10.

FIGURE 1.10 An Argument to Be Completed



Part of the skill of being an effective teacher is to know the arguments not only for the scientific worldview but also for why students' commonsense conceptions are flawed (Sadler et al., 2013). What, for instance, would you say to a student who argued the following:

- Gases do not weigh anything.
- Sugar disappears forever when dissolved in water.
- Heavier things fall faster.
- There is no gravity in space.
- The matter in a plant comes from the soil.
- Humans are not animals.

Again, try mapping out the substance of your response using Figure 1.10.

What we are trying to show with all of these examples is that science is a body of ideas that we have had to argue for. The history of science is a litany of mistakes of what might be seen as flawed arguments—just think of phlogiston, Ptolemy's epicycles, the ether, the Church's defense of a geocentric worldview, Lamarckianism and the claim that species could adapt within their lifetime, Weber and his claim to detect gravity waves, and more recently cold fusion. In the end, a scientific idea succeeds because the arguments for it are more coherent with the data and the ideas have greater predictive power. Thus, Torricelli's arguments that the space at the top of the barometer tube is a vacuum wins in the end as it better explains why the height of the column of mercury drops when you go up a mountain. Einstein's theory of special relativity explains why measurements of the speed of light do not vary depending on which direction the Earth is moving and, moreover, it predicts a relationship between matter and energy that is later confirmed by experiment.

What Is the Difference Between an Explanation and an Argument?

The Next Generation Science Standards have two practices that seem related—constructing explanations and engaging in argument from evidence. Inevitably, you might ask, what is the difference? The issue is especially confusing as there is a view that explanations consist of claims, evidence, and reasoning. This is unfortunately wrong. Arguments consist of claims, evidence, and reasoning. Explanations consist of the thing to be explained (e.g., why it rained yesterday, how humans reproduce, why earthquakes happen). All of these explanations have sets of descriptive or factual statements, which are causally related and that describe how the thing to be explained came to be. Thus, the dinosaurs became extinct because an enormous meteorite threw a large amount of dust and ash into the atmosphere (a descriptive statement) that caused (defining the link) a sudden temperature drop on the Earth's surface (a descriptive statement). Explanations need to be consistent with the evidence, and arguments are needed to show that they are consistent, but it is not correct to say that argument and explanation are the same thing.

Explanations work because they generate a feeling of increased understanding. As a consequence, there are various levels of explanation, and this is well illustrated by Richard Feynman's response to a reporter asking for an explanation of why magnets attract each other (https://www.youtube.com/watch?v=MO0r930Sn_8). Basically, he responds by asking, what level of explanation do you want and what would you be satisfied with?

By contrast, arguments in science are claims about the world. Such claims draw on evidence and theories to produce the justification or reason that relates the evidence to the claim. Such claims often include an explanatory hypothesis and so look very similar to explanations, but the language is couched in conditional language. So *if* carbon dioxide levels rise above 400 parts per million, the argument is made that the global temperature *may* then rise by more than 2°C because of the way in which carbon dioxide traps solar radiation and re-radiates it at wavelengths that

cannot escape the atmosphere (which is an explanation). However, fundamentally, this is an argument that exists in competition with another explanation that such warming is a product of natural variation. Thus, another vital feature of any situation where argumentation might occur is that there exist different or competing views.

Moreover, another big distinction between explanations and arguments is that an explanation—the thing to be explained—is often something that is well established. Clearly, day and night do happen, the dinosaurs did die out, and sugar does dissolve. Why these happen, or happened, requires an explanation. There may be more than one explanation. Deciding which is best requires an argument. So Galileo makes an argument that the heliocentric theory is a better explanation than the geocentric explanation of the motion of the Sun and stars. While there are many arguments for Galileo's position, at the time, there were many arguments against it. Thus, in science, what happens is that there are arguments about which of the competing explanations is best.

In school science, for instance, students may argue that most of the mass in a plant comes from the soil. After all, why does the plant have roots and why do we water it? As the teacher of science, you are putting forward a competing explanation that most of the mass comes from the synthesis of carbon dioxide and water in the plant to make sugar. To convince students that your explanation (an explanatory hypothesis) is better, you will have to point to the evidence that supports your view, as well as point to the evidence for why their argument is flawed.

What Is Argumentation and How Does It Contribute to Learning?

Argumentation is a process of deliberative discussion of competing claims. Commonly, it is done orally, but it can also be done in writing. Its purpose is to allow students to contest competing claims and come to an agreement about “how they might know something,” “in turn, building more secure conceptual models” or “inspiring new questions or models” (Manz, 2015). Over the past two decades, research has explored the contribution of collaborative discourse and argumentation to learning. Drawing on the notion that language is core to learning and thought and language are inseparable, the implications of these ideas for education have been developed by a number of people (Alexander, 2005; Halliday, 1993; Mercer & Littleton, 2007; Mercier & Sperber, 2011; Wertsch, 1991). A critical feature of this work is a view that learning is the product of the difference between the intuitive or old models we hold and the new ideas we encounter (Bachelard, 1968). Through a process of comparison and contrast, supported by discussion, the individual then develops a new understanding. Consequently, learning requires opportunities for students to advance claims, to justify the ideas they hold, and then to be challenged. Although this may happen internally, it is debate and discussion with others that are most likely to enable new meanings to be tested through argument and counterargument.

In this sense, learning to argue is seen as a core process in learning to think and construct new understandings (Billig, 1996; Kuhn, 1992). Comprehending why ideas are wrong then matters as much as understanding why other ideas might be right. For example, students who read texts that explained why common misconceptions were flawed (as well as explaining why the right idea was right) had a more secure knowledge than those who had only read texts that explained the correct idea (Hynd & Alvermann, 1986). Likewise, researchers have found that groups holding differing ideas learn more than those who hold similar preconceptions, many of whom make no progress whatsoever (Howe, Tolmie, & Rodgers, 1992; Schwarz, Neuman, & Biezuner, 2000). Indeed, one study found that even if the difference between individuals was based for both on incorrect premises, significant learning gains can occur—a case of two wrongs making a right—and with learning effects that were still significant on delayed posttests (Ames & Murray, 1982).

These findings are also supported by a number of classroom-based studies, all of which show improvements in conceptual learning when students engage in argumentation (Asterhan & Schwarz, 2007; Mercer, Dawes, Wegerif, & Sams, 2004; Sampson & Clark, 2009; Zohar & Nemet,

2002). For instance, students who were asked to engage in small-group discussions significantly outperformed a group of control students in their use of extended utterances and verbal reasoning, something that is rare in formal science education (Lemke, 1990). Significant improvements were also produced in their nonverbal reasoning and understanding of science concepts (Mercer et al., 2004). Another study with two classes of 16- to 17-year-old students studying genetics required students to engage in argumentative discourse about the appropriate answer to specific problems. Compared to a control group, the frequency of students who used biological knowledge appropriately (53.2% vs. 8.9%) was significantly higher (Zohar & Nemet, 2002).

Finally, a meta-analysis of 18 studies grouped learning activities into three major categories: those that are interactive and require collaborative discourse and argumentation (either with a peer or an expert tutor), those that are constructive and require individuals to produce a product such as an essay or lab report, or those that are active, such as conducting an experiment (Chi, 2009). Research shows conclusively that a hierarchy of learning activities exists from interactive (the most effective), to constructive, to active (the least effective). That is, students are more likely to learn when they have the opportunity to discuss and argue about the ideas than when they simply write essays or do experiments.

Studies show, however, that group discourse that contributes to effective learning depends on a number of factors. Most important, students need to be taught the norms of social interaction and to understand that the function of their discussion is to persuade others of the validity of their arguments. In addition, exemplary arguments need to be modeled, and teachers need to define a clear and specific outcome while groups need materials to support them in asking the appropriate questions and help in identifying relevant and irrelevant evidence (Barron, 2003; Berland & Reiser, 2008; Blatchford, Kutnick, Baines, & Galton, 2003; Mercer, Wegerif, & Dawes, 1999).

So in Summary . . .

Argumentation is not something that is peripheral to science but lies at its very core. It is also tremendously important in learning science, as science is a set of rather strange ideas about the world. Students are only going to start believing these ideas if (a) they hear what the evidence is for the scientific case, and (b) time is spent convincing them that the commonsense view of science (e.g., that plants get their food from the ground, that air has no weight, or that heavier things fall faster) is challenged through a process of discussion and argumentation.

Argumentation is the process of engaging in constructing both arguments and counterarguments. A sound scientific argument has three essential features—a claim that it is seeking to advance about the material or living world, evidence to support that claim, and a reason that shows how that evidence justifies the claim.

How, though, do we engage students in this process? In Chapter 2, we will look at ways of supporting argumentation in the classroom, some of the challenges that it poses, and how to address them.