7. Investigation and Experimentation

Scientific progress is made by asking meaningful questions and conducting careful investigations. As a basis for understanding this concept and addressing the content in the other three strands, students should develop their own questions and perform investigations. Students will:

a. Develop a hypothesis.

b. Select and use appropriate tools and technology (including calculators, computers, balances, spring scales, microscopes, and binoculars) to perform tests, collect data, and display data.

c. Construct appropriate graphs from data and develop qualitative statements about the relationships between variables.

d. Communicate the steps and results from an investigation in written reports and oral presentations.

e. Recognize whether evidence is consistent with a proposed explanation.

f. Read a topographic map and a geologic map for evidence provided on the maps and construct and interpret a simple scale map.

g. Interpret events by sequence and time from natural phenomena (e.g., the relative ages of rocks and intrusions).

h. Identify changes in natural phenomena over time without manipulating the phenomena (e.g., a tree limb, a grove of trees, a stream, a hillslope).

To the teacher: In this final letter, I have had Priestley address the general question of "What is Science" rather than the particular method of testing an hypothesis that is well-outlined in the Standards and printed above.

My dear Friends in California,

In this, my last letter to you, I will tell you something that is more important than anything in my other letters. In fact, it is more important than *everything* in all the other letters put together. Those letters presented you with important facts *about* several of the branches of science. This letter will tell you about science *itself.* We will talk about how science itself works and corrects its own mistakes.

Many people, or should I say "most people", do not really understand how science works. Because they do not understand, they often make ridiculous claims about what science is or what it has proved, what it has not proved, or what a scientific result really means. This is dangerous for a democratic nation. It leads to disastrous mistakes in governmental policy and corporate decisions.

I don't have to tell you that science has changed our lives amazingly since I died. In my day there was no electricity; the only way to have light at night was by burning something. There were no trains, let alone automobiles, airplanes, and steamships or even bicycles. To travel by land you either walked or some animal had to move you. To cross an ocean or a lake or a big river you either rowed or were pushed by the wind. And if you wanted to find out what was happening in the world, where could you turn? A friend might write you a letter, which could take weeks to arrive. There was no Internet, no radio, no television, no telephone; you could read newspapers (which were invented just before I was born) but every word of those newspapers had to be set by hand. All of the technology you use today relies upon discoveries of basic science.

But what is science?

Well, science is the greatest game ever invented. Yes, it's a game. That's the best way to start understanding how it works. It works like a game: the most important game in the world, and the most fascinating.

Who can play this game? Anyone. Anyone in the world. And even if you don't play it, you can become a fan and appreciate the way the game evolves, and how interesting the moves of the game can be.

What do you need to play? Three things: Curiosity, Perseverance, and Self Criticism. Every human being is born with the capacities of Curiosity, Perseverance, and Self Criticism. To become a scientist you must develop those capacities. And to be an informed fan of science you need these same characteristics to get the most out of following the game.

Let's take them one at a time.

Number one: Curiosity. The scientist is curious about the natural world. She wants to know why and how things happen in nature. Before the rise of science, all societies looked for supernatural causes to many troubling things. If there was an earthquake we asked why God was angry. If the cows got sick we looked for the witch that was cursing them. But now we know the natural causes of earthquakes and science has learned that Mad Cow Disease is caused by a strange form of life called a "prion." Science has learned how this prion spreads and so we know how to manage outbreaks of Mad Cow Disease, though the cure is still an open question. We don't need to look for witches and burn innocent women. But only the curiosity of thousands and thousands of scientists over the last three hundred years has built science up to the place where we can identify the natural causes of nature's problems and stop looking for supernatural explanations.

Number two: Perseverance. While curiosity is the seed of all scientific discovery, it is perseverance that nurtures the seed and helps enables it to grow big enough to be noticed in the world. The scientist may be curious about all sorts of things, but she will find some questions so compelling that she must learn everything about them. At first she can probably find answers from what is already written. *Wikipedia* may get her started. But inevitably every answer she finds will lead her to new questions. Soon she will encounter a problem that no one knows the answer to–or to questions that are hotly contested by the experts. At this point, the scientist has to decide if she will use the new question to compete in the world of professional science. If she can use what she has learned, together with new experiments or observations, to solve the problem, then she will be winner in the big game of science.

To take a famous example: when Einstein was a boy of sixteen he became curious about what would happen if a man could chase a beam of light, what if he could travel at the speed of light and look at the beam as he was moving along beside it. He persevered by learning everything that science had to say, back in 1895. He found problems with what he read so he persevered with his own original thinking and ten years later came up with his theory of special relativity.

Number three: Self Criticism. I'm not saying that scientists don't have big egos. In fact a big ego comes in handy when you have to go against what other people are saying. It can help you stand up for your ideas under severe pressure. But it can also be a disadvantage. You can fall in love with your ideas just because they are YOUR ideas. A big ego can defend an idea because it feels that an attack on your idea is an attack on you. This is where self-criticism comes in. No matter how much you love your own beautiful idea, you should pay attention to the evidence that is presented against it. And when the weight of the evidence against your idea becomes much greater than the weight of the evidence on your side, you should admit that your beautiful idea is not true. If you don't do this, you will most likely become an irrelevant bystander on the progress of science– no matter how much your earlier work may have contributed.

To give you an example of where Self-Criticism was left out of the picture and a person lost his usefulness at the frontier of science, I need go no further than my own experience. If you remember from my talk when I was at your school, my scientific work all grew out of my questioning: What is air? What is fire? This led to my discovering oxygen and photosynthesis. This got me into the controversy with Lavoisier, whom I did not like because he was secretive about his methods and sometimes stole other people's work. Then Lavoisier challenged my theory of fire and proposed his theory of chemical reactions. Well, I stuck with my old theory till the day I died. Was that a good thing for me to do? No! It was a pity, because Lavoisier was right. The chemical-reaction theory of fire opened up all sorts of fascinating new questions which I should have been working on. I let my dislike of the man keep me from applying proper self-criticism and it removed me from the cutting edge of science.

Fortunately, science itself was not stopped either by Lavoisier's secrecy or by my failure. Science went on exploring the idea of chemical reactions and that provoked scientists to ask all the questions that have resulted in the chemistry of today, touching every aspect of our lives from the air we breathe, to the water we drink, the food we eat, the clothes we wear, the medicines we take and on and on and on.

So you see this is an example of science correcting itself. My theory of fire provoked me to make certain experiments. I hoped and expected these experiments would strengthen the evidence that my theory was right. But when I produced pure oxygen I actually set in motion another series of experiments that would provoke Lavoisier to dream up the chemical-reaction theory of fire. And that theory led the way forward for science.

The history of "science as a game" is full of many games fought out within the rules of science. Sometimes the ultimate winner looks like a loser and can't even get taken seriously for a very long time. Plate tectonics, which we talked about earlier, was such a winner.

When Arthur Wegener first proposed the idea of continents moving around, he was largely ridiculed. Other geologists said, "What force could possibly be strong enough to move continents?" There was no good answer. Nevertheless the theory did explain many things about the kinds of rocks and fossils that could be found in places now far apart – places that would have been close together if the continents moved as the theory predicted. Arguments went back and forth for forty years or more as the proponents of plates looked for a way to answer that question: "What force could move a continent?" The arguments that evolved are too complex to describe in this letter but they are covered in the *Wikipedia* article on Plate tectonics. Suffice it to say that by 1967 the backers of the theory had accumulated enough evidence that the majority of geologists had to agree with them and the whole field of geology was revolutionized.

Let me end with another example of a theory that couldn't rouse the support of most scientists for a long time but now is central to its field. I am talking about "Stress."

When you hear the word "stress" today, the first thing that comes to mind is a factor that has an effect on the human body or mind. You may have heard that people under stress for long periods cannot fight off disease as well. Their immune systems are affected. They get more colds and influenza vruses. They are more liable to get heart attacks. If something really terrible has happened to them – whether it's being bullied, or assaulted, or in awful accidents, or they've participated in a war and were involved in killings or seeing their friends killed – these things and others can cause what is called "post traumatic stress syndrome" and make them mentally or physically ill even many years after they suffered the terrible thing.

You might think that medicine has known about the effects of stress on the human being for a long time, but not so. The person most responsible for putting stress near the center of medical thought was named Hans Selye. He formed the basic idea of stress in 1936 while working with laboratory rats. Over the next forty years he published over 1000 papers and 33 books, conducting thousands of further experiments, expanding his insight into a theory that would revolutionize medicine. In 1945 he was lucky to land a job at the University of Montreal in Canada where he had 40 assistants and 15,000 laboratory animals. Nevertheless the medical establishment was quite slow to realize the importance of his ideas. Only in the late 1960s did stress begin to appear as a factor in the considerations of many doctors. Now, it is unthinkable to disregard it because it explains so many observations made by doctors and research scientists.

So the theory of stress has been a big winner over the last forty years. Does that mean that it will remain at the center of medicine, forever unchanged from what it is now? Absolutely not!

Perhaps the most important thing that Selye's theory did was to make scientists ask questions that they would not otherwise have asked. Those thousand papers that Selye wrote were all investigating such questions. As we discover more and more about how the brain works in conjunction with the rest of the body we will most likely discover that stress is more than one thing and expresses itself in different ways. Will this decrease the importance of Selye's work? Absolutely not! He was the explorer who discovered a new continent. The greatest honor any explorer can hope for is to discover things that will provoke questions that will push science beyond where the explorer was able to reach.

This is true of all the greatest scientists from Galileo to Newton, to Lavoisier, to Darwin, to Pasteur, to Einstein and Bohr, and on into the future. It is not that their ideas are true forever. It's that their ideas opened new realms of questions and provoked those who came after to improve on what advances science and reject what can no longer be justified. That is what the game of science is all about.

I have gotten such joy out of my life working in science and being a fan of science that I hope you will be moved to pay attention to your own curiosity, find questions that you will persevere in answering, and always have access to your own self-criticism whenever you suspect that what you think you believe may not, after all, be the whole truth.

Your friend,

Joseph Priestley