WHAT SCIENCE IS AND HOW IT WORKS

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Prologue

WHAT IS SCIENCE?

Science is the last step in man's mental development and it may be regarded as the highest and most characteristic attainment of human culture.
(Ernst Cassirer)

The belief that science developed solely out of a pursuit of knowledge for its own sake is at best only a half truth, and at worst, mere self-flattery or self-deception on the part of the scientists.
(Lewis Mumford)

AS THE OPENING QUOTATIONS by two noted philosophers indicate, opinions about science span a wide range. But it's not clear whether these two eminent thinkers are really talking about the same thing when they refer to "science." Cassirer is discussing science as an abstract method to bring constancy and regularity to the world. Mumford, in contrast, is considering science as a driver of technology, a method to bring about practical changes in life. Both of these viewpoints contain an element of truth; neither is comprehensive. A simple, brief, and comprehensive way to define science is in fact not so easy to come up with. A colleague of mine recently remarked that the defining characteristic of science is that statements in science must be tested against the behavior of the outside world. This statement is fine as far as it goes, but represents a rather impoverished picture of science. Where are imagination, logic, creativity, judgment, metaphor, and instrumentation in this viewpoint? All these things are a part of what science is.

Science is sometimes taken to be the sum total of all the facts, definitions, theories, techniques, and relationships found in all of the individual scientific disciplines. In other words, science is what is taught in science textbooks. Many beginning science students have this idea. But an opposing opinion, which is becoming increasingly influential, has been expressed in academic circles. In this view, the heart of science is in its methods of investigation and ways of thinking, not in specific facts and results. The science taught in textbooks is a lifeless husk, whereas real science is the activity going on in the laboratories and fieldwork. Once again, both of these ideas have merit while neither can claim to be complete. Methodology without content is at best merely a faint image of science (at worst, it's totally meaningless). And yet the content itself, divorced from the thought processes that create such knowledge, surely can't be all there is to science. After all, this body of scientific results changes from year to year, and may sometimes be unrecognizable from one generation to another. The results of science are inseparably intertwined with its thought processes; both together are needed to understand what science is.

There are many other such debates and contrasting perspectives among scientists and philosophers concerning the true nature of science, and we'll consider a number of them as we go along. For now, though, let's take a rest from these abstractions and look at a small example of science in action. Our example concerns something of interest to almost everyone: food.

Example: Why should you whip a meringue in a copper bowl?

As anyone who has made a lemon meringue pie knows, whipping egg whites results in a somewhat stiff foam (the meringue). A tradition in cooking, which can be traced at least back to the eighteenth century, is that egg whites are best whipped in a copper bowl when making meringues. The meringue turns out creamier and less prone to overbeating if the bowl is made of copper (the creamy meringue also has a somewhat yellowish color). Less elite cooks, like myself, achieve a somewhat similar result by using cream of tartar in the meringue instead of beating it in a copper bowl. The interesting question then presents itself: How and why does using a copper bowl affect the meringue?

To understand the influence of the copper bowl, we must first understand why a meringue forms at all. Why do egg whites make a stiff foam when they are whipped? The answer to this question is related to the composition of the egg white (also called albumen), which is a complex substance containing many different proteins (ovalbumen, conalbumen, ovomucin, lysozyme, etc.) suspended in water. These proteins contain long chains of amino acids twisted together into a compact form. The compact protein structure is maintained by chemical bonds between various parts of the twisted chains, acting as a kind of glue. As you whip the egg whites, these bonds weaken and the amino acid chains start to unfold, mostly due to contact with the air contained within the bubbles you create by whipping. The unfolded chains of *different* protein molecules can then start bonding to each other, eventually forming a latticework of overlapping chains that surrounds the bubble wall. The water in the egg white is also held together within this network of protein chains. The protein network reinforces the bubble walls and so maintains the structural integrity of the foam. And we have a meringue.

If you overbeat the egg whites, however, the meringue turns into curdled lumps floating in a watery liquid. The reason this happens is that the network of protein chains becomes too tightly woven and can no longer hold enough water within its structure. The bonding between chains has become too effective, leaving few bonding sites for water molecules. The protein turns into clumps while the water drains out. Adding a little cream of tartar helps to avoid this unfortunate outcome. The cream of tartar is slightly acidic, contributing excess hydrogen ions that interfere with the cross-chain bonding. With weaker bonding, the meringue is less likely to become overbeaten.

This brings us back to the copper bowls, which confer the same virtue: less likelihood of overbeating. Basing our reasoning on the cream of tartar example, we might guess that the copper bowl somehow increases the acidity of the egg white. But such an increase would be difficult to understand, and in any event a simple measurement of the acidity proves that this idea is wrong. Instead, the answer turns out to be related to the ability of conalbumen, one of the proteins making up egg white, to bind metal ions (in this case, copper) to itself. The copper ions that are incorporated into the conalbumen molecule have a striking effect; they stabilize the coiled structure of the protein, acting to prevent the chains from unfolding. Standard laboratory chemistry experiments had demonstrated this fact many decades ago. Since the conalbumen (with copper added) isn't unfolded, its chains don't take part in the formation of a stable foam. If we assume that a small but significant number of copper atoms are scraped from the sides of the bowl into the egg white, then we have a good possible explanation of why copper bowls help to prevent overbeating.

We can test our explanation. These conalbumen/copper complexes absorb light of certain specific colors. Looking at the light absorbed by meringues, we can find out if they really do have such conalbumen/copper complexes. This test has actually been performed, and light absorption experiments using meringues beaten in a copper bowl do indeed reveal the presence of stable conalbumen/copper molecules. Incidentally, the light absorption properties of the complex give it a characteristic yellow color, and so we also have an explanation for the yellowish color of the meringue. This modest example is far removed from the grand philosophical debates about science, but it nicely illustrates a number of important themes: science is about real things that happen in the world; science tries to provide a coherent understanding of these things; our specific observations must be placed in a more general framework to be understood; interpretations are often based on pictorial models; we often use instruments and measurements to augment our observations; a genuinely coherent picture often leads to predictions of new observations, which serve as tests of how correct our present interpretation is. Most of these themes, as well as many others, will recur throughout the book.

An Overview

The first part of the book is about scientific discoveries. More particularly, we examine the question of how discoveries are made. I'm not interested in undertaking a systematic and exhaustive investigation of the sources of scientific discovery, however, and I'm certainly not trying to devise a theory to explain the process of discovery. My firm belief is that there are many, many factors involved in this process, and they vary greatly from one situation to another. My only goal is to illustrate some of these factors by looking at examples. Since I'm looking at particular examples of discoveries, this part of the book is primarily historical. The historical approach allows us to look at the rich context of each discovery, without distorting the narrative to fit into a preconceived notion. On the other hand, I am trying to use each example to illustrate some particular element that played a dominant role in the discovery under discussion (even when several other factors were also important). Some of these dominant elements include: the apprehension of patterns in data; increased power of instrumentation; luck (serendipity); the role of discrepancies; thematic imagination; the hypothetico-deductive method; the consequences of a priori postulates; and inspired flashes of intuition.

In the second part of the book, we shift gears and approach science from quite a different angle. For some time now, it has seemed to me that scientists often approach the world with a rather distinctive kind of thinking process. I don't mean by this that any particular method is applied; rather, I'm referring to a style of looking at questions and approaching problems. Let me illustrate this vague statement with an example. When I was on a jury deciding an automobile accident lawsuit, I was the only person who asked: "What plausible model can we construct for the accident that is consistent with the photographs of the damage?" The other jurors weren't entirely sure what I meant by this. Constructing models is a very typical way for a scientist to think about a situation. Science is often done this way, and scientists naturally extend the practice to other situations. As I said, this practice (thinking in terms of models) is only one example of the style I'm talking about. Another customary approach is to employ quantitative thinking about a situation (for example, "how precisely do I know this number?" or "does the order of magnitude of that number make sense?"). Yet another example is the habit of looking for general principles of known validity against which to judge particular claims. These sorts of characteristic scientific thought processes and approaches are the subject of the second part of the book.

The third part of the book is an endeavor to place science within a broader matrix of ideas. An important part of this undertaking is to look at what science *is* by looking more closely at what science is *not*. Of course, a great deal of human experience and thought lies outside science, but we're mostly concerned with those areas that do have some overlapping interests. For this reason, vast subjects like religion, politics, and ethics are discussed somewhat narrowly, primarily in terms of how they relate to science. On a much different note, we also contrast science with pseudoscience, which might be described as a burlesque of real science (but unfortunately is often taken seriously). Moving from there into controversial territory, we look at some areas where arguments are still raging over whether the topics in question are science or not. Then, after a rather condensed summary of the main ideas and issues in the philosophy of science, we again enter into an intellectual minefield and briefly discuss the arguments of the postmodern critics of science.

In the fourth and final part of the book, we consider some of the broad concepts and ideas important in the sciences. Although each of the individual scientific disciplines has its own central principles (for example, natural selection in biology or plate tectonics in geology), the concepts emphasized in this part of the book are transdisciplinary. In other words, the subjects discussed here cut across disciplinary boundaries and are important in a variety of different sciences. In this way, I hope to show some of the underlying unity of the sciences, which can become lost in the fragmentary treatment of particular results. A prime example of such broadly important concepts is symmetry. Though symmetry is in many ways a mathematical concept, it is significant in art and aesthetics as well as in virtually every science. Another good example is the dependence of volume and surface area on the characteristic size of an object; this too turns out to be important in many areas of science (as well as in practical affairs). Very often in the sciences, a prominent consideration is how something changes. Two of the most common and useful kinds of change are discussed here: linear variation (one thing proportional to another) and exponential variation (growth rate proportional to amount). Profound issues at the heart of many sciences turn on the concepts of order and disorder, which are treated here in some detail. We then round out this part of the book with a discussion of feedback loops and homeostasis in the sciences. The book ends with a brief epilogue in which we will reconsider the question: what is science?

For Further Reading

Ideas of Science, by Bernard Dixon and Geoffrey Holister, Basil Blackwell, 1984.
On Food and Cooking: The Science and Lore of the Kitchen, by Harold McGee, Macmillan, 1984.
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The Scientific Companion, by Cesare Emiliani, John Wiley & Sons, 1988.
The Scientific Attitude, by Frederick Grinnell, Guilford Press, 1992.
Science and Its Ways of Knowing, edited by John Hatton and Paul B. Plouffe, Prentice-Hall, 1997.

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Chapter 1

A BIRD'S EYE VIEW: THE MANY ROUTES TO SCIENTIFIC DISCOVERY

> Now, I am not suggesting that it is impossible to find natural laws; but only that this is not done, and cannot be done, by applying some explicitly known operation. . . .
>
> *(Michael Polanyi)*

HOW DOES A SCIENTIST go about making a discovery? The idea that there's a single answer to this question (the "scientific method") persists in some quarters. But many thoughtful people, scientists and science critics alike, would now agree that science is too wide-ranging, multifaceted, and far too interesting for any single answer to suffice. No simple methodology of discovery is available for looking up in a recipe book. To illustrate some of the rich variety in the ways scientists have discovered new knowledge, I have chosen five cases to recount in this chapter: the accidental discovery of x-rays; the flash of intuition leading to the structure of benzene; the calculations through which band structure in solids was discovered; the voyages of exploration inspiring the invention of biogeography; and the observations and experiments resulting in smallpox vaccine.

§1. Serendipity and Methodical Work: Roentgen's Discovery of X-rays

Working late in his laboratory one evening in 1895, a competent (but not very famous) scientist named Wilhelm Roentgen made a sensational discovery. His experiments revealed the existence of a new kind of ray that had exotic and interesting properties. Because these mysterious rays were then unknown, Roentgen called them x-rays (*x* standing for the unknown), a name that we still use to this day. After he reported his new discovery, Roentgen immediately became a highly celebrated figure and won the first Nobel Prize in physics just a few years later.

Of course, we now know what x-rays are. X-rays are similar to light, radio waves, infrared and ultraviolet rays, and a variety of other such radiations. All of these things are particular kinds of electromagnetic waves, so called because they are wavelike transmissions in electric and magnetic fields. The major difference between light and x-rays (and all the other types) is the wavelength of the radiation (this is the distance over which the wave repeats itself; different colors of light also differ in wavelength). The energy of the radiation also changes with the wavelength. X-rays have hundreds of times more energy than light, which accounts for both their usefulness and also their potential danger. This high energy also played an important role in Roentgen's discovery.

The experiments that Roentgen had in mind built on the work of many other nineteenth-century scientists (Thomson, Crookes, Lenard, and others). This work consisted of experiments with something called a cathode ray tube. These devices are not as unfamiliar as you may think; the picture tube in your television is a cathode ray tube. Basically, a cathode ray tube is just an airtight glass container with all the air pumped out to create a vacuum inside, and pieces of metal sealed into the glass wall so that electrical connections outside the tube can produce voltages on the metal inside the tube. If the voltage is high enough, a beam of electrons leaving the metal can be produced. A substance that glows when high-energy rays strike it, called a phosphor, can also be placed inside the tube. When the beam of electrons strikes the phosphor, we can see the presence of the beam by the telltale glow emitted. In essence, this is how your television creates the picture you see on the screen.

In 1895, the existence of electrons was not known (Thomson was soon to discover the electron in 1897). The cathode rays, which we now call electron beams, were at that time simply another mysterious radiation that scientists were still investigating. One important property known to be true of the cathode rays is that they are not very penetrating, that is, do not go through matter easily. For example, cathode rays couldn't escape through the glass walls of the tube. Lenard had discovered that a thin aluminum sheet covering a hole in the glass allows the cathode rays through, but the rays can then only make it through about an inch of air. All these observations were made using the glow of phosphors to detect the presence of the beam. Roentgen wondered whether some tiny portion of the cathode rays might after all be escaping through the glass walls undetected. The glass itself is weakly luminescent when struck by cathode rays, so the whole tube produces a kind of background glow. If an escaping beam were very weak, the slight glow it caused on a detecting phosphor might be washed out by this background glow of the tube. So Roentgen designed an experiment to test this hypothesis. He covered the tube with black cardboard to screen out the background glow, and his plan was to look for a weak glow on the phosphor he used as a detector when he brought it close to the covered tube wall.

As a first step, Roentgen needed to check his cardboard covering to make sure that no stray light escaped. As he turned on the high voltage, he noticed a slight glimmering, out of the corner of his eye, coming from the other side of his workbench (several feet away from the tube). At first, he thought that this must be a reflection from some stray light that he had not managed to block successfully. But when he examined the source of the glimmer more carefully, he was shocked to discover that it was coming from a faint glow of the phosphor he planned to use later as a detector. Something coming from the tube was causing a slight glow from a phosphor located over thirty times as far away as cathode rays can travel through air. Roentgen immediately realized that he had discovered some fundamentally new kind of ray, and he excitedly embarked upon the task of studying its properties. He found that these rays had extremely high penetrating powers. His phosphor continued to glow when a thousand page book or a thick wooden board was placed between the tube and the phosphor. Even thick plates of metals such as aluminum and copper failed to stop the rays completely (although heavy metals such as lead and platinum did block them). In addition to their penetrating power, Roentgen found that his new rays were not affected by magnetic and electric fields (in contrast to cathode rays, which are deflected by such fields).

In the course of his investigations, Roentgen made another accidental discovery that insured his fame in the history both of physics and of medicine. While holding a small lead disk between the phosphor screen and cathode ray tube, Roentgen observed on the screen not only the shadow of the disk but also the shadow of the bones within his hand! Perhaps to convince himself that the eerie image was truly there, Roentgen used photographic film to make a permanent record. After he completed his systematic and methodical investigations of the properties of x-rays, Roentgen published a report of his findings. The experiments were quickly replicated and justly celebrated. In physics, the discovery of x-rays opened up whole new avenues in the investigations of atoms and turned out to be the first of several revolutionary discoveries (followed quickly by radioactivity, the electron, the nucleus, etc.). In medicine, practitioners quickly realized the diagnostic value of x-rays as a way to look inside the body without cutting it open. The use of x-rays in medicine is one of the fastest practical applications of a new scientific discovery on record.

Roentgen's discovery of x-rays was a marvelous combination of luck and skill. Discovering something you aren't looking for, a process often referred to as serendipity, is not uncommon in the sciences. But as Pasteur's famous maxim says, "chance favors only the prepared mind." Roentgen's mind was extremely well prepared to make this discovery, both by his skill in experimental techniques and by his thorough knowledge of the previous work on cathode ray phenomena. Also, Roentgen's painstaking detailed investigation of the x-rays, following his initial lucky break, was crucial to the discovery process. He recognized the importance of the faint glimmer he did not expect to see.

§2. Detailed Background and Dreamlike Vision: Kekulé's Discovery of the Structure of Benzene

The carbon atom has chemical properties that set it apart from all other elements. Carbon is able to form a wide variety of chemical bonds with other elements, particularly with hydrogen, oxygen, nitrogen, and with other carbon atoms. The tendency to form various kinds of carbon-carbon bonds, in addition to the C-H, C-O, and C-N bonds, fosters the creation of complicated chainlike structures in such carbon-based molecules. For these reasons, many thousands of these carbon compounds exist, so many in fact that the study of them is a separate branch of chemistry. This branch is called organic chemistry, because it was once thought that only living organisms could produce these compounds. It's true that the molecules of living organisms (carbohydrates, fats, proteins) are all in this category, but "organic" is a misnomer in the sense that many organic chemistry compounds have nothing at all to do with life.

We might say that organic chemistry started with the synthesis of urea in 1828 by F. Wöhler. For many years thereafter, organic chemistry proceeded by trial and error, with chemists using their experience and various rules of thumb to synthesize new compounds. Organic chemists had no theory underlying their work and didn't know the structures of the compounds they created. Around the middle of the nineteenth century, the work of many chemists contributed to a growing understanding of the science underlying organic reactions and syntheses. Prominent among these chemists was August Kekulé. Kekulé's major contribution to organic chemistry was the idea that a molecule's three-dimensional structure was a key ingredient in determining that molecule's properties. The number of atoms of each element making up the molecule is obviously important, but how they are connected to each other in space is equally important. Kekulé's theories concerning molecular structure in general, along with his determinations of the structures of many specific compounds, advanced the field considerably.

By 1865, Kekulé had worked out the structures of many compounds, but the structure of benzene had proven to be intractable. Benzene is a volatile liquid that can be obtained from coal tar. Benzene is sometimes used as an industrial solvent, but the major importance of benzene is its role as the structural basis for many dyes, drugs, and other important chemicals. Michael Faraday had already determined the atomic composition of benzene in 1825. Benzene consists simply of six carbon atoms and six hydrogen atoms. But forming these six C and six H atoms into a structure that makes sense had defied the efforts of organic chemists, including Kekulé. One major problem with devising a reasonable benzene structure is the 1:1 ratio of C atoms to H atoms. Kekulé had already previously concluded that C atoms make four bonds to other atoms and that H atoms make one such bond, a system that works well for methane (see chapter 18) and similar compounds. But it's hard to reconcile this idea with the 1:1 ratio of C atoms to H atoms in benzene. Another big problem was the chemical behavior of benzene, especially compared to other compounds in which hydrogen atoms don't use up all of the available carbon bonds. These other compounds, such as acetylene (the gas used in welding torches), can be chemically reacted with hydrogen to produce new compounds that have more H atoms. Benzene, however, wouldn't accept any new H atoms in such a reaction.

Kekulé had pondered these problems for a long time. He combed his knowledge of organic chemistry in general, reviewed everything that was known about the reactions of benzene with other chemicals, and expended great effort in order to devise a suitable structure that made sense. Then, Kekulé hit upon the answer in a flash of inspiration. As Kekulé recounts the episode:

> I turned my chair to the fire and dozed. Again the atoms were gamboling before my eyes. . . . My mental eye, rendered more acute by repeated visions of this kind, could now distinguish larger structures of manifold conformation: long rows sometimes more closely fitted together all twining and twisting in snake-like motion. But look! What was that? One of the snakes had seized hold of its own tail, and the form whirled mockingly before my eyes. As if by a flash of lightning I awoke; and this time also I spent the rest of the night in working out the consequences of the hypothesis.

Kekulé's vision had suggested to him the ring structure of benzene shown in Figure 1. By having the chain of carbon atoms close on itself, he was able to satisfy the bonding numbers for C and H while leaving no room for additional H atoms. The question then became purely empirical. Does this benzene structure explain all of the known reactions and syntheses involving benzene? Does it predict new reactions and syntheses accurately? To make a long story short, the answer to these questions turned out to be, basically, yes.

Other structures were also proposed for benzene, and a vigorous debate went on for some years. In the end, Kekulé's ring structure had the most

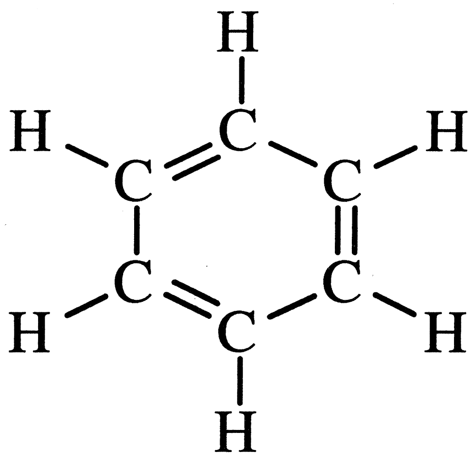

Figure 1. The structural model of the benzene molecule worked out by Kekulé, often referred to as a benzene ring. The ring structure was inspired by Kekulé's vision of a snakelike chain of atoms closing on itself.

success in explaining the data and became accepted as the correct structure. Some inconsistencies remained; calculated energies for the molecule were higher than the measured energies, and the placement of the three double bonds was distressingly arbitrary. These problems were finally cleared up many decades later when the modern quantum theory of chemical bonding was applied to the benzene ring, showing that all six bonds are really identical (circulating clouds of electrons bonding the carbons might be a more appropriate image than alternating double and single bonds). Meanwhile, Kekulé's proposed benzene ring was extremely successful in suggesting reaction pathways for commercially important organic compounds. The German chemical industry soon became the envy of the world, producing dyes, drugs, perfumes, fuels, and so on. The solution of the benzene structure problem was a key to much of this activity, which was an important segment of the German economy prior to World War I. Kekulé himself, however, had little interest in commercial ventures and confined his attention largely to scientific understanding.

A number of scientists have reported experiences similar to that of Kekulé. After a prolonged period of apparently fruitless concentration on a problem, the solution seems to arrive all at once during a brief period of relaxation. It's crucial to immerse oneself completely in the details of the problem before the flash of inspiration can come. An unusual aspect of Kekulé's experience is the highly visual character of his insight. His earlier development of the structural theory of organic chemistry had also been informed by such visions of dancing atoms, so this seems to have been a general part of his thinking process. Kekulé's early training had been in architecture, and it's possible that this training influenced his rather visual approach to chemistry and his tendency to think in terms of the spatial "architecture" of molecules.

§3. Idealized Models and Mathematical Calculations: The Discovery of Band Structure in Solids

Semiconductors are now an essential part of modern life, forming the heart of integrated circuits and diode lasers. Computers, compact discs, telecommunications, audio amplifiers, television, and many other devices would not exist if we didn't understand the behavior of semiconductors. The essential concept needed to understand semiconductor behavior is the concept of energy bands separated by band gaps, although few people have ever heard these terms. The existence of energy bands in solid materials was discovered by several people during the years from 1928 to 1931, at a time when semiconductors were merely a laboratory curiosity of little or no interest to anyone. The motivation for the work that led to this discovery was a desire to understand how electrons can even move through metals at all. If you imagine the negative electrons in a metal as moving through the array of fixed positive ions (which are much more massive than the electrons), the problem becomes apparent. The electrons and ions exert strong forces on each other. As the electrons try to move, they soon collide with an ion and are scattered into a different direction. This kind of scattering, in fact, is what causes electrical resistance in the first place. However, all the calculations done before 1928 indicated that the electrons shouldn't get much farther than one or two ions; experimental resistance measurements required electrons to get past hundreds of ions before colliding. This was a mystery.

In an effort to solve this mystery, Felix Bloch applied the newly invented theory called quantum mechanics to the problem. In the strange world of quantum mechanics, the electrons may be pictured as waves rather than as particles. Bloch also used another recently discovered fact: the ions in a metal are arranged in an orderly periodic fashion (a crystal lattice; see chapter 18). So Bloch's model (see chapter 6) of a metal consisted of quantum mechanical electron waves traveling through a periodic lattice of positive ions. Bloch succeeded; he was able to calculate the motion of the electrons in such a system, and the results were remarkable. It turned out that the electrons could sail effortlessly through the lattice without hitting ions. Resistance was due to vibrations of the ions and imperfections in the crystal. The results agreed well with experiments.

Another important step was taken by Rudolf Peierls, building on the foundation of Bloch's work. Peierls kept the same basic model that Bloch used, but now he varied the strength of the forces between the electrons and the ions. In his previous work, Peierls had already shown that a more detailed examination of Bloch's calculations reveals a "flattening" of the energy curve for the electrons. (This energy curve tells us how the electron's energy changes as its momentum increases.) His experience with this previous work enabled Peierls to recognize the significance of his new calculations. He discovered that where the flattening of the energy curve ends, there is an energy range above it in which no electron states at all can exist. Above this range of forbidden energies, another allowed band of electron energy states occurs. In other words, we have bands of allowed energy states for electrons in solids, separated by a zone of forbidden energies with no states. This zone of forbidden energies is what we now call a band gap. Above the second band of states, there is another gap, and so on. This discovery was an unexpected result of the calculations, and its importance can't be overemphasized. The idea of energy bands and gaps is at the heart of our understanding of the behavior of electrons in solids, but even Peierls did not see this clearly at first. One more ingredient was needed in order to fully appreciate the true significance of band structure in solids.

This final ingredient was supplied by Alan Wilson in 1931. The problem that Wilson was pondering concerned a peculiar implication of the work done by Bloch and Peierls. If electrons can move easily through a lattice of ions, no matter how strong or weak the electron-ion forces are, *then why isn't every solid a metal*? While grappling with this puzzle, Wilson realized that the proper interpretation of the band calculations not only answers the question, but does so in a fundamental and illuminating fashion. Wilson realized that if a band was full (all possible states occupied by electrons), then no electron could gain energy, because to gain energy puts the electron into the band gap where no states exist for it to occupy. Electrons must gain some energy to become a current (i.e., to move), as in a conductor. A solid with a full energy band must then be an electrical insulator (like quartz or sapphire). Solids with partly empty bands have higher energy states available for the conduction electrons to go into, and so these are metals (like copper or aluminum). Wilson's idea explained the essential difference between metals and insulators, which had been an unsolved problem since the first attempts to understand the properties of matter.

Going further, Wilson extended his theory to explain electrical conduction in semiconductors (like silicon). The major riddle presented by semiconductors was that they, in contrast to metals, became *better* conductors at higher temperatures instead of worse. Wilson pictured semiconductors as solids with full bands but having rather small band gaps. Electrons can be thermally excited into the empty band above the gap, and these electrons conduct the current. Naturally, more electrons can acquire enough energy to cross the gap at higher temperatures, and so the sample becomes a better conductor. Using the idea of energy bands and gaps, we could now understand the electrical behavior of metals, insulators, and semiconductors in a unified manner. At the time, experimentalists were still debating whether semiconductor behavior was real or just an artifact caused by low-quality samples. Several decades later, our understanding of semiconductors became the basis for the microelectronics revolution. The central unifying idea of energy band structure in solids arose unexpectedly from the results of calculations. No one anticipated the existence of band gaps in solids (in fact, as we've seen, it took a while to recognize their importance even after the discovery). The concept just turned out to be a result of assuming electron waves in a periodic lattice of ions, and calculating the consequences of this assumption.

§4. Exploration and Observation: Alexander von Humboldt and the Biogeography of Ecosystems

Although he is not a famous figure today, Alexander von Humboldt was one of the leading natural scientists of his own time. He was a friend or correspondent to virtually every noted scientist in Europe, he socialized with the elite in the court of Napoleon, he was admired by Goethe, he stayed at Jefferson's home Monticello as an honored guest, and the King of Prussia put some effort towards attracting Humboldt into his service. Humboldt was probably more well known to his contemporaries in the educated public than any scientist alive now is known. His fame is reflected in the twenty-four places (towns, counties, mountains, rivers, even a glacier) named after him. Humboldt's scientific work is voluminous, and he worked in virtually every field in the natural sciences. He made contributions to astronomy (studying meteor showers), botany (discovering over three thousand new species), geology (studying volcanoes and geologic strata), geophysics (studying the earth's magnetic field), meteorology (studying tropical storms), and oceanography (studying the major ocean currents). And this list isn't even complete. Many of these studies were observational in nature; Humboldt's sharp mind, natural curiosity, and keen powers of observation gave him the intellectual tools needed for such work. But what also set Humboldt apart from the average naturalist was that he embarked on a voyage of exploration that can only be called epic. Humboldt was the scientist who opened up the New World for study.

In 1799, Humboldt embarked on his journey of exploration to South America and Mexico. When he left Latin America in 1804, he had collected thirty cases of geological and botanical specimens, as well as innumerable notes, records, measurements, maps, and codices. Among his adventures on this trip, he traveled by boat down the Orinoco River through the tropical jungles of Brazil (coming down with typhoid in the process). In Ecuador, he scaled the highest peak in the Andes, setting a new record for the highest altitude ever achieved. Everywhere he went, he made precise measurements of the latitude (using astronomical instruments), barometric pressure, and the earth's magnetic field (strength and direction). He collected gases from the fumes of active volcanoes and analyzed their chemical composition. He described the geological structures and climates of the different regions he visited. Everywhere he went, Humboldt collected samples of minerals, plants, and animals. In the mountains of the Andes, Humboldt made one of his most important and fruitful discoveries. As he climbed the mountains on exploratory expeditions, Humboldt was struck by the dramatic changes in the vegetation and animal life at different elevations. At the base of the mountains grew palms, bananas, and sugar, typical of the tropical climate. At higher elevations, coffee and cotton were found, along with maize, wheat, and barley on the flatter areas. Above this, the vegetation became more sparse, mostly evergreen shrubs, while at the highest elevations only alpine grasses and lichens could be seen. He realized, based on his extensive travels, that this sequence was similar to the changes in vegetation with latitude as one moved from the tropics towards the poles. As Humboldt pondered the meaning of these changes, he realized that the climate was a major, but not the only, part of the physical environment that determined the plant life found in a geographical area.

Based on his studies and observations, Humboldt developed a theory of biogeography, of how the physical conditions of an area influence the features of the ecosystem (to use the term we now employ) found there. The temperature, soil conditions, amount of sunlight, rainfall, and topography all work together to determine what kind of plant and animal life might inhabit a place. This may seem obvious today, but the idea was both novel and important when Humboldt proposed and explicated it. Much of his work consisted of describing and classifying parts of nature, but this theory gave meaning and context to the classifications. Humboldt believed in the underlying unity of nature, and in the biogeography idea he could see a reflection of this unity. Like any important discovery, his idea also opened up new areas of investigation and suggested new ideas to other scientists who followed Humboldt.

Before leaving Humboldt, I can't resist the temptation to mention his work in cultural anthropology. The native cultures of the Inca, Aztecs, and Maya had been partially decimated by conquest, but a keen and intelligent observer like Humboldt was still able to learn and record a great deal. He studied their languages, visited archeological sites (such as the pyramids at Teotihuacan), collected ancient writings and sculptures, recorded their myths and legends, and examined petroglyphs. The knowledge of astronomy possessed by the vanished cultures was an especially interesting area studied by Humboldt, and he looked in detail at the calendar systems that they had created. These cultures had mostly been ignored before Humboldt's work, and his efforts stimulated further interest by later scholars. Humboldt's insatiable curiosity and sharp analytical mind ranged over every part of the natural world. His travels and explorations gave him the opportunity to deliver a treasure trove of new knowledge to the intellectual community of Europe, and this knowledge contributed to the great integrative theoretical work in geology and biology done by scholars who followed him in succeeding generations. Humboldt's own attempt at a grand integration of all knowledge was his masterpiece, *Cosmos*. This work is informed by Humboldt's conviction of the harmony and unity underlying the diversity of nature. Subsequent discoveries and theories have rendered the details of *Cosmos* obsolete, but it remains a remarkable testament to the depth of Humboldt's thinking.

§5. The Hypothetico-Deductive Method: Edward Jenner and the Discovery of Smallpox Vaccine

Edward Jenner started his career as an apprentice country doctor in Gloucestershire, the rural area of England where he grew up. After his apprenticeship, Jenner went to London in 1770 for more advanced training under the highly regarded surgeon, John Hunter. Medicine was still in a somewhat primitive state at this time, using many traditional methods of doubtful efficacy. Hunter was a pioneer in the application of scientific thinking to medical practice, and he taught Jenner to do the same. Jenner proved to be an excellent student, and he developed into a first rate doctor under the guidance of the brilliant Hunter. Equally able as both a medical practitioner and as a scientist, Jenner embarked on his own career after his time with Hunter ended.

Against his teacher's wishes, Jenner decided to move back to Gloucestershire (Hunter wanted Jenner to stay in London, where he could make a reputation). His move back to the countryside, however, gave Jenner the opportunity to follow up on an idea he had gotten when he was still a young apprentice. While treating a milkmaid for a minor ailment known as cowpox, Jenner had become acquainted with one of the local legends of the Gloucestershire region. The milkmaid told him that she was lucky to have the cowpox, because now she would never contract smallpox. Smallpox was one of the most dreaded diseases of the time, and the milkmaid assured Jenner that having had cowpox protects against getting smallpox. Jenner put this conversation in the back of his mind at the time, but now he was hoping to look into the matter more thoroughly. Gloucestershire was a major dairy farming area, and this made it an ideal place to conduct his study. Cowpox was a disease that the cows contracted, and the cows often then transmitted the illness to humans (through cuts on their hands, for example) as they milked the cows. Cowpox wasn't very serious; it caused fever, aching, and some temporary blisters around the hands. The illness lasted a few days, and a full recovery could be expected. The cowpox sometimes came to the dairies in epidemics, but sometimes it vanished for years on end.

Smallpox at that time was a worldwide scourge, highly contagious and often fatal. In the century before Jenner began his work, smallpox had claimed over twenty million people in Europe. Almost a third of the children under age three in Britain succumbed to the Red Death. The smallpox sometimes raged unchecked in terrible epidemics, and there was no treatment available. Among the victims who did not die, many were left horribly disfigured, blinded, or insane. The only preventative measure known was inoculation, the practice of purposely infecting people with material from active smallpox pustules. This action might produce a less severe case of the illness, which then protects the person against contracting it again. But, the procedure often could go awry and produce a severe case, even death. Worse yet, even when the procedure worked well, the inoculated person might give the disease to others. In Russia, an entire epidemic had started this way. So Jenner's idea that there might be a safe way to prevent smallpox was exciting. It had taken root in his mind and become his dream: a world free from the Red Death. But the matter was not simple. There were a number of cases in which people who had once had cowpox did come down with the smallpox. For that reason, many of the local Gloucestershire doctors dismissed the old legend completely. And yet, there was enough anecdotal evidence in favor of the legend to still convince many people of its truth. Jenner, excellent scientist that he was, realized that he needed to start making careful observations, including keeping good notes and records, if he wished to untangle the situation.

After his medical practice was established, Jenner began his work in earnest. He made a scientific study of the cowpox, which no one had ever done before. A more precise description of the symptoms and course of the disease was needed, both in cows and in humans. For several years, Jenner carefully observed all the cases which occurred in the dairies, and he interviewed people who had gotten cowpox in the past. Making careful notes on these case histories, he began to achieve a more thorough understanding of the cowpox. At the same time, Jenner began to make a systematic study of the cases in which cowpox had apparently conferred immunity to smallpox. Just as importantly, he also studied those cases where it had not done so. If he wished to use cowpox as a tool in the fight against smallpox, Jenner would have to solve the puzzle of why some people still contract smallpox even after having cowpox. These cases were often taken to be proof that the old legend was merely superstition, and Jenner's work was widely regarded by his colleagues as a waste of time.

But Jenner did not give up easily, and he continued to look for some clue that would solve this puzzle. As he pored over his records, he came to realize that different sets of symptoms were observed (the appearance of the pustules, swelling in the armpits, headaches, body pains, vomiting, etc.) in different victims; in other words, the cowpox had no single fixed description. The same thing was true in cows (sometimes the pustules were circular, sometimes irregular; sometimes they lasted weeks, sometimes days, and so on). Jenner concluded that what dairy farmers had been calling cowpox was actually several distinctly different diseases. This fact solved Jenner's puzzle, because only *one* of these diseases conferred immunity to the smallpox. Once he had this idea with which to organize his observations, Jenner was soon able to distinguish these different versions from each other. His next step was to determine which disease (he referred to it as the true cowpox) was able to protect against smallpox. Based on his records and observations, Jenner was able to give a very complete and accurate description of the true cowpox. One of the major clues that helped him was the lack of symptoms in response to inoculation with smallpox matter on the part of people who had contracted the true cowpox in the past. In this manner, after five years of patient work, Jenner was able to distill a hypothesis from his observations.

He then put his hypothesis to the test, and he discovered that some mysteries still remained. At one of the local dairies, there was a major outbreak of the true cowpox. Jenner continued to keep his meticulous records, and so there was no doubt in his mind when these same milkers came down with smallpox the following year. His hypothesis, and his dream of defeating smallpox, seemed shattered. He pored over his records and continued to study the cowpox, looking for a solution to this new puzzle. For several more years, Jenner tried in vain to figure out why even the true cowpox sometimes failed to protect against smallpox. There seemed to be no answer. Then, while looking at two cows in different stages of the disease, Jenner realized the factor he had been overlooking for so long. The disease, and in particular the appearance of the pustules, gains in strength for a few days, then the disease is at its worst for a while, and finally it declines and goes away over a few days. This much Jenner had known well for years. But now he hypothesized that the virulence of the matter in the pustules, which transmits the disease, should also likewise gain and decline in strength; *and cowpox only protects against smallpox when the matter in the pustules is at its strongest*. This new hypothesis solved the puzzle, and was consistent with the facts he knew. For example, the milkers whose smallpox epidemic so mystified him had gotten cowpox in its earliest stages.

Jenner now designed an experiment to test this latest hypothesis. In May of 1796, Jenner extracted some material from a pustule on the hands of a milkmaid named Sarah Nelmes. She had contracted the disease from a cow while it was at its worst, and her own case was also now at its strongest. These conditions were ideal for Jenner's experiment, and he used the material to purposely infect a young boy named James Phipps. After the cowpox had run its course in young Phipps, Jenner inoculated him with live smallpox matter the following July. Tensely, day after day, Jenner and the Phipps family looked for any sign of a smallpox infection beginning. But even several days after the expected time of onset, the boy had absolutely no smallpox symptoms! The experiment had succeeded. The cowpox material, deliberately introduced into a human body, had been shown to confer immunity to the Red Death.

Our story ends here, but Edward Jenner's story went on for several more years. He had an uphill battle convincing the medical community and the general public that his method, which came to be known as vaccination (from the Latin word for cow), was an effective method to prevent smallpox. His problems were compounded by incompetent people who tried to steal his idea but couldn't perform the procedures properly (in one terrible case, a quack mixed up cowpox and smallpox material, actually starting an epidemic). Such mishaps gave the vaccine an undeserved reputation for being unsafe and ineffectual. But Jenner managed to sort these problems out, and in the end his smallpox vaccine derived from the cowpox material came into widespread use, saving untold numbers of people from the ravages of smallpox. For this service to humanity, Jenner became a hero in his own time and had numerous honors bestowed on him.

There are certainly elements of luck and inspiration in this story, but it mainly illustrates the pathway to discovery that we now often call the hypothetico-deductive method. We start by making observations; organize these observations into a hypothesis; test the hypothesis against further observations and modify it as needed; make predictions based on the modified hypothesis and design experiments to test our predictions. This highly successful methodology is also sometimes enshrined in elementary textbooks as the "scientific method." The discovery of the smallpox vaccine is a good example of just how powerful this method can be.

Although Jenner is most famous for discovering vaccination, he had a productive career as both a medical researcher and as a naturalist. In medicine, he deserves some credit for discovering the role of hardening of the arteries in causing heart attacks. As a naturalist, he made important studies of hibernation in animals, and he also discovered the cuckoo hatchling's habit of pushing fellow hatchlings out of the nest. In all of his work, Jenner's careful, accurate, and honest observations were always the foundation for his conclusions.

For Further Reading

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