Chapter 2

NATURE'S JIGSAW: LOOKING FOR PATTERNS
AS A KEY TO DISCOVERY

... merely to observe is not enough. We must use our observations and to do that we must generalize. ... The scientist must set in order. Science is built up with facts, as a house is with stones. But a collection of facts is no more a science than a heap of stones is a house.

(Henri Poincaré)

To DISCOVER an underlying coherence and regularity in nature, buried within reams of observational and experimental data that has so far defied understanding, is at the heart of science. Finding such previously unseen patterns is one of the key processes of scientific discovery. In this chapter, we look at the stories of two highly important discoveries. Each story has its own interesting features, but they both have in common the finding of a pattern, like the pieces of a jigsaw puzzle falling into place once you see the picture they form.

§1. The Periodic Table of the Elements

Our concept of an element, a chemical substance that cannot be broken down or changed into anything else, was unknown to antiquity. Nevertheless, a few of the substances we now recognize as elements (mostly metals like gold, iron, and copper) were known in ancient times, and the alchemists later isolated a few more (such as antimony and arsenic). During the seventeenth and eighteenth centuries, chemistry became established as an empirical science, but it still lacked a theory in the modern sense. Valuable discoveries were made, especially in the work with gases; hydrogen, oxygen, and nitrogen were all observed during this time, but their nature was not understood. Lavoisier was finally able to reconceptualize chemistry in a way that made these observations sensible. He introduced the idea of an element in its modern form and he enumerated the substances that he considered elements at that time. Lavoisier published his work in 1789, and chemistry progressed rapidly after this. Many new elements were isolated and identified, using ingenious new techniques.

The novel science of electrochemistry, made possible by the invention of the battery, played a major role in this work. By about 1850, the number of known elements had grown to roughly sixty, compared to only around twenty in Lavoisier's time. Thanks to the skillful and methodical work of many chemists, a great deal of information about the chemical and physical properties of these elements was available.

What kind of chemical and physical properties are interesting? Whether an element is a metal or a nonmetal; a solid, a liquid, or a gas; brittle or ductile; highly reactive or fairly inert; all these are basic questions. The density, melting point, boiling point, and crystal structure are all basic physical measurements. Chemically, the first interesting question is: with what other elements does this form a compound? What are the ratios of these elements in the compounds they form? Based on the answers to these questions, chemists were able to assign a valency to each element, a measure of how much is needed to form a compound. Potassium, for example, has a valence of one and forms a compound with chlorine in a 1:1 ratio, a compound with oxygen in a 2:1 ratio, a compound with phosphorus in a 3:1 ratio, and so on. Calcium, with a valence of two, forms a compound with chlorine in a 1:2 ratio, a compound with oxygen in a 1:1 ratio, and so on. If you multiply these two simple examples many times over, you begin to have a sense of the vast quantity of information that chemists had acquired by the middle of the nineteenth century.

As the properties of the elements were explored, patterns began to emerge. For example, several of the metals all had very similar chemical properties (highly reactive with a valence of one) and physical properties (low densities and low melting points); they were called the alkali metals. Other sets of elements with strikingly similar properties were also known (the halogen gasses, the alkaline earth metals). Other more complex patterns were seen, such as the similarity in crystal structures between analogous compounds of elements (e.g., the cubic structure of salts like NaCl, KCl, LiF, NaI, etc.). The formation and reactions of acids and bases, carbonates, sulfates, and others could all be systematized based on the patterns seen in elemental properties. But there was no underlying concept to tie all of these patterns together coherently. The underlying concept turned out to be related to the atomic weights of the elements. (The atomic weight is a measure of the relative mass of an element's atom, based on some agreed-upon standard.) The nineteenth century chemists realized that the atomic weight of an element is a fundamentally important quantity, and they spent considerable effort to measure it well. Such measurements were very difficult, however, and the tabulated atomic weights remained very uncertain in many cases even toward the end of the century.

Relationships between chemical properties and atomic weights were noted as early as 1817, when a German chemist named Dobereiner de-
vised a system of “triads.” He observed that for various sets of chemically similar elements, the atomic weight of one is the average of the atomic weights of the other two (e.g., Ca is the average of Mg and Sr). In the following decades, a variety of relationships between chemical properties and atomic weights were proposed. Between 1862 and 1870, six different scientists devised periodic systems that were similar in conception to that used today. The most famous of these scientists, who is usually credited with the discovery of the periodic table of the elements, was Dmitri Mendeleev. The periodicity of the relationship between the atomic weights and the properties of elements was strongly hinted at by the known properties of the lighter elements, which seemed to recur in a cycle of eight (John Newlands in England referred to this in 1865 as the law of octaves). But not all of the elements fit into such a system; given the presence of discrepancies, many skeptics attributed the seeming pattern to coincidence. What set Mendeleev apart from the other investigators of this problem was his dogged determination to have a system that really worked and his vast detailed knowledge of the chemical and physical properties of virtually every known element.

Many of those properties he measured himself. Other properties he found by combing through the chemistry literature, always keeping up-to-date with the very latest work. In addition to reading the published work, Mendeleev kept up a lively correspondence with other chemists in order to make sure that he had the very best information about the elements. He was especially scrupulous about having the most accurate atomic weights possible, since these weights were the key variable in the periodic system. For Mendeleev, every single element was like a close friend whom he knew well. All of the information he gathered was written down on a little white card, one card for each element. Each new chemical fact he learned was added to the appropriate card. As Mendeleev slowly worked out the correct pattern for the variation of the elements’ properties, he hung the cards on his wall in the proper order, moving them around as he got new ideas and updated information. Slowly, the patterns came to make more and more sense, and Mendeleev was able to apprehend a unified order amidst the multiplicity of elemental properties; he announced his periodic system of the elements in 1869. As the pieces of the puzzle fell into place and Mendeleev was able to fit most of the elements into his system, he became more confident. Because his work was grounded in an intimate knowledge of the elements, which included many thousands of pieces of factual information, this work was built on a sturdy foundation. After many years of work, the pattern seemed to be authentic and the system seemed complete barring a few exceptions. Mendeleev then became extremely confident. He became so confident, in fact, that he took an unprecedented action: Mendeleev claimed that the accepted atomic weights of several elements were wrong because they did not fit into his periodic system. He proposed changing the atomic weights of indium, uranium, cerium, and titanium so that these elements would fall into their proper place in the pattern. These changes weren’t made in order to cheat by brushing exceptions under the rug; on the contrary, Mendeleev proposed these new atomic weights as bold predictions of his system, which could be experimentally tested to verify or refute the periodic law. After many careful measurements had been made, Mendeleev’s predictions were in fact largely verified.

Mendeleev made another set of predictions that were even more dramatic. His periodic table contained a number of blank spaces. Mendeleev declared that these blank spaces must correspond to elements as yet undiscovered. By using the periodic table, the thorough Russian chemist was able to predict the atomic weights of the unknown elements and to provide a long detailed list of the chemical and physical properties that these predicted elements would possess. The new (still undiscovered) elements were named after the elements with analogous properties above them in the table, for example ekasilicon and ekaluminum. Just a few years later (in 1875), a new element was discovered in France with an atomic weight and set of properties matching the predictions for ekaluminum; we now know this element as gallium, named after its country of origin. Another new element, named germanium, was later discovered and matched with ekasilicon in atomic weight, physical properties, and chemistry. Few could doubt the correctness of the periodic law after this. Mendeleev lived to see a number of his predictions verified. Another stunning verification of the system, however, could not have been predicted. When the first inert gas was discovered (argon; see chapter 4), it didn’t fit anywhere in the periodic system. But a whole set of such inert gases were soon found, and they filled up a whole new column placed between the halogens and the alkali metals, with atomic weights that were just right to keep the period system intact. The most recent additions to the periodic table are the short-lived artificial elements of very high atomic weight, one of which is named mendelevium in honor of the discoverer of the periodic law.

Actually, a number of people discovered some version of the periodic law at roughly the same time. New versions have also been devised since then. An explanation for the amazing regularity in the elements was found after Mendeleev died by Bohr, Pauli, and others (see chapter 18). Mendeleev was not the first to note these regularities and did not explain them. What Mendeleev is justly honored for is the discovery of a pattern incorporating such a wealth of factual detail that it had to be real.
§2. Drifting Continents

If you look at a world map or globe, you may be struck by how the coastlines of Africa and Europe (on the eastern side of the Atlantic Ocean) seem to match up with the coastline of the Americas (on the western side). It's not a perfect fit, of course, but the correspondence of these coastlines is striking enough to have fired the imagination of several writers. A number of people before the twentieth century had speculated that these continents might have once been joined together. In 1910, this thought crossed the mind of Alfred Wegener. The major difference between Wegener and the other people who had noticed this fit between the continents is that Wegener looked into the matter more closely. He studied the geology of the African and South American coastal regions, and learned about the plants and animals living there. Paleontologists had collected a lot of information about the fossils of plants and animals that had once lived on these coasts, and Wegener also studied this fossil record. Much of the information fit together like the pieces of a puzzle, and Wegener became convinced that these continents had once been joined together, 250 million years ago. Since then, they have been drifting apart to their present positions. It turns out that similar correspondences exist between the coasts of east Africa and India.

The idea of continental drift was not accepted by very many people when Wegener proposed it. After all, the thought of continents drifting around like icebergs is rather absurd by common sense standards, and probably aroused opposition for that reason alone. But even on strictly scientific grounds (logic and evidence), there were good reasons not to believe. An alternate explanation for the similarities in geology, fossil record, and plant/animal life had already been advanced and was widely held. This alternate theory assumed that land bridges connected the continents in the past, and these bridges have now sunk under the oceans. Meanwhile, there was a major problem with the drift theory: no mechanism was known that could account for the huge forces that might cause continents to move. Wegener had in fact proposed such a mechanism, but it was easy to show that his proposal must be wrong. He speculated that small differences in gravity between poles and equator might be combined with tidal forces to move the continents. These forces, however, are millions of times too small for this job. Critics of continental drift, ignoring the vast amount of empirical support Wegener had presented, dismissed the theory because his mechanism seemed so clearly wrong.

Wegener admitted that his mechanism was speculative, but he insisted that the evidence in favor of moving continents was strong (whatever the mechanism may turn out to be). Sinking land masses (in other words, the proposed former bridges) made no sense to him. Land masses are higher (continents) because they are less dense or lower (ocean floors) because they are more dense. Large land mass areas wouldn't sink or rise at random. Also, certain life forms were found only in a narrow range near both coasts. Surely detached and drifting continents explained this fact better than a vast former land bridge. Finally, Wegener's theory explained why the climates of the continents had been so very different in the distant past (namely, these continents had been located at very different places on the earth's surface then). The opponents of drift also had some good arguments. For example, the lower crust of the earth is not fluid enough to allow the upper crust to move. In their judgement, the geological and paleontological evidence was too fragmentary and incomplete to prove the case for drift. These opponents also charged that many of Wegener's coastal fits were not as good as he claimed (the opponents were mistaken in this case; Wegener had quite rightly used the boundaries of the continental shelf rather than the coastline itself).

As you can see, both sides of the controversy had some good arguments. The pieces of the puzzle could be fit together in more than one way, and there was no definite choice as to which picture was correct. Wegener had a few influential allies in the scientific world, but his opponents were both influential and also far more numerous. Wegener's theory was a radical innovation, and the majority of people in the scientific community were not prepared to accept it without decisive proof. More pieces of the puzzle were needed.

One major missing piece, obviously, was a credible mechanism to drive the drift process. Such a mechanism was actually proposed as early as 1928 by Arthur Holmes: convection currents (see chapter 17) in the earth's mantle. The idea is based on a well-known fact, namely, that the earth's interior is continually heated by radioactivity. This heat must somehow escape from deep inside the earth. Holmes proposed that the heat moves upward in a convection current (i.e., fluid mantle material carrying the heat as it moves) that then flows sideways along the boundary with the crust and eventually flows back downward (where it heats up again to renew the cycle). As the mantle convection current moves along under the crust, the crust is carried along with it like a ship carried by a water current. Interestingly, this work did not attract much support for the idea of continental drift. Perhaps the concept had been too thoroughly dismissed by that time for anyone to think seriously about it. And of course, the convection currents themselves were still unproven ideas. Few scientists are willing to give up lightly the ideas on which their entire careers are based. In any event, Wegener had little support for his theory when he died in 1930 during an expedition to Greenland. The new pieces
of the puzzle needed to support drift theory would be empirical, not conceptual. These pieces would not be found for several decades, in unexplored territory at the bottom of the oceans.

Almost nothing was known about the ocean floor before 1940, with one exception. A major mountain had been discovered in the middle of the Atlantic Ocean (the Mid-Atlantic Ridge) when the first telegraph cables were strung from America to Europe. After World War II, a great deal of effort was expended using newly available technologies (like sonar, deep-sea core sampling, and seismography) to learn about the bottom of the sea. The result of this research revolutionized our thinking. The Mid-Atlantic Ridge turned out to be part of a worldwide system of undersea mountain chains. Remarkably, these mountains have at their heart a huge chasm, about one mile deep and twenty miles wide. This rift is a major source of seismic and volcanic activity. Another amazing discovery was that the ocean floors are quite young (by geological standards, anyway). No fossils or rocks older than a few hundred million years could be found. This may sound old, but the long-held idea of geologists was that the ocean floor must be among the oldest places on earth, undisturbed for perhaps billions of years. The composition of the ocean floor was also unexpected, being mostly basaltic rocks in contrast to the mostly granitic rocks making up the continents. These surprising results were very difficult to explain.

An explanation that integrates all of these new facts was proposed around 1960 by Harry Hess. Termed "sea-floor spreading," the idea is that new material is continuously welling up (from the earth's interior) in the great oceanic rifts. This new rock is added to the ocean floor as it comes up, pushing the previously added rock outward from the rift. The sea floor is being newly created and spreading outward (from the rift) all the time. The engine driving this process is the mantle convection mechanism that we've already considered. Meanwhile, the continents ride along on the spreading sea floor like boxes on a conveyor belt. In this way, new ideas that were proposed in order to explain perplexing new oceanographic facts also implied the reality of continental drift. At the same time these new explorations of the ocean floor were going on, other geologists were engaged in studying a very different field: paleomagnetism. The basic idea is simple. If lava contains magnetic minerals, those minerals will line up with the earth's magnetic field like a compass needle to point toward the magnetic North Pole. As the lava cools and solidifies, these pointers will be frozen in place and keep their original direction forever. If you go to various locations on the earth's surface, you might then expect to find the magnetic orientation of the rocks pointing toward the North Pole. Geologists did indeed expect this result. Instead, they discovered a variety of different directions. This work is complicated, because you have to be sure the rock hasn't been moved (by earthquakes, water, etc.) since the lava cooled. Eventually, a great deal of work led to a consensus that the differences in direction were real. The perplexing conclusion seemed to be that the North Pole wanders around over geological time periods.

But there is another way to interpret this data. Perhaps it is not the Pole that is wandering; perhaps the continents are wandering. Based on this hypothesis that the continents are moving with respect to the North Pole, geologists compared the magnetic directions of the rocks at many geographic locations and time periods to figure out the motions that the continents must have had. The results were astounding. Based on this study of fossil magnetism, the continents must have moved in just the way that Wegener had claimed that they moved. Another piece of the pattern fell into place. Oceanography and paleomagnetism then joined forces to produce a striking confirmation of the picture that was emerging. Magnetic studies of rocks, on both the continental land masses and the ocean floor, revealed another initially confusing fact: a complete reversal of the magnetic direction for some rocks. This magnetic reversal is found to occur simultaneously at many places on the earth, and it has taken place more than once. In other words, the magnetic poles periodically flip places (this field reversal is a well-confirmed empirical fact, but we still don't fully understand why it happens). What does this magnetic reversal have to do with our story about continental drift?

The magnetic studies of the ocean floor, near the great oceanic rifts, revealed another strange pattern. Stripes of sea floor, hundreds of miles wide and running parallel to the rifts, contained rock with the same magnetic orientation. As you move out away from the rift, the stripes alternate in their orientation (imagine a map with North-pointing rock colored black and South-pointing rock colored white; this map will look a bit like a zebra). Once you realize that the earth's magnetic field periodically reverses itself, however, this seemingly bizarre result begins to make perfect sense. In fact, this result is a startling vindication of the theory of seafloor spreading. The fresh lava emerges from the rift to create new ocean bottom. As the lava cools, it freezes in the direction of the earth's field. As time progresses, the new rock moves outward, creating one of the observed stripes. When the field reverses, creation of a new stripe begins. As the field reverses periodically, a pattern of alternating stripes is created. The theory predicts exactly what we observe. All of the puzzle pieces had now been found. The time was ripe for geologists to assemble all of these pieces into a coherent picture. This was accomplished in the middle of the 1960s by a number of people, the key player perhaps being Tuzo Wilson. The resulting picture, a synthesis of all available information, is what we now call plate tectonics. The continents ride on giant pieces of the earth's crust called plates. The plates themselves fit together on the earth's surface
like the pieces of a puzzle. The bottoms of these plates reach down into
the mantle to a region (called the asthenosphere), which is more plastic
and fluidlike due to the high temperature. This region is where the great
convection currents exist, slowly driving the movements of the plates. The
oceanic rifts, the Pacific “ring of fire,” and other unstable regions of high
volcanic and seismic activity are plate boundaries where the mantle mate-
rial is welling up or sinking down. The continental mountain ranges are
the result of momentous collisions between the plates. Plate tectonics is
now one of the fundamental organizing principles of modern geology.

FOR FURTHER READING

Famous Chemists, by W. A. Tilden, George Routledge & Sons, 1921.
The Periodic System of Chemical Elements, by J. W. van Sponsen, Elsevier,
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Chapter 3
NEW VISTAS: EXPANDING OUR WORLD
WITH INSTRUMENTATION

Not only do we use instruments to give us fineness of detail
inaccessible to direct sense perception, but we also use them
to extend qualitatively the range of our senses into regions
where our senses no longer operate. . . .

(P. W. Bridgman)

WE EXTEND our powers of observation by the use of instru-
ments. We sometimes increase the range of our senses into
new regimes of size or intensity, but we can also do more than
just magnify our usual means of perceiving the world. By using ap-
propriate instruments, we can even “observe” new phenomena that our
senses can’t detect at all. Chemists, for example, learn about the motions
of atoms within a molecule by measuring the infrared rays that a molecule
emits but our eyes can’t see. Beyond extending the range of our senses,
there is another way in which instruments help us discover new things.
Instruments can also create new and exotic conditions under which to do
experiments and make observations. (In technical jargon, instruments can
extend the range of an independent variable.) For example, the behavior
of matter undergoes fascinating transformations at extremes (very high
and very low) of temperature, pressure, energy, and so on. A famous par-
ticular case is graphite (pencil lead) turning into diamond at very high
pressures and temperatures. In this chapter, we’ll look in more detail at
some examples of discoveries made by using new instrumentation to ex-
tend the range of our observations. It may happen that only marginal

 gains are made by such extensions; we learn a little more, increase our
precision, tidy up a few details. But sometimes, dramatic new discoveries
are made in these new territories and totally unsuspected phenomena
emerge. The examples I’ve chosen mostly illustrate the latter, more dra-
matic, cases. Not only are such cases more interesting, but I think they
are also more typical.