SCIENTIFIC CULTURE,

AND OTHER ESSAYS.

BY

JOSIAH PARSONS COOKE, LL. D.,

PROFESSOR OF CHEMISTRY AND MINERALOGY, IN HARVARD COLLEGE.

SECOND EDITION; WITH ADDITIONS.

NEW YORK:

D. APPLETON AND COMPANY,

1, 3, AND 5 BOND STREET.

1885.

TO

MY ASSOCIATES

IN

THE CHEMICAL LABORATORY

OF

HARVARD COLLEGE

THIS VOLUME

IS

AFFECTIONATELY DEDICATED.

PREFACE.

The essays collected in this volume, although written for special occasions without reference to each other, have all a bearing on the subject selected as the title of the volume, and are an outcome of a somewhat large experience in teaching physical science to college students. Thirty years ago, when the writer began his work at Cambridge, instruction in the experimental sciences was given in our American colleges solely by means of lectures and recitations. Chemistry and Physics were allowed a limited space in the college curriculum as branches of useful knowledge, but were regarded as wholly subordinate to the classics and mathematics as a means of education; and as physical science was then taught, there can be no question that the accepted opinion was correct. Experimental science can never be made of value as a means of education unless taught by its own methods, with the one great aim in view to train the faculties of the mind so as to enable the educated man to read the Book of Nature for himself.

Since the period just referred to, the example early set at Cambridge of making the student's own observations in the laboratory or cabinet the basis of all teaching, either in experimental or natural history science, has been generally followed. But in most centers of education the old traditions so far survive that the great end of scientific culture is lost in attempting to conform even laboratory instruction to the old academic methods of recitations and examinations. These, as usually conducted, are simply hindrances in a course of scientific training, because they are no tests of the only ability or acquirement which science values, and therefore set before the student a false aim. To point out this error, and to claim for science teaching its appropriate methods, was one object of the writer in these essays.

It is, however, too often the case that, in following out our theories of education, we avoid Scylla only to encounter Charybdis, and so, in specializing our courses of laboratory instruction, there is great danger of falling into the mechanical routine of a technical art, and losing sight of those grand ideas and generalizations which give breadth and dignity to scientific knowledge. That these great truths are as important an element of scientific culture as experimental skill, the author has also endeavored to illustrate, and he has added brief notices of the lives of two noble men of science which may add force to the illustrations.

CONTENTS.

ESSAYS.

I.

SCIENTIFIC CULTURE.

An Address delivered July 7, 1875, at the Opening of the Summer Courses of Instruction in Chemistry, at Harvard University.

You have come together this morning to begin various elementary courses of instruction in chemistry and mineralogy. As I have been informed, most of you are teachers by profession, and your chief object is to become acquainted with the experimental methods of teaching physical science, and to gain the advantages in your study which the large apparatus of this university is capable of affording.

In all this I hope you will not be disappointed. You, as teachers, know perfectly well that success must depend, first of all, on your own efforts; but, since the methods of studying Nature are so different from those with which you are familiar in literary studies, I feel that the best service I can render, in this introductory address, is to state, as clearly as I can, the great objects which [Pg 5] should be kept in view in the courses on which you are now entering.

By your very attendance on these courses you have given the strongest evidence of your appreciation of the value of chemical studies as a part of the system of education, and let me say, in the first place, that you have not overvalued their importance. The elementary principles and more conspicuous facts of chemistry are so intimately associated with the experience of every-day life, and find such important applications in the useful arts, that no man at the present day can be regarded as educated who is ignorant of them. Not to know why the fire burns, or how the sulphur trade affects the industries of the world, will be regarded, by the generation of men among whom your pupils will have to win their places in society, as a greater mark of ignorance than a false quantity in Latin prosody or a solecism in grammar.

Moreover, I need not tell you that physical science has become a great power in the world. Indeed, after religion, it is the greatest power of our modern civilization. Consider how much it has accomplished during the last century toward increasing the comforts and enlarging the intellectual vision of mankind. The railroad, the steamship, the electric telegraph, photography, gaslights, petroleum oils, coal-tar colors, chlorine bleaching, anæsthesia, are a few of its recent [Pg 6] material gifts to the world; and not only has it made one pair of hands to do the work of twenty, but it has so improved and facilitated the old industries that what were luxuries to the fathers of our republic have become necessities to our generation.

And when, passing from these material fruits, you consider the purely intellectual triumphs of physical science, such as those which have been gained with the telescope, the microscope, and the spectroscope, you can not wonder at the esteem in which these branches of study are held in this practical age of the world.

Now, these immense results have been gained by the application to the study of Nature of a method which was so admirably described by Lord Bacon in his "Novum Organon," and which is now generally called the experimental method. What we observe in Nature is an orderly succession of phenomena. The ancients speculated about these phenomena as well as ourselves, but they contented themselves with speculations, animating Nature with the products of their wild fancies. Their great master, Aristotle, has never been excelled in the art of dialectics; but his method of logic applied to the external world was of very necessity an utter failure. It is frequently said, in defense of the exclusive study of the records of ancient learning, that they are the products of thinking, loving, and hating men, like ourselves, and it is claimed that the study of [Pg 7] science can never rise to the same nobility because it deals only with lifeless matter. But this is a mere play on words, a repetition of the error of the old schoolmen.

Physical science is noble because it does deal with thought, and with the very noblest of all thought. Nature at once manifests and conceals an Infinite Presence: her methods and orderly successions are the manifestations of Omnipotent Will; her contrivances and laws the embodiment of Omniscient Thought. The disciples of Aristotle so signally failed simply because they could see in Nature only a reflection of their idle fancies. The followers of Bacon have so gloriously succeeded because they approached Nature as humble students, and, having first learned how to question her, have been content to be taught and not sought to teach. The ancient logic never relieved a moment of pain, or lifted an ounce of the burden of human misery. The modern logic has made a very large share of material comfort the common heritage of all civilized men.

In what, then, does this Baconian system consist? Simply in these elements: 1. Careful observation of the conditions under which a given phenomenon occurs; 2. The varying of these conditions by experiments, and observing the effects produced by the variation. We thus find that [Pg 8] some of the conditions are merely accidental circumstances, having no necessary connection with the phenomenon, while others are its invariable antecedent. Having now discovered the true relations of the phenomenon we are studying, a happy guess, suggested probably by analogy, furnishes us with a clew to the real causes on which it depends. We next test our guess by further experiments. If our hypothesis is true, this or that must follow; and, if in all points the theory holds, we have discovered the law of which we are in search. If, however, these necessary inferences are not realized, then we must abandon our hypothesis, make another guess, and test that in its turn. Let me illustrate by two well-known examples:

The, of old, universally accepted principle that all living organisms are propagated by seeds or germs (*omnia ex ovo*) has been seriously questioned by a modern school of naturalists. Various observers have maintained that there were conditions under which the lower forms of organic life were developed independently of all such accessories, but other, and equally competent, naturalists, who have attempted to investigate the subject, have obtained conflicting results.

Thus it was observed that certain low forms of life were quite constantly developed in beef juice that had been carefully prepared and hermetically sealed in glass flasks, even after these flasks [Pg 9] had been exposed for a long time to the temperature of boiling water. "Here," proclaims the new school, "is unmistakable evidence of spontaneous generation; for, if past experience is any guide, all germs must have been killed by the boiling water." "No," answer the more cautious naturalists, "you have not yet proved your point. You have no right to assume that all germs are killed at this temperature."

The experiments, therefore, were repeated under various conditions and at different temperatures, but with unsatisfactory results, until Pasteur, a distinguished French physicist, devised a very simple mode of testing the question. He reasoned thus: "If, as is generally believed, the presence of invisible spores in the air is an essential condition of the development of these lower growths, then their production must bear some proportion to the abundance of these spores. Near the habitations of animals and plants, where the spores are known to be in abundance, the development would be naturally at a maximum, and we should expect that the growth would diminish in proportion as the microscope indicated that the spores diminished in the atmosphere."

Accordingly, Pasteur selected a region in the Jura Mountains suitable for his purpose, and repeated the well-known experiment with beef juice, first at the inn of a town at the foot of the [Pg 10] mountains, and then at various elevations up to the bare rocks which covered the top of the ridge, a height of some eight thousand feet. At each point he sealed up beef juice in a large number of flasks, and watched the result. He found that while in the town the animalcules were developed in almost all the flasks, they appeared only in two or three out of a hundred cases where the flasks had been sealed at the top of the mountain, and to a proportionate extent in those sealed at the intermediate elevations. What, now, did these experiments prove? Simply this, that the development of these organic forms was in direct proportion to the number of germs in the air. It did not settle the question of spontaneous generation, but it showed that false conclusions had been deduced from the experiments which had been cited to prove it.

A still more striking illustration of the same method of questioning Nature is to be found in the investigation of Sir Humphry Davy, on the composition of water. The voltaic battery which works our telegraphs was invented by Volta in 1800; and later, during the same year, it was discovered in London, by Nicholson and Carlisle, that this remarkable instrument had the power of decomposing water. These physicists at once recognized that the chief products of the action of the battery on water were hydrogen and oxygen gases, thus confirming the results of Cavendish, [Pg 11] who, in 1781, had obtained water by combining these elementary substances; oxygen having been previously discovered in 1775, and hydrogen, at least, as early as 1766. It was, however, very soon also observed that there were always formed by the action of the battery on water, besides these aëriform products, an alkali and an acid, the alkali collecting around the negative pole, and the acid around the positive pole of the electrical combination. In regard to the nature of this acid and alkali, there was the greatest difference of opinion among the early experimenters on this subject. Cruickshanks supposed that the acid was nitrous acid, and the alkali ammonia. Desormes, a French chemist, attempted to prove that the acid was muriatic acid; while Brugnatelli asserted that a new and peculiar acid was formed, which he called the electric acid.

It was in this state of the question that Sir Humphry Davy began his investigation. From the analogies of chemical science, as well as from the previous experiments of Cavendish and Lavoisier, he was persuaded that water consisted solely of oxygen and hydrogen gases, and that the acid and alkali were merely adventitious products. This opinion was undoubtedly well founded; but, great disciple of Bacon as he was, Davy felt that his opinion was worth nothing unless substantiated by experimental evidence, and accordingly he set himself to work to obtain [Pg 12] the required proof.

In Davy's first experiments the two glass tubes which he used to contain the water were connected together by an animal membrane, and he found, on immersing the poles of his battery in their respective tubes, that, besides the now well-known gases, there were really formed muriatic acid in one tube, and a fixed alkali in the other. Davy at once, however, suspected that the acid and alkali came from common salt contained in the animal membrane, and he therefore rejected this material and connected the glass tubes by carefully washed cotton fiber, when, on submitting the water as before to the action of the voltaic current, and continuing the experiment through a great length of time, no *muriatic* acid appeared; but he still found that the water in the one tube was strongly alkaline, and in the other strongly acid, although the acid was chiefly, at least, nitrous acid. A part of the acid evidently came from the animal membrane, but not the whole, and the source of the alkali was as obscure as before.

Davy then made another guess. He knew that alkali was used in the manufacture of glass; and it occurred to him that the glass of the tubes, decomposed by the electric current, might be the origin of the alkali in his experiments. He therefore substituted for the glass tubes cups of agate, [Pg 13] which contains no alkali, and repeated the experiment, but still the troublesome acid and alkali appeared. Nevertheless, he said, it is possible that these products may be derived from some impurities existing in the agate cups, or adhering to them; and so, in order to make his experiments as refined as possible, he rejected the agate vessels and procured two conical cups of pure gold, but, on repeating the experiments, the acid and alkali again appeared.

And now let me ask who is there of us who would not have concluded at this stage of the inquiry that the acid and alkali were essential products of the decomposition of water? But not so with Davy. He knew perfectly well that all the circumstances of his experiments had not been tested, and until this had been done he had no right to draw such a conclusion. He next turned to the water he was using. It was distilled water, which he supposed to be pure, but still, he said, it is possible that the impurities of the spring-water may be carried over to a slight extent by the steam in the process of distillation, and may therefore exist in my distilled water to a sufficient amount to have caused the difficulty. Accordingly, he evaporated a quart of this water in a silver dish, and obtained seven-tenths of a grain of dry residue. He then added this residue to the small amount of water in the gold cones and again repeated the experiment. The proportion of alkali [Pg 14] and acid was sensibly increased.

You think he has found at last the source of the acid and alkali in the impurities of the water. So thought Davy, but he was too faithful a disciple of Bacon to leave this legitimate inference unverified. Accordingly, he repeatedly distilled the water from a silver alembic until it left absolutely no residue on evaporation, and then with water which he knew to be pure, and contained in vessels of gold from which he knew it could acquire no taint, he still again repeated the already well-tried experiment. He dipped his test-paper into the vessel connected with the positive pole, and the water was still decidedly acid. He dipped the paper into the vessel connected with the negative pole, and the water was still alkaline.

You might well think that Davy would have been discouraged here. But not in the least. The path to the great truths which Nature hides often leads through a far denser and a more bewildering forest than this; but then there is not infrequently a "blaze" on the trees which points out the way, although it may require a sharp eye in a clear head to see the marks. And Davy was well enough trained to observe a circumstance which showed that he was now on the right path and heading straight for the goal.

[Pg 15] On examining the alkali formed in this last experiment, he found that it was not, as before, a fixed alkali, soda or potash, but the volatile alkali ammonia. Evidently the fixed alkali came from the impurities of the water, and when, on repeating the experiment with pure water in agate cups or glass tubes, the same results followed, he felt assured that so much at least had been established. There was still, however, the production of the volatile alkali and of nitrous acid to be accounted for. As these contain only the elements of air and water, Davy thought that possibly they might be formed by the combination of hydrogen at the one pole and of oxygen at the other with the nitrogen of the air, which was necessarily dissolved in the water. In order, therefore, to eliminate the effect of the air, he again repeated the experiment under the receiver of an air-pump from which the atmosphere had been exhausted, but still the acid and alkali appeared in the two cups.

Davy, however, was not discouraged by this, for the "blazes" on the trees were becoming more numerous, and he now felt sure that he was fast approaching the end. He observed that the quantity of acid and alkali had been greatly diminished by exhausting the air, and this was all that could be expected, for, as Davy knew perfectly well, the best air-pumps do not remove all the air. He therefore, for the last experiment, not only exhausted the air, but replaced it with pure hydrogen, and then exhausted the hydrogen and refilled the receiver with the same gas several [Pg 16] times in succession, until he was perfectly sure that the last traces of air had been as it were washed out. In this atmosphere of pure hydrogen he allowed the battery to act on the water, and not until the end of twenty-four hours did he disconnect the apparatus. He then dips his test-paper into the water connected with the positive pole, and there is no trace of acid; he dips it into the water at the negative pole, and there is no alkali; and you may judge with what satisfaction he withdraws those slips of test-paper, whose unaltered surfaces showed that he had been guided at last to the truth, and that his perseverance had been rewarded.

The fame of Sir Humphry Davy rests on his discovery of the metals of the alkalies and earths which first revealed the wonderful truth that the crust of our globe consists of metallic cinders; but none of these brilliant results show so great scientific merit or such eminent power of investigating Nature as the experiments which I have just detailed. I have not, however, described them here for the purpose of glorifying that renowned man. His honored memory needs no such office at my hands. My only object was to show you what is meant by the Baconian method of science, and to give some idea of the nature of that modern logic which within the last [Pg 17] fifty years has produced more wonderful transformations in human society than the author of

Aladdin ever imagined in his wildest dreams. In this short address I can of course give you but a very dim and imperfect idea of what I have called the Baconian system of experimental reasoning. Indeed, you can not form any clear conception of it, until in some humble way you have attempted to use the method, each one for himself, and you have come here in order that you may acquire such experience.

My object, however, will be gained if these illustrations serve to give emphasis to the following statements, which I feel I ought to make at the opening of these courses of instruction—statements which have an especial appropriateness in this place, since I am addressing teachers, who are in a position to exert an important influence on the system of education in this country.

In the first place, then, I must declare my conviction that no educated man can expect to realize his best possibilities of usefulness without a practical knowledge of the methods of experimental science. If he is to be a physician, his whole success will depend on the skill with which he can use these great tools of modern civilization. If he is to be a lawyer, his advancement will in no small measure be determined by the acuteness with which he can criticise the manner in which the same tools have been used by his own or his opponent's clients. If he is to be a clergyman, he [Pg 18]
must take sides in the great conflict between theology and science which is now raging in the world, and, unless he wishes to play the part of the doughty knight Don Quixote, and think he is winning great victories by knocking down the imaginary adversaries which his ignorance has set up, he must try the steel of his adversary's blade.

Let me be fully understood. It is not to be expected or desired that many of our students should become professional men of science. The places of employment for scientific men are but few, and more in the future than in the past they will naturally be secured by those whom Nature has endowed with special aptitudes or tastes—usually the signs of aptitudes—to investigate her laws. That our country will always offer an honorable career to her men of genius, we have every reason to expect, and these born students of Nature will usually follow the plain indications of Providence without encouragement or direction from us.

It is different, however, with the great body of earnest students who are conscious of no special aptitudes, but who are desirous of doing the best thing to fit themselves for usefulness in the world; and I feel that any system of education is radically defective which does not comprise a sufficient training in the methods of experimental science to make the mass of our educated men [Pg 19]
familiar with this tool of modern civilization: so that, when, hereafter, new conquests over matter are announced and great discoveries are proclaimed, they may be able not only to understand but also to criticise the methods by which the assumed results have been reached, and thus be in a position to distinguish between the true and the false. Whether we will or not, we must live under the direction of this great power of modern society, and the only question is whether we will be its ignorant slave or its intelligent servant.

In the second place, it seems fitting that I should state to you what I regard as the true aims to be kept in view in a course of scientific study, and to give my reasons for the methods we have adopted in arranging the courses you are about beginning.

In our day there has arisen a warm discussion as to the relative claims of two kinds of culture, and attempts are made to create an antagonism between them. But all culture is the same in spirit. Its object is to awaken and strengthen the powers of the mind; for these, like the muscles of the body, are developed and rendered strong and active only by exercise; while, on the other hand, they may become atrophied from mere want of use. Science culture differs in its methods from the old classical culture, but it has the same spirit and the same object. You must not, [Pg 20]
therefore, expect me to advocate the former at the expense of the latter; for, although I have labored assiduously during a quarter of a century to establish the methods of science teaching which have now become general, I am far from believing that they are the only true modes of obtaining a liberal education. So far from this, if it were necessary to choose one of two systems, I should favor the classical; and why?

Language is the medium of thought, and can not be separated from it. He who would think well must have a good command of language, and he who has the best command of language I am almost tempted to say will think the best. For this reason a certain amount of critical study of language is essential for every educated man, and such study is not likely to be gained except through the great ancient languages; the advocates of classical scholarship frequently say, can not be gained. I am not ready to accept this dictum; but I most willingly concede that in the present state of our schools it is not likely to be gained. I never had any taste myself for classical studies; but I know that I owe to the study a great part of the mental culture which has enabled me to do the work that has fallen to my share in life.

But, while I concede all this, I do not believe, on the other hand, that the classical is the only effective method of culture; you evidently do not think so, for you would not be here if you did. [Pg 21]
But, in abandoning the old tried method, which is known to be good, for the new, you must be careful that you gain the advantages which the new offers; and you will not gain the new culture you seek unless you study science in the right way. In the classical departments the methods are so well established, and have been so long tested by experience, that there can hardly be a wrong way. But in science there is not only a wrong way, but this wrong way is so easy and alluring that you will most certainly stray into it unless you strive earnestly to keep out of it. Hence I am most anxious to point out to you the right way, and do what I can to keep you in it; and you will find that our courses and methods have been devised with this object.

When advocating in our mother University of Cambridge, in Old England, the claims of scientific culture, I was pushed with an argument which had very great weight with the eminent English scholars present, and which you will be surprised to learn was regarded as fatal to the success of the science "triposes" then under debate. The argument was that the experimental sciences could not be made the subjects of competitive examinations. Some may smile at such an objection; but, as viewed from the English standpoint, there was really a great deal in it, and the argument brought out the radical difference between scientific and classical culture. [Pg 22]

The old method of culture may be said to have culminated in the competitive examinations of the English universities. We have no such examinations here. Success depends not simply on knowing your subject thoroughly, but on having it at your fingers' ends, and those fingers so agile that they can accomplish not only a prodigious amount of work in a short time, but can do this work with absolute accuracy. For the only approach we make to an experience of this kind, we must look to our athletic contests. It may of course be doubted whether the ability, once in a man's life, to perform such mental feats, is worth what it costs. Still it implies a very high degree of mental culture, and it is perfectly certain that the experimental sciences give no field for that sort of mental prize-fights. It is easy to prepare written examinations which will show whether the students have been faithful to their work, but they can not be adapted to such competitions as I have described without abandoning the true object of science culture. The ability of the scientific student can only be shown by long-continued work at the laboratory table, and by his success in investigating the problems which Nature presents.

We have here struck the true key-note of the scientific method. The great object of all our study should be to study Nature, and all our methods should be directed to this one object. This aim alone will ennoble our scholarship as students, and will give dignity to our scientific calling as [Pg 23] men of science. It is this high aim, moreover, which vindicates the worth of the mode of culture we have chosen. What is it that ennobles literary culture but the great minds which, through this culture, have honored the nations to which they belong?

The culture we have chosen is capable of even greater things; not because science is nobler than art, for both are equally noble—it is the thought, the conception, which ennobles, and I care not whether it be attained through one kind of exercise of the mental faculties or another—but we are capable of grander and nobler thoughts than Plato, Cicero, Shakespeare, or Newton, because we live in a later period of the world's history, when, through science, the world has become richer in great ideas. It is, I repeat, the great thought which ennobles, and it ennobles because it raises to a higher plane that which is immortal in our manhood.

If I have made my meaning clear, and if you sympathize with my feelings, you will understand why I regard culture as so important to the individual and to the nation. The works of Shakespeare and of Bacon are of more value to England to-day than the memories of Blenheim or Trafalgar; and those great minds will still be living powers in the world when Marlborough and Nelson are only remembered as historical names. [Pg 24]

I therefore believe that it is the first duty of a country to foster the highest culture, and that it should be the aim of every scholar to promote this culture both by his own efforts and his active influence. A nation can become really great in no other way. We live in a country of great possibilities; and the danger is that, as with many men I have known in college, of great potential abilities, the greatness will end where it begins. The scholars of the country should have but one voice in this matter, and urge upon the government and upon individuals the duty of encouraging and supporting mental culture for its own sake.

The time has passed when we can afford to limit the work of our higher institutions of learning to teaching knowledge already acquired. Henceforth the investigation of unsolved problems, and the discovery of new truth, should be one of the main objects at our American universities, and no cost grudged which is required to maintain at them the most active minds, in every branch of knowledge which the country can be stimulated to produce.

I could urge this on the self-interest of the nation as an obvious dictate of political economy. I could say, and say truly, that the culture of science will help us to develop those latent resources of which we are so proud; will enable us to grow two blades of grass where one grew before; to [Pg 25] extract a larger percentage of metal from our ores; to economize our coal, and in general to direct our waiting energies so that they may produce a more abundant pecuniary reward. I could tell of Galvani studying for twenty long years, to no apparent purpose, the twitching of frogs' hind-legs, and thus sowing the seed from which has sprung the greatest invention of modern times. Or, if our Yankee impatience would be unwilling to wait half a century for the fruit to ripen, I could point to the purely theoretical investigations of organic chemistry, which in less than five years have revolutionized one of the great industries of Europe, and liberated thousands of acres for a more beneficent agriculture. This is all true, and may be urged properly if higher considerations will not prevail. It is an argument I have used in other places, but I will not use it here; although I gladly acknowledge the Providence which brings at last even material fruits to reward conscientious labor for the advancement of knowledge and the intellectual elevation of mankind. I would rather point to that far greater multitude who worked in faith for the love of knowledge, and who ennobled themselves and ennobled their nation, not because they added to its material prosperity, but because they made themselves and made their fellows more noble men.

I come back now again to the moral of all this, to urge upon you, as the noblest patriotism and [Pg 26] the most enlightened self-interest, the duty of striving for yourselves and encouraging in others the highest culture in the studies you have chosen, and this culture with one end in view, to advance knowledge. I am far, of course, from advising you to grapple immaturely with unsolved problems, or, when you have gained the knowledge with which you can dare to venture from the beaten track, to undertake work beyond your power. Many a young scientific man has suffered the fate of Icarus in attempting to soar too high. Moreover, I am far from expecting that all or many of you will ever have the opportunity of going beyond the well-explored fields of knowledge; but you can all have the aim, and that aim will make your work more worthy and more profitable to yourselves. Every American boy can not be President of the United States, but if, as our English cousins allege, he believes that he can be, the very belief makes him an abler man.

We have dwelt long enough on these generalities, and it is time to come down to commonplaces, and to inquire what are the essential conditions of this scientific culture which shall fit us to investigate Nature; and the first thought that occurs to me in this connection may be expressed thus: Science presents to us two aspects, which I may call its objective and its subjective aspect. Objectively it is a body of facts, which we have to observe, and subjectively it is a body of truths, [Pg 27] conclusions, or inferences, deduced from these facts; and the two sides of the subject should always be kept in view.

I propose next to say a few words in regard to each of these two aspects of our study, and in regard to the best means of training our faculties so as to work successfully in each sphere. First, then, success in the observation of phenomena implies three qualities at least, namely, quickness and sharpness of perception, accuracy in details, and truthfulness; and on its power to cultivate these qualities a large part of the value of science, as a means of education, depends.

To begin with the cultivation of our perceptions. We are all gifted with senses, but how few of us use them to the best advantage! "We have eyes and see not"; for, although the light paints the picture on the retina, our dull perceptions give no attention to the details, and we retain only a confused impression of what has passed before our eyes. "But how," you may ask, "are we to cultivate this sharpness of perception?" I answer, only by making a conscious effort to fix our attention on the objects we study until the habit becomes a second nature. I have often noticed, with surprise, the power which uneducated miners frequently possess of recognizing many minerals at sight. This they have acquired by long experience and close familiarity with such [Pg 28] objects, and such power of observation is with them so purely a habit that they are frequently unable to state clearly the grounds on which their conclusions are based. They recognize the minerals by what in common language is called their "looks" and they notice delicate differences in the "looks" to which most men are blind. It is, however, the business of the scientific mineralogist to analyze these "looks," and to point out in what the differences consist; so that by fixing his attention on these points the student may gain, by a few hours' study, the power which the miner acquires only after long experience.

The chief difficulty, however, which we find in teaching mineralogy is, that the students do not readily see the differences when they are pointed out, or, if they see them, do not remember them with sufficient precision to render their subsequent observations conclusive and precise. This either arises from a failure to cultivate the powers of observation in childhood, or the subsequent blunting of them by disuse. The ladies will scout the idea that a brooch of cut-glass is as ornamental as one of diamond, and yet I venture to assert that there is not one person in fifty, at least of those who have not made a study of the subject, who can tell the difference between the two. The external appearance depends simply on what we call lustre. The lustre of glass is [Pg 29] vitreous, that of the diamond adamantine; and I know of no other distinction which it is more difficult for students to recognize than this. Those of you who study mineralogy will experience this difficulty, and it can be overcome only by giving careful attention to the subject. The teacher can do nothing more than put in your hands the specimens which illustrate the point, and you must study these specimens until you see the difference. It is a question of sight, not of understanding, and all the optical theories of the cause of the lustre will not help you in the least toward seeing the difference between diamond and glass, or anglesite and heavy spar.

Another illustration of the same fact is the constant failure of students to distinguish by the eye alone between the two minerals called copper-glance and gray copper. There is a difference of color and lustre which, although usually well marked, it requires an educated eye to distinguish.

Mineralogy undoubtedly demands a more careful cultivation of the perceptions than the other branches of chemistry; but still you will find abundant practice for close observation in them all. I have often known students to reach erroneous results in qualitative analysis by mistaking a white precipitate in a colored liquid for a colored precipitate, or by not attending to similar broad [Pg 30] distinctions, which would have been obvious to any careful observer; and so in quantitative analysis, mere delicacy of touch or handling is a great element of success.

But I must pass on to speak of the importance in the study of Nature of accuracy in detail, which is the second condition of successful observation of which I spoke. We must cultivate not only accuracy in observing details, but also accuracy in following details which have been laid down by others for our guidance. In science we can not draw correct conclusions from our premises unless we are sure that we have all the facts, and what seemed at first an unimportant detail often proves to be the determining condition of the result; and, again, if we are told that under certain conditions a certain sign is the proof of the presence of a certain substance, we have no right to assume that the sign is of any value unless the conditions are fulfilled. A black precipitate, for example, obtained under certain conditions, is a proof of the presence of nickel, but we can not assert that we have found nickel unless we have followed out those details in every particular.

Of course, we must avoid empiricism as far as we can. We must seek to learn the reasons of the details, and such knowledge will not only render our work intelligent, but will also frequently enable us to judge how far the details are essential, and to what extent our processes may be [Pg 31] varied with safety. We must also avoid trifling, and, above all, "the straining at a gnat and swallowing a camel," as is the habit with triflers. Large knowledge and good judgment will avoid all such errors; but, if we must choose between fussiness and carelessness, the first is the least evil. Slovenly work means slovenly results, and habits of carefulness, neatness, and order produce as excellent fruits in the laboratory as in the home.

Last in order but first in importance of the conditions of successful observation, mentioned above, stands truthfulness. Here you may think I am approaching a delicate subject, of which even to speak might seem to cast a reproach. But not so at all. I am not speaking here of conscious deception, for I assume that no one who aspires to be a student of Nature can be guilty of that. But I am speaking of a quality whose absence is not necessarily a mark of sinfulness, but whose possession, in a high degree, is a characteristic of the greatest scientific talent. As every lawyer knows, he is a rare man whose testimony is not colored by his interests, and a very large amount of self-deception is compatible with conscious honesty of purpose.

So among scientific students the power to keep the mind unbiased, and not to color our observations in the least degree, is one of the rarest as it is one of the noblest of qualities. It is a [Pg 32] quality we must strive after with all our might, and we shall not attain it unless we strive. Remember, our observations are our data, and, unless accurate, everything deduced from them must have the taint of our deception. We can not deceive Nature, however much we may deceive ourselves; and there is many a student who would cut off his right hand rather than be guilty of a conscious untruth, who is yet constantly untruthful to himself. Every year students of mineralogy present to me written descriptions of mineral specimens which particularize, as observed, characters that do not appear on the specimen given them to determine, although they may be the correct characters of some other mineral.

There is usually no want of honesty in this, but, deceived by some accident, the student has made a wrong guess, and then imagined that he saw on the specimen those characters which he knew from the descriptions ought to appear on the assumed mineral. So, also, it not unfrequently happens that a student in qualitative analysis, who has obtained some hints in regard to the composition of his solution, will torture his observations until they seem to him to confirm his erroneous inferences; and again the student in quantitative analysis, who finds out the exact weight he ought to obtain, is often insensibly influenced by this knowledge—in the washing and [Pg 33] ignition of his precipitate, or in some other way—and thus obtains results whose only apparent fault may be a too close agreement with theory, but which, nevertheless, are not accurate because not true. It is evident how fatal such faults as these must be to the investigation of truth, and they are equally destructive of all scientific scholarship. Their effect on the student is so marked that, although he may deceive himself, he will rarely deceive his teacher. That he should lose confidence in his own results is, to the teacher, one of the most marked indications of such false methods of study, but the student usually refers his want of success to any cause but the real one—his own untruthfulness. He will complain of the teacher, or of the methods of instruction, and may even persuade himself that all scientific results are as uncertain as his own. As I have said, mere ordinary truthfulness, which spurns any conscious deception, will not save us from falling into such faults. Our scientific study demands a much higher order of truthfulness than this. We should so love the truth above all price as to strive for it with single-hearted and unswerving purpose. We must be constantly on our guard to avoid any circumstance which would tend to bias our minds or warp our judgments, and we must make the attainment of the truth our sole motive, guide, and end. [Pg 34]

It remains for me, before closing this address, to say a few words on what I have called the subjective aspect of scientific study. Science offers us not only a mass of phenomena to be observed, but also a body of truths which have been deduced from these observations; and, without the power of drawing correct inferences from the data acquired, exact observations would be of little value. I have already described the inductive method of reasoning, and illustrated it by two noteworthy examples, and, in a humbler measure, we must apply the same method in our daily work in the laboratory. We must learn how to vary our experiments so as to eliminate the accidental circumstances, and make evident the essential conditions of the phenomena we are studying. Such power can only be acquired by practice, and a somewhat long experience in active teaching has convinced me that there is no better means of training this logical faculty than the study of qualitative chemical analysis in which many of you are to engage.

The results of the processes of qualitative analysis are perfectly definite and trustworthy; but they are only reached by following out the indications of experiments which are frequently obscure, and even apparently contradictory; reconciling by new experiments the seeming discrepancies, and, at last, having eliminated all other possible causes of the phenomena observed, discovering the true nature of the substances under examination. [Pg 35]

The study of mineralogy affords an almost equally good practice, although in a somewhat different form. By comparing carefully many specimens of the same mineral, you learn to distinguish the accidental from the essential characters, and on this distinction you must base your inferences in regard to the nature of the specimens you may be called upon to determine. A single remark occurs to me which may aid you in cultivating this scientific logic.

Do not attempt to reason on insufficient data. Multiply your observations or experiments, and when your premises are ample, the conclusion will generally take care of itself. Are you in doubt in regard to a mineral specimen? Repeat your observations again and again, multiply them with the aid of the blow-pipe or goniometer, compare the specimen with known specimens which it resembles, until either your doubts are removed or you are satisfied that you are unequal to the task; and remember that, in many cases, the last is the only honest conclusion.

Are you in doubt in regard to the reactions of the substance you are analyzing, whether they are really those of a metal you suspect to be present? Do not rest in such a frame of mind, and, above all, do not try to remove the doubt by comparing your experience with that of your neighbor, but [Pg 36] multiply your own experiments; procure some compound of the metal, and compare its reactions with those you have observed until you reach either a positive or a negative result.

Remember that the way to remove your doubts is to widen your own knowledge, and not to depend on the knowledge of others. When your knowledge of the facts is ample, your inferences will be satisfactory, and then an unexplained phenomenon is the guide to a new discovery. Do not be discouraged if you have to labor long in the dark before the day begins to dawn. It will at last dawn to you, as it has dawned to others before, and, when the morning breaks, you will be satisfied with the result of your labor.

Moreover, I feel confident that such experience will very greatly tend to increase your appreciation of the value of scientific studies in training the reasoning faculties of the mind. This, as every one must admit, is the best test of their utility in a scheme of education, and it is precisely here that I claim for them the very highest place. It has generally been admitted that mathematical studies are peculiarly well adapted to train the logical faculties, but still many persons have maintained that, since the mathematics deal wholly with absolute certainties, an exclusive devotion to this class of subjects unfits the mind for weighing the probable evidence by [Pg 37] which men are chiefly guided in the affairs of life.

But, without attempting to discuss this question, on which much might be said on both sides, it is certain that no such objection can be urged against the study of the physical sciences if conducted in the manner I have attempted to describe. These subjects present to the consideration of the student every degree of probable evidence, accustoming him to weigh all the evidence for or against a given conclusion, and to reject or to provisionally accept only on the balance of probabilities. Moreover, in practical science, the student is taught to follow out a chain of probable evidence with care and caution, to eliminate all accidental phenomena, and supply, by experiment or observation, the missing links, until he reaches the final conclusion—an intellectual process which, though based wholly on probable evidence, may have all the force and certainty of a mathematical demonstration.

Indeed, that highly valued scientific acumen and skill which enables the student to brush away the accidental circumstances by which the laws of Nature are always concealed until the truth stands out in bold relief, is but a higher phase of the same talent which marks professional skill in all the higher walks of life. The physician who looks through the external symptoms of his patient [Pg 38] to the real disease which lurks beneath; the lawyer, who disentangles a mass of conflicting testimony, and follows out the truth successfully to the end; the statesman, who sees beneath the froth of political life the great fundamental principles which will inevitably rule the conduct of the state, and thus foresees and provides for the coming change; the general, who discovers amid the confusion of the battlefield the weak point of his enemy's front; the merchant, even, who can interpret the signs of the unsettled market—employ the same faculty, and frequently in not a much lower degree, that discovered the law of gravitation, and which, since the days of Newton, has worked so successfully to unveil the mysteries of the material creation.

Moreover, I hope, my friends, that you will come to value scientific studies, not simply because they cultivate the perceptive and reasoning faculties, but also because they fill the mind with lofty ideals, elevated conceptions, and noble thoughts. Indeed, I claim that there is no better school in which to train the æsthetical faculties of the mind, the tastes, and the imagination, than the study of natural science.

The beauty of Nature is infinite, and the more we study her works the more her loveliness unfolds. The upheaved mountain, with its mantle of eternal snow; the majestic cataract, with its whirl and roar of waters; the sunset cloud, with its blending of gorgeous hues, lose nothing of [Pg 39] their beauty for him who knows the mystery they conceal. On the contrary, they become, one and all, irradiated by the Infinite Presence which shines through them, and fill the mind with grander conceptions and nobler ideas than your uneducated child of Nature could ever attain.

Remember that I am not recommending an exclusive devotion to the natural sciences. I am only claiming for them their proper place in the scheme of education, and I do not, of course, deny the unquestionable value of both the ancient and the modern classics in cultivating a pure and elevated taste. But I do say that the poet-laureate of England has drawn a deeper inspiration from Nature interpreted by science than any of his predecessors of the classical school; and I do also affirm that the pre-Raphaelite school of painting, with all its grotesque mimicry of Nature, embodies a truer and purer ideal than that of any Roman fable or Grecian dream.

And what shall we say of the imagination? Where can you find a wider field for its exercise than that opened by the discoveries of modern science? And as the mind wanders over the vast expanse, crossing boundless spaces, dwelling in illimitable time, witnessing the displays of immeasurable power, and studying the adaptations of Omniscient skill, it lives in a realm of [Pg 40] beauty, of wonder, and of awe, such as no artist has ever attained to in word, in sound, in color, or in form. And if such a life does not lead man to feel his own dependence, to yearn toward the Infinite Father, and to rest on the bosom of Infinite Love, it is simply because it is not the noble in intellect, not the great in talent, not the profound in knowledge, not the rich in experience, not the lofty in aspiration, not the gifted in imagery, but solely the pure in heart, who see God.

Such, then, is a very imperfect presentation of what I believe to be the value of scientific studies as a means of education. In what I have stated I have implied that, for these studies to be of any real value, the end must be constantly kept in view, and everything made subservient to the one great object.

To study the natural sciences merely as a collection of interesting facts which it is well for every educated man to know, seldom serves a useful purpose. The young mind becomes wearied with the details, and soon forgets what it has never more than half acquired. The lessons become an exercise of the memory and of nothing more; and if, as is too frequently the case, an attempt is made to cram the half-formed mind in a single school-year with an epitome of half the natural sciences—natural philosophy, astronomy, and chemistry, physiology, zoölogy, botany, and [Pg 41] mineralogy, following each other in rapid succession—these studies become a great evil, an actual nuisance, which I should be the first to vote to abate. The tone of mind is not only not improved, but seriously impaired, and the best product is a superficial, smattering smartness, which is the crying evil not only of our schools but also of our country.

In order that the sciences should be of value in our educational system, they must be taught more from things than from books, and never from books without the things. They must be taught, also, by real living teachers, who are themselves interested in what they teach, are interested also in their pupils, and understand how to direct them aright. Above all, the teachers must see to it that their pupils study with the understanding, and not solely with the memory, not permitting a single lesson to be recited which is not thoroughly understood, taking the greatest care not to load the memory with any useless lumber, and eschewing merely memorized rules as they would deadly poison. The great difficulty against which the teachers of natural science have to contend in the colleges are the wretched tread-mill habits the students bring with them from the schools. Allow our students to memorize their lessons, and they will appear respectably well, but you might as easily remove a mountain as to make many of them think. They will solve an involved [Pg 42] equation of algebra readily enough so long as they can do it by turning their mental crank, when they will break down on the simplest practical problem of arithmetic which requires of them only thought enough to decide whether they shall multiply or divide.

Many a boy of good capabilities has been irretrievably ruined, as a scholar, by being compelled to learn the Latin grammar by rote at an age when he was incapable of understanding it; and I fear that schools may still be found where young minds are tortured by this stupefying exercise. Those of us who have faith in the educational value of scientific studies are most anxious that the students who resort to our colleges should be as well fitted in the physical sciences as in the classics, for otherwise the best results of scientific culture can not be expected. As it is, our students come to the university, not only with no preparation in physical science, but with their perceptive and reasoning faculties so undeveloped that the acquisition of the elementary principles of science is burdensome and distasteful; and good scholars, who are ambitious of distinction, can more readily win their laurels on the old familiar track than on an untried course of which they know nothing, and for which they must begin their training anew.

We have improved our system of instruction in the college as fast as we could obtain the means, [Pg 43] but we are persuaded that the best results can not be reached without the coöperation of the schools. We feel, therefore, that it is incumbent upon us, in the first place, to do everything in our power to prove to the teachers of this country how great is the educational value of the physical sciences, when properly taught; and secondly, to aid them in acquiring the best methods of teaching these subjects. It is with such aims that our summer courses have been instituted, and your presence here in such numbers is the best evidence that they have met a real want of the community. We welcome you to the university and to such advantages as it can afford, and we shall do all in our power to render your brief residence here fruitful, both in experience and in knowledge; hoping, also, that the university may become to you, as she has to so many others, a bright light shining calmly over the troubled sea of active life, ever suggesting lofty thoughts, encouraging noble endeavors, and inciting all her children to work together toward those great ends, the advancement of knowledge and the education of mankind. [Pg 44]

II.

THE NOBILITY OF KNOWLEDGE.

An Address delivered before the Free Institute at Worcester, Massachusetts, July 28, 1874.

Within a comparatively few years schools for the instruction of artisans have become a prominent feature in the educational systems both of this country and of Europe, and seem destined to supersede the old system of apprenticeships. The establishment of these schools has been an important step in human progress, not because any great advantage has been gained in the cultivation of mechanical skill, but because here the future mechanic acquires culture of the mind as well as skill of the hand. Indeed, it may be doubted whether our utilitarian age can ever successfully compete with those "elder days of art" when

"Builders wrought with greatest care
Each minute and unseen part."

[Pg 45]

But, if our industrial schools do not make better mechanics than the workshops of the olden time, they certainly educate better men, and, by adding to skill, knowledge, they are elevating the mechanic and ennobling his calling.

If, therefore, these schools are the representatives in our age of the workshops with their bands of apprentices in the days of yore, then that by which the schools are distinguished, that which they have added to the old system, is not art but mental culture; and therefore, when asked to address you on this occasion, I could think of no more appropriate subject than the Nobility of Knowledge.

Identified with an institution in which mental culture is the chief aim, I felt that I was asked to address a body of cultivated working-men with whom, though employed in the mechanic arts, the acquisition of knowledge was also a privilege and a pride. I felt, moreover, that a proper appreciation of the true dignity of knowledge, in itself considered, and apart from all economical considerations, is one of the great wants of our age and of our country.

"Knowledge is power." "Knowledge is wealth." These trite maxims are sufficiently esteemed in our community, and need not that they be enforced by any one. So far as knowledge will yield immediate distinction or gain, it is sought and fostered by multitudes. But, when the aim is low, [Pg 46] the attainment is low, and too many of our students are satisfied with superficiality, if it only glitters, and with charlatanry, if it only brings gold.

Let me not be understood to depreciate the material advantages of learning. I rejoice that in this world knowledge frequently yields wealth and fame, and I should have little hope for human progress were the prizes of scholarship less than they are. Power and wealth are noble aims, and when rightly used may be the means of conferring unmeasured blessings on mankind; but I desire at this time to impress upon you, my friends, the fact that knowledge has nobler fruits than these, and that the worth of your knowledge is to be measured not by the credits it will add to your account in the ledger, or the position it may give you among men, but by the extent to which it educates your higher nature, and elevates you in the scale of manhood.

I address young men who are just entering on life, who are at an age when the mystery of our being usually presses most closely upon the soul, and whose aspirations for higher culture and clearer vision have not been deadened by the sordid damps of the world. Trust no croakers who tell you that your youthful visions are illusions, which a little contact with the real business of the world will dispel.

It is only too true that these visions will become fainter and fainter, if you allow the cares of the [Pg 47] world to engross your thoughts; but, unless your higher nature becomes wholly deadened, you will look back to the time when the visions were brightest, as the golden period of your life, and let me assure you that, if you only are true to the aspirations of your youth, the visions will become clearer and clearer to the last, and, as we firmly believe, will prove to be the dawn of the perfect day.

My friends, if you have seen these visions, "the nobility of knowledge" has been a reality of your experience. You know that there is a life lived in communion with the thoughts of great men or with the thoughts of God as we can read them in Nature and Revelation, which is purer and nobler than a life of money-making or political intrigue, and I would that I could so bring you to appreciate not only the nobility, but also the happiness, of such a life as to induce you to try to live it.

Do you tell me that it is only granted to a few men to become scholars, and that you have been educated for some industrial pursuit? Remember, as I said before, that it is your special privilege to have been educated, to have added knowledge to your handicraft, and that this very knowledge, if kept alive so far as you are able, will ennoble your life. Knowledge, like the fairy's wand, ennobles whatever it touches. The humblest occupations are adorned by it, and without it [Pg 48] the most exalted positions appear to true men mean and low.

Nor is it the extent of the knowledge alone which ennobles, but much more the spirit and aim with which it is cultivated, and that spirit and aim you may carry into any occupation, however engrossing, and into any condition of life, however obscure.

And let me add that what I have said is true not only of the individual, but also, and to an even greater degree, of the nation. Our people, for the most part, look upon universities and other higher institutions of learning as merely schools for recruiting the learned professions, and estimate their efficiency solely by the amount of teaching work which they perform. But, however important the teaching function of the university may be, I need not tell you that this is not its only or chief value to a community. The university should be the center of scientific investigation and literary culture, the nursery of lofty aspirations and noble thoughts, and thus should become the soul of the higher life of the nation. For this and this chiefly it should be sustained and honored, and no cost and no sacrifice can be too great which are required to maintain its efficiency; and its success should be measured by the amount of knowledge it produces rather than by the amount of instruction it imparts.

Harvard College, by cherishing and honoring the great naturalist she has recently lost, has done [Pg 49] more for Massachusetts than by educating hosts of commonplace professional men. The simple title of teacher, which in his last will Louis Agassiz wrote after his name, was a nobler distinction than any earthly authority could confer; but remember he was a teacher not of boys, but of men, and his influence depended not on the instruction in natural history which he gave in his lecture-room, but on his great discoveries, his far-reaching generalization, and his noble thoughts. Although that man died poor, as the world counts poverty, yet the bequest which he left to this people can not be estimated in coin.

It is a sorry confession to make, but it is nevertheless the truth, that, if we compare our American universities, in point of literary or scientific productiveness, with those of the Old World, they will appear lamentably deficient. Let me add, however, that this deficiency arises not from any want of proper aims in our scholars, but simply from the circumstance that our people do not sufficiently appreciate the value of the higher forms of literary and scientific work to bear the burden which the production necessary entails. Scholars must live, as well as other men, and in a style which is in harmony with their surroundings and cultivated tastes, and their best efforts can not be devoted to the extension of knowledge unless they are relieved from anxiety in regard to their daily bread. [Pg 50]

In our colleges the professors are paid for teaching and for teaching only, while in a foreign university the teaching is wholly secondary, and the professor is expected to announce in his lectures the results of his own study, and not the thoughts of other men. Until the whole status of the professors in our chief universities can be changed, very little original thought or investigation can be expected, and these institutions can not become what they should be, the soul of the higher life of the nation.

It is in your power, however, to bring about this change, but the reform can be effected in only one way. You must give to your universities the means of supporting fully and generously those men of genius who have shown themselves capable of extending the boundaries of human knowledge, and demand of them, only, that they devote their lives to study and research, and let me assure you that no money can be spent which will yield a larger or more valuable return.

If you do not look beyond your material interests, the higher life of the nation, which you will thus serve to cherish and foster, will guard your honor and protect your home; and, on the other hand, what can you expect in a nation whose highest ideal is the dollar or what the dollar will buy, but venality, corruption, and ultimate ruin? [Pg 51]

But, rising at once to the noblest considerations, and regarding only the welfare of your country and the education of your race, what higher service can you render than by sustaining and cherishing the grandest thought, the purest ideals, and the loftiest aspirations which humanity has reached, and making your universities the altars where the holy fire shall be kept ever burning bright and warm?

Do you think me an enthusiast? Look back through history, and see for yourselves what has made the nations great and glorious. Why is it that, after twenty centuries, the memory of ancient Greece is still enshrined among the most cherished traditions of our race? Is it not because Homer sang, Phidias wrought, and Plato, Aristotle, Demosthenes, Thucydides, with a host of others, thought and wrote? Or, if for you the military exploits of that classic age have the greater charm, do not forget that were it not for Grecian literature, Thermopylæ, Marathon, and Salamis would have been long since forgotten, and that the bravery, self-devotion, and patriotism which these names embalm were the direct fruits of that higher life which those great thinkers illustrated and sustained.

And, coming down to modern times, what are the shrines in our mother country which we chiefly venerate, and to which the transatlantic pilgrim oftenest directs his steps? Is it her battlefields, [Pg 52] her castles and baronial halls, or such spots as Stratford-on-Avon, Abbotsford, and Rydal Mount? Why, then, will we not learn the lesson which history so plainly teaches, and strive for those achievements in knowledge and mental culture which will be remembered with gratitude when all local distinctions and political differences shall have passed away and been forgotten?

While I was considering the line of discourse which I should follow on this occasion, an incident occurred suggesting an historical parallel, which will illustrate, better than any reflections of mine, the truth I would enforce. The ship Faraday arrived on our coast after laying over the bed of the Atlantic another of those electric nerves through which pulsate the thoughts of two continents, and as I read the description of that noble ship, fitted out with all the appliances which modern science had created to insure the successful accomplishment of the enterprise, I remembered that not a century had elapsed since the first obscure phenomena were observed, whose conscientious study, pursued with the unselfish spirit of the scientific investigator, had led to these momentous results, and my imagination carried me back to an autumn day of the year 1786, in the old city of Bologna, in Italy, and I seemed to assist at the memorable experiment which has associated the name of Aloysius Galvani with that mode of electrical energy which [Pg 53] flashes through the wire cords that now unite the four quarters of the globe.

Galvani is Professor of Anatomy in the University of Bologna, and there is hanging from the iron balcony of his house a small animal preparation, which is not an unfamiliar sight in Southern Europe, where it is regarded as a delicacy of the table. It is the hind-legs of a frog, from which the skin had been removed, and the great nerve of the back exposed. Six years before, his attention had been called to the fact that the muscles of the frog were convulsed by the indirect action of an electrical machine, under conditions which he had found very difficult to interpret. He had connected the phenomenon with a theory of his own: that electricity—that is, common friction electricity, the only mode of electrical action then known—was the medium of all nervous action; and this had led him into a protracted investigation of the subject, during which he had varied the original experiment in a thousand ways, and he had now suspended the frog's legs to the iron balcony, in order to discover if atmospheric electricity would have any effect on the muscles of the animal.

Galvani has spent a long day in fruitless watching, when, while holding in his hand a brass wire, connected with the muscles of the frog, he rubs the end, apparently listlessly, against the iron [Pg 54] railing, when, lo! the frog's legs are convulsed.

The patient waiting had been rewarded, for this observation was the beginning of a line of discovery which was ere long to revolutionize the world. But Galvani was not destined to follow far the new path he had thus opened. The remarkable fact observed was this: The convulsions of the frog's legs could be produced without the intervention of electricity, or, at least, of the one kind of electricity then known, and Galvani soon found out that the only condition necessary to produce the result was, that the nerve of the frog should be connected with the muscle of the leg by some good electrical conductor.

But, although Galvani followed up this observation with the greatest zeal, and showed remarkable sagacity throughout his whole investigation, yet he was too strongly wedded to his own theory to interpret correctly the facts he observed. He supposed, to the end of his life, that the whole effect was caused by animal electricity flowing through the conductor from the nerve to the muscle, and his experiments were chiefly interesting to himself and to his contemporaries from the light they were supposed to throw on the mysterious principle of life. We now know that animal electricity played only a small part in the phenomena he observed, and that the chief [Pg 55] effects were due to a cause of which he was wholly ignorant.

Galvani published his observations in 1791, in a monograph entitled "The Action of Electricity in Muscular Motion." This publication excited the most marked attention, and, within a year, all Europe was experimenting on frogs' legs. The phenomena were everywhere reproduced, but Galvani's explanation of the phenomena was by no means so universally accepted. His theory was controverted in many quarters, and by no one more successfully than by Alexander Volta, Professor of Physics in the neighboring University of Pavia.

Volta, while admitting, with Galvani, that the muscular contractions were caused by electricity, explained the origin of the electricity in a wholly different way. According to Volta, the electricity originated not in the animal, but in the contact of the dissimilar metals or other materials used in the experiment. This difference of opinion led to one of the most remarkable controversies in the history of science, and for six years, until his death in 1798, Galvani was occupied in defending his theory of animal electricity against the assaults of his distinguished countryman.

This discussion created the liveliest interest throughout Europe. Every scholar of science took sides with one or the other of these eminent Italian philosophers, and the scientific world became [Pg 56] divided into the school of Galvani and the school of Volta. Yet, so far at least as the fundamental experiment was concerned, both were wrong. The electricity came neither from the body of the frog nor from the contact of dissimilar kinds of matter, but was the result of chemical action, which both had equally overlooked.

But, nevertheless, the controversy led to the most important results: for Volta, while endeavoring to sustain his false theory by experimental proofs, was led to the discovery of the Voltaic pile, or, as we now call it, the Voltaic battery, an instrument whose influence on civilization can be compared only with the printing-press and the steam-engine. Yet, although the whole action of the battery was in direct contradiction to his pet theory, still, to the last, Volta persistently defended the erroneous doctrine he had espoused in his controversy with Galvani thirty years before, and he died in 1827, without realizing how great a boon he had been instrumental in conferring on mankind; so true it is that Providence works out his bright designs even through the blindness and mistakes of man.

But there is another lesson to be learned from this history, which can not be too often rehearsed in this self-sufficient age, which boasts so proudly of its practical wisdom. There were, doubtless, many practical men in that city of Bologna to smile at their sage professor, who had spent ten [Pg 57] long years in studying, to little apparent purpose, the twitchings of frogs' hind-legs, and there was many a jest among the courtiers of Europe at the expense of the learned philosophers who "wasted" so much time in discussing the cause of such trivial phenomena. But how is it now?

Less than a century has passed since Galvani's death, and in a small hut on the shores of Valentia Bay may be seen one of the most skillful of a new class of practical men, representing a profession which owes its origin to Galvani and Volta. The *electrician* is watching a spot of light on the scale of an instrument which is called a *galvanometer*. Since the fathers fell asleep, the field of knowledge which they first entered has spread out wider and wider before the untiring explorers who have succeeded them. Oersted and Seebeck, Arago and Ampère, Faraday and our own Henry, have made wonderful discoveries in that field; and other great men, like Steinheil, Wheatstone, Morse, and Thomson, have invented ingenious instruments and appliances, by which these discoveries might be made to yield great practical results.

The spot of light, which the electrician is watching, is reflected from one of the latest of these inventions, the reflecting galvanometer of Thomson. He and his assistants had been watching by [Pg 58] turns the same spot for several days, since the Great Eastern had steamed from the bay, paying out a cable of insulated wire. These electricians had no anxiety as to the result, for daily signals had been exchanged between the ship and the shore, as hundreds after hundreds of miles of this electrical conductor had been laid on the bed of the broad ocean. The coast of Newfoundland had already been reached, and they were only waiting for the landing of the cable at the now far-distant end.

At length the light quivers, and the spot begins to move. It answers to concerted signals. And soon the operator spells out the joyful message. The ocean has been spanned with an electric nerve, and the New World responds to the greetings of the Old.

Here is something practical, which all can appreciate, and all are ready to honor. We honor the courage which conceived, the skill which executed, and, above all, the success which crowned the undertaking. But do we not forget that professor of Bologna, with his frogs' legs, who sowed the seed from which all this has sprung? He labored without hope of temporal reward, stimulated by the pure love of truth, and the grain which he planted has brought forth this abundant harvest. Do we not forget, also, that succession of equally noble men, Volta, and Oersted, and Faraday, with many other not less devoted investigators of electrical science, without whose [Pg 59] unselfish labors the great result never could have been achieved? Such men, of course, need no recognition at our hands, and I ask the question not for their sakes, but for ours. The intellectual elevation of the lives they led was their all-sufficient reward.

It is, however, of the utmost importance for us, citizens of a country with almost unlimited resources, that we should recognize what are the real springs of true national greatness and enduring influence. In this age of material interests, the hand is too ready to say to the head, "I have no need of thee"; and, amid the ephemeral applause which follows the realization of some triumph over matter, we are apt to be deceived, and not observe whence the power came. We associate the great invention with some man of affairs man who overcame the last material obstacle, and who, although worthy of all praise, probably added very little to the total wealth of knowledge of which the invention was an immediate consequence; and, not seeing the antecedents, we are apt to underrate the part which the student or scientific investigator may have contributed to the result.

It is idle, for example, to speak of the electric telegraph as invented by any single man. It was a growth of time, and many of the men who contributed to win this great victory of mind over space "builded far better than they knew." As I view the subject, that invention is as much a gift [Pg 60] of Providence as if the details had been supernaturally revealed. But, whatever may be our speculative views, it is of the utmost importance to the welfare of our community that we should realize the fact that purely theoretical scientific study, pursued for truth's sake, is the essential prerequisite for such inventions. Knowledge is the condition of invention. The old Latin word *invenio* signifies *to meet with*, as well as to *find*, and these great gifts of God are *met with* along the pathway of civilization; but the throng of the world passes them unnoticed, for only those can recognize the treasure whose minds have been stored with the knowledge which the scholar has discovered and made known.

If, then, as no one will deny, science and scholarship are the powers by which improvements in the useful arts are made, I might appeal to your self-interest to support and cherish them. But I should despise myself for appealing to such a motive, and you for requiring it. The supreme importance of science and scholarship to a nation does not depend in the least on the circumstance that important practical results may follow. When, as in the case of Galvani's frogs, they come in the order of Providence, let us thank God for them as a gift which we had no right either to expect or demand. Science, if studied successfully, must be studied for the pure love of [Pg 61] truth; and, if we serve her solely for mercenary ends, her truths, the only gold she offers, will turn to dross in our hands, and we shall degrade ourselves in proportion as we dishonor her.

Galvani, and Volta, and Oersted, who discovered the truths of which the electric telegraph is a simple application, sure to be made as soon as the time was ripe, are not the less to be honored because they died before the fullness of that time had come. We honor them for the truths they discovered, and the lustre of their consecrated lives could be neither enhanced nor impaired by subsequent events; and it is because I am persuaded that such lives are the salt of the world, the saviours of society, that I would lead you to cherish and sustain them; and, that I may enforce this conclusion, allow me to ask your attention to another historical incident, which presents a striking parallelism to the last.

I must take you back to a period which we, of a nation born but yesterday, regard as distant, but which was one of the most noted epochs of modern history—the age of Luther and the Reformation. I must ask you to accompany me to the small town of Allenstein, near Frauenberg, in Eastern Prussia, where, on May 23, 1543, there lay dying one of the great benefactors of mankind.

This man, old at seventy years, "bent and furrowed with labor, but in whose eye the fire of genius was still glowing," was then known as one of the most learned men of his time. Doctor of [Pg 62] medicine as well as of theology, Canon of Frauenberg, Honorary Professor of Bologna and Rome, while devoting his leisure to study, he had passed a life of active benevolence in administering to the bodily as well as the spiritual wants of the ignorant people among whom his lot had been cast. He was also a great mechanical genius, and, by various labor-saving machines, of his own invention, he had contributed greatly to the welfare of the surrounding country.

But the superstitious peasants, although they had hitherto reverenced the great man as their best friend and benefactor, had been recently incited by his enemies and rivals in the church to curse him as a heretic and a wizard. A few days back he had been the unwilling witness of one of those out-of-door spectacles, so common at that time, in which his scientific opinions had been travestied, his charities ridiculed, and his devoted life made the object of slander and reproach. This ingratitude of his flock had broken his heart, and he could not recover from the blow.

The occasion of this outburst of fanaticism was the approaching publication of a work in which he had dared to question the received opinions of theologians and schoolmen, in regard to cosmogony. He had, forsooth, denied that the visible firmament was a solid azure-colored shell, to which the sun and planets were fastened, and through whose opened doors the rain [Pg 63] descended. He had proved that the sun was the center of the system, around which the earth and planets revolved, and, with his clear scientific vision, he had been able to gain glimpses, at least, of the grand conceptions of modern astronomy: For this man was Nicolas Copernicus, and the expected book was his great work—"De Orbium Cœlestium Revolutionibus"—destined to form the broad basis of astronomical science.

The work was printing at Nuremberg, and the last proofs had been returned; but reports had come that a similar outburst of fanaticism was raging at that place, that a mob had burned the manuscript on the public square, and had threatened to break the press should the printing proceed. But, thanks to God! the old man was not to die before the hour of triumph came. While still conscious, a horse, covered with foam, gallops to the door of his humble dwelling, and an armed messenger enters the chamber, who, breathless with haste, places in the hands of the dying man a volume still wet from the press. He has only strength to return a smile of recognition, and murmur the last words:

"Nunc dimittis servum tuum, Domine."

Grand close of a noble life! The seed has been sown—what could we desire more? [Pg 64]

Again the centuries roll on—not one, but three—while the seed grows to a great tree, which overshadows the nations. Great minds have never been wanting to cherish and prime it, like Tycho Brahe and Kepler, Galileo and Newton, Laplace and Lagrange; and although at times some, while lingering in the deep shade of the foliage, may have lost sight of the summit, the noble tree has ever pointed upward to direct aspiration and encourage hope.

On the evening of the 24th of September, 1846, in the Observatory of Berlin, a trained astronomical observer was carefully measuring the position of a faint star in the constellation Capricorn. Only the day before, he had received from Le Verrier a letter announcing the result of that remarkable investigation which has made the name of this distinguished French astronomer so justly celebrated. By the studies of the great men who succeeded Copernicus, his system had become so perfected as to enable the astronomer to predict, with unerring certainty, the paths of the planets through the heavens. But there was one failing case. The planet Uranus, then supposed to be the outer planet of the solar system, wandered from the path which theory assigned to it; and although the deviations were but small, yet any discrepancy between theory and observation in so accurate a science as astronomy could not be overlooked. [Pg 65]

Long before this, the hypothesis had been advanced that the deviations were caused by the attractive force of an unseen and still more distant planet; but, as no such planet had been discovered, the hypothesis had remained until now wholly barren. The hypothesis, however, was reasonable, and furnished the only conceivable explanation of the facts; and, moreover, if true, the received system of astronomy ought to be able to assign the position and magnitude of the disturbing body, the magnitude and direction of the displacements being given.

This possibility was generally appreciated by astronomers, and the very great length and difficulty of the mathematical calculation which the investigation involved was probably the reason that no one had hitherto undertaken it. Le Verrier, however, had both the courage and the youthful strength required for the work. And now the great work had been done; and, on the 18th of September, Le Verrier had sent to the Observatory of Berlin his communication announcing the final result, namely, that the planet would be found about 5° to the east of the star Delta of Capricorn.

The letter containing this announcement was received by Galle, at Berlin, on the 23d, and it was Galle whom we left measuring the position of that faint star on the evening of the 24th. It so happened that a chart of that portion of the heavens had recently been prepared by the Berlin [Pg 66] Observatory, and was on the eve of publication; and, on the very evening he received the letter, Galle had found, near the position assigned by Le Verrier, a faint star, which was not marked on this chart. The object differed in appearance from the surrounding stars, but still it was perfectly possible that it might be a fixed star which had escaped previous observation.

But, if a fixed star, its position in the constellation would not vary, while, if a planet, a single night would show a perceptible change of place. Hence, you may conceive of the interest with which Galle was measuring anew its position on the evening of the 24th.

The star had moved, and in the direction which theory indicated; and for once, at least, the world rang with applause at a brilliant scientific conquest from which there was not one cent of money to be made. Yet, was that conquest any less important to the world? What had it secured? It had confirmed the theory of astronomy which Copernicus and his successors had built up, and it had clinched the last nail in the proof that those grand conceptions of modern astronomy, now household thoughts, are realities, and not dreams. Certainly no military conquest can compare with this.

Do not smile at the enthusiasm which rates so high a purely intellectual achievement? Go out with me under the heavens, in some starlight night, and, looking up into the depths of space, [Pg 67] recall the truths you have learned in regard to that immensity, and allow the imagination free scope as it stretches out into the infinitudes of time, space, and power, carrying the mind on, bound by bound, through the limitless expanse, until even the imagination refuses to follow, and fairly quails before the mighty form of the Infinite, which rises to confront it! Remember now that your forefathers, of only a few centuries back, saw there nothing but a solid dome hemming in the earth and skies, and that you are able to look upon this grand spectacle only because great minds have lived who have opened your intellectual eyes; and then answer me, is not this result worth all the labor, all the sacrifice, all the treasure it has cost?

Every educated man, who has not sold his birthright for a mess of pottage, lives a grander and nobler life, because the great astronomers have thought and taught, and this elevation of human life is the greatest achievement of which man can boast. Before it all material conquests appear of little worth, and the lustre of all military or civil glory grows dim. Cherish this intellectual life; foster it; sustain it; do what you can by your own spirit and influence, and, if you are blessed with riches, give of your abundance to support and encourage those who, by genius, talent, and devotion, will widen the intellectual kingdom. Be assured you will thus help to confer an [Pg 68] inestimable boon on your race and on your country; and the influence for good will not be felt by the intellectual life of the nation only. That corruption which is now festering at the heart of our body politic, and threatening its destruction, can in no way be fought and conquered so effectually as by keeping constantly before the nation noble and high ideals; for, where the higher life is cherished and honored, the mercenary and sensual motives of action, which both invite and shield corruption, lose much of their force and power.

But you may tell me that there is a life higher than the intellectual life, and that I have ascribed to science and scholarship influences which come only from a source which I have forgotten, or left out of view. My friends, all truth is one and inseparable, and I have therefore made no distinction in this address between the truths of science and truths of religion. The grand old word knowledge, as I have used it, includes both, and, in just the proportion that you reverence religion, you must reverence also true science. All truth is God's truth, and, in praying for the coming of his kingdom, you certainly do not expect that Nature will be divorced from Grace. If the truths of religion required a special revelation, it must be expected that they would transcend human intelligence. These very conditions imply conflict, but the conflict comes not from the [Pg 69] knowledge, but from the ignorance and conceit of men; and the only proper attitude for the devout scholar is "to labor and to wait." And what more wonderful confirmation could we have of the essential unity of the two phases of truth than is to be found in the fact that the characteristic of science, which I have been endeavoring to illustrate in this address, is the great prominent feature of Christianity? Christianity was revealed in a life, and ever abides a life in the soul of man, to purify, ennoble, and redeem humanity.

"And so the Word had breath, and wrought,
With human hands, the creed of creeds,
In loveliness of perfect deeds,
More strong than all poetic thought—

"Which he may read that binds the sheaf,
Or builds the house, or digs the grave,
And those wild eyes that watch the wave,
In roarings round the coral reef."

[Pg 70]

III.

THE ELEMENTARY TEACHING OF PHYSICAL SCIENCE.

An Address to the Schoolmasters of Boston, delivered February 4, 1878.

I felt a great reluctance at accepting the invitation of your excellent superintendent to address you on this occasion; for, although I could claim an unusually long experience in presenting the elements of physical science to college students, I was fully conscious that I knew little of the conditions under which such subjects must be studied, if at all, in the elementary schools, and

was therefore in danger of appearing in a capacity which I should most sedulously shun, that of a babbler about impracticable theories of education. It is very easy to criticize another man's labor, and such criticisms, however plausible, do the grossest injustice when, as is often the case, they leave out of view the necessary conditions and limitations under which the work must be done. [Pg 71]
While, however, I felt most keenly my incapacity to deal with many of the practical problems which you have to solve, yet, on consideration, I concluded that it was my duty under the circumstances to state as clearly and forcibly as I could the very definite opinions which I had formed on the subject you are discussing, knowing that you will only give such weight to these opinions as your mature judgment can allow. In stating the results of my experience, I can not avoid a certain personal element, which would be wholly inexcusable were it not that the facts, as I think you will admit, form the basis of my argument.

I am a Boston boy, born in this immediate neighborhood, and fitted for college at the "Latin School." It so happened that, while I was very unsuccessfully endeavoring to commit to memory, in the old school-house on School Street, Andrews and Stoddard's Latin grammar, not one word of which I could understand, the "Lowell Institute" lectures were opened at the "Odeon" on Congress Street. At those lectures I got my first taste of real knowledge, and that taste awakened an appetite which has never yet been satisfied. As a boy, I eagerly sought the small amount of popular science which the English literature of that day afforded; and I can now distinctly recall almost every page of Mrs. Marcet's "Conversations on Chemistry," which was the first book on [Pg 72]
my science that I ever read. More to the point than this, a boy's pertinacity, favored by a kind father's indulgence, found the means of repeating, in a small way, most of the experiments first seen at the Lowell Institute lecture; and thus it came to pass that, before I entered college, I had acquired a real, available knowledge of the facts of chemistry; although, with much labor and intense weariness, I had gained only a formal knowledge of those subjects which were then regarded as the only essential preparation for the college course. In college, my attention was almost exclusively devoted to other studies—for, in my day at Cambridge, chemistry was one of the lost arts. But when, the year after I graduated, I was most unexpectedly called upon to give my first course of lectures, the only laboratory in which I had worked was the shed of my father's house on Winthrop Place, and the only apparatus at my command was what this boy's laboratory contained. With these simple tools, or, as I should rather say, because they were so simple, I gained that measure of success which determined my subsequent career.

I feel that I owe you a constant apology for these personal details, and I should not be guilty of them did I not believe that they establish two points more conclusively than I could prove them in any other way. First, that it is perfectly possible for a child before fifteen years of age to acquire [Pg 73]
a real and living knowledge of the fundamental facts of nature on which physical science is based. Secondly, that this knowledge can be effectually gained by the use of the simplest tools. Let me add that this is not a question of natural endowments or special aptitudes, for every one who has studied from the love of knowledge has had the same experience; and I do not believe that, if my first taste of real knowledge had been of history, nay, I will even say, of philology, instead of chemistry, the circumstance would have materially influenced my success in life, however different the direction into which it might have turned my study. My early tastes were utterly at variance with all my surroundings and all my inheritances, and were simply determined by the accident which first satisfied that natural thirst for knowledge which every child experiences to a greater or less degree—a desire most rudely repressed in our usual methods of teaching.

My bitter experience as a pupil in the Boston Latin School and my subsequent more fortunate experience of thirty years as a teacher in Harvard College have impressed me most profoundly with the conviction that the only way to arouse and sustain a love for knowledge in children is to cultivate their perceptive faculties. To present the rudiments of knowledge to immature minds in [Pg 74]
an abstract form, whether the subject be grammar or physical science, is, in my judgment, not only culpable folly, but also downright wrong. And, if, to those who have been accustomed to the long established routine of our public school, my opinions may appear revolutionary and extreme, I am, nevertheless, sure that they would receive the universal assent of the men whom all would recognize as the foremost scientific teachers of the world. I can well remember that when, many years ago, the late Professor Agassiz declared in my hearing that he would have no text-books used in his museum, I thought his plan of pure object-teaching chimerical in the extreme, and yet experience has not only convinced me of the wisdom of his judgment in regard to the teaching of natural history, but brought me to a similar conclusion in regard to the elementary teaching both of natural philosophy and of chemistry.

Allow me then to express my firm persuasion that it is not only useless but injurious to the education of young minds to present to them at the outset any department of physical science as a body of definitions, principles, laws, or theories; and that in elementary schools only such facts should be taught as can be verified by the experience of the pupil, or by such simple experiments as the pupils can try for themselves. The usual method of committing by heart the words of a [Pg 75]
school-book, and repeating them at the dictation of a teacher, may afford a good exercise for the memory, but it is absurd to regard such a task as a lesson in physical science, and this kind of study can be spent with vastly greater profit on the spelling-book.

There is one department of physical science which has been taught in this absurd way in our schools from time immemorial. I refer, of course, to the study of geography, and I leave for you to judge whether the result is worth the one hundredth part of the toil and drudgery spent in obtaining it. Let us suppose that your child is able to give you the names of all the rivers, bays, and capes from Greenland to Patagonia, how much more does that child know of the structure and social relations of this globe on which its lot has been cast than it did before this senseless feat was attempted, a feat, moreover, to which only a child's memory would be equal? And, when you turn to your own experience, what is the outcome of all the time and labor spent on geography? Is it not solely just that portion of your knowledge which, in spite of the system, was direct object-teaching—the images you insensibly acquired from the maps and pictures in the school-books?

But there is a very different way of teaching geography, by which the study may be made a pleasure, not a task. The teacher does not begin with abstract definitions of rivers, and bays, and [Pg 76] oceans, which convey no definite meaning to a child, but with Charles River, Boston Harbor, and the Atlantic Ocean, which are to him real things, however imperfect his conceptions of their extent. The child is first shown, not a map of the globe, which he can not by any possibility understand, but a map of a very limited region around his own home. He is taught how to find the north and south, the east and west directions. He is encouraged to make excursions to verify the map, or to add to its details, and such excursions may be made to have for him all the zest of voyages of discovery; and when thus the rudiments of geographical science have been mastered, not in technical terms, but in substance, then the teacher may begin to expand the horizon of the pupil's knowledge, judiciously omitting details in proportion as distance increases, until at length the general survey embraces the globe. Of course, such teaching as this can only be given orally with the help of proper apparatus, such as wall maps, and globes, and photographs. It must take the interrogative form, and the questions should be directed to bring out the child's already acquired knowledge, and to lead him to observe facts which had hitherto escaped his notice. What a child reads in a book, or even what you tell him, is never one half learnt, unless his interest is aroused. But what a child observes for himself he never forgets, and when you have [Pg 77] thus aroused his interest you can associate a large number of facts with one observation, and these all crystallize in his memory around this nucleus.

This is no mere theory, no untried method which I am advocating. So far from it, I am describing the precise method which has been used for many years in Germany, where the science of education is far better understood than with us, and where economy both of time and labor in teaching is most carefully studied. If our school committees could attend and understand a single exercise in geography, such as are daily given in the elementary schools of Prussia, I am sure that at least one form of child torture would soon disappear from the primary schools of this country. Indeed, I already see evidence of a growing public opinion on this subject, an effect which I trace in no small measure to the influence of the Department of Education of the Exhibition at Philadelphia in 1876.

That which is true of geography applies with still greater force to such subjects as physics and chemistry, since the abstract conceptions which these sciences involve are more abstruse, and the language by which the conceptions are expressed or defined far less plain than is the case with the older and more descriptive branch of knowledge. Hence, as sciences, properly so called, [Pg 78] that is, as philosophical systems, they have no place whatever in elementary education. But, underlying these systems, there is a great multitude of phenomena which a child can be led to observe and apprehend as readily as the facts of geography. Take that subject—mechanics—which our ordinary school-books very philosophically but most unpractically place at the beginning of what they call "Natural" Philosophy. How many of the fundamental facts of this difficult subject can be made familiar to a child? Select, as an example, Newton's "First Law of Motion." Suppose you make a boy memorize the ordinary rule, "Every body continues in a state of rest or of uniform motion in a straight line until acted upon by some external force," how much will he know about it? Suppose you make him do a lot of problems involving distances, velocities, and times, will he know any more about it? But ask him, "Can you pitch a ball as well as your playmate?" and he answers at once, "No; John is stronger than I am." And then, if again you ask, "Can you catch John's ball?" he will probably reply, "Of course, not! It requires a boy as strong as John to catch his balls." And thus, by a few well-directed questions, you would bring that boy to learn a lesson which he would never forget, and which he would recall every time he played base-ball; namely, that John's swift balls could not be set in motion without an expenditure of a definite [Pg 79] amount of muscular effort, and could not be stopped without the exertion of an equal amount of what, after a while, you could get him to call *force*. From the ball you would naturally pass to the railroad train or the steamboat, and I should not wonder if, with a little patience, you could bring even a boy to understand that motion can not be maintained against a resistance, in other words, that work can not be done without a constant expenditure of muscular effort, or of some other source of power; and it is a fond hope of mine that by the time these boys grow into men our intelligent New England community might become so far educated in the elementary principles of mechanics that no self-sustained motors, nor other mechanical nostrums which claim to have superseded the primeval curse—if that law was a curse, which compels man to earn his bread with the sweat of his brow—will receive the sanction of our respectable journals; and then—if they have not previously learned the lesson by dire experience—we may hope to persuade our people of the parallel and equally elementary principle of political economy, that value can not be legislated into rags.

But, my friends, our subject gives no occasion for banter, and presents aspects too serious to be treated lightly or in jests. As inhabitants of a not over-fruitful land, and, therefore, members of a community which must excel, if at all, solely by its enterprise and intelligence, we have a duty to [Pg 80] our children which we can not avoid, if we would, and for which we shall be held responsible by our posterity. These children are entering life surrounded not only by all the wonders and glories of nature, but, also, by giant conditions, which, whether stationed on their path as a blessing or a curse, will inevitably strike if their behests are not obeyed. So far as science has been able to define these giant forms, it is our duty, as it is our privilege, to point them out to those we are bound to protect and guide; and in many cases it is in our power to change the curse into a blessing, and to transform the destructive demon into a guardian angel. After that command of language which the necessities of civilized life imperatively require, there is no acquisition which we can give our children that will exert so important an influence on their material welfare as a knowledge of the laws of nature, under which they must live and to which they must conform; and throughout whose universal dominion the only question is whether men shall grovel as ignorant slaves or shall rule as intelligent servants. Yes; rule by obeying. "Ich Dien"; for only under that motto, which, five hundred years ago, the great Black Prince bore so victoriously through the fields of Cressy and Poitiers, can man ever rule in Nature's kingdom. [Pg 81]

I regard it, therefore, as the highest duty and the most enlightened self-interest of a community like this to provide the best means for the instruction of its children in the elements of physical science; and I was, therefore, most anxious to do all in my power to second the enlightened efforts of your eminent Superintendent in this direction. You must remember, however, that the best tools are worthless in themselves, and can secure no valuable results unless judiciously used. Indeed, there is danger in too many tools, and I have a great horror of that array of brass-work which is usually miscalled "philosophical" apparatus. The greater part of this is, in my opinion, a mere hindrance to the teacher, because it at once erects a barrier between the scholar and the simple facts of nature, and the child inevitably associates with the phenomenon illustrated some legerdemain, and looks on your experiments very much as he would on the exhibition of a Houdin or a Signor Blitz. The secret of success in teaching physical science is to use the simplest and most familiar means to illustrate your point.

When a very young man I was favored with an introduction to Michael Faraday, and had the privilege of attending a portion of a course of lectures which this noble man was then in the habit of giving every Christmas season to a juvenile auditory at the Royal Institution of London. As a boy, I had become familiar with lectures on chemistry at the Lowell Institute, where they did not [Pg 82] lack the pomp of circumstance or the display of apparatus, and I had come to associate these elements with the conditions of success in lectures of this kind. What, then, was my surprise to find Faraday, the acknowledged leader of the world in his science, and who had every means of illustration at his command, using the plainest language and the simplest tools. When, in my youthful admiration at the result, I expressed, after one of the lectures, my surprise at the simplicity of the means employed, the great master replied: "That is the whole secret of interesting these young people. I always use the simplest means, but I never leave a point not illustrated. If I mention the force of gravitation I take up a stone and let it drop." At this distance of time, I can not be sure that I quote his exact language, but the lesson and the illustration I could not forget; and to this lesson, more than to any other one thing, I owe whatever success I have had as a teacher of physical science.

I repeat, therefore, it is not only useless but injurious in the education of young minds to present any department of physical science as a body of definitions, principles, laws, or theories; and that in elementary schools such facts only should be taught as can be verified either by the experience of the pupils or by the simplest experiments, which the pupils can repeat by themselves; and [Pg 83] now, after this discussion, I add, that the teacher must depend on his own ingenuity for his experiments, and on his intercourse with his pupils for his instruction.

But you will tell me all this involves grave difficulties, and conditions incompatible with our ordinary school life. I freely admit the difficulties, but I am none the less sure that, unless science can be taught on the principles I have endeavored to illustrate, it had better not be taught at all. I know very well that the proper teaching of physical science is wholly incompatible with our usual school methods. But this only proves to me that these methods ought to be changed, and I am persuaded that the changes required will benefit the literary and classical as well as the scientific courses of study. For do not the same general principles apply to the acquisition of knowledge in all subjects? And when a child's perceptive faculties have been duly stimulated, and his intelligence fully awakened, he will find interest in grammar, in literature, or in history, as well as in science.

In repelling the reproach of narrowness, to which our elective system at Cambridge undoubtedly frequently leads, how often have I urged the self-evident proposition that to arouse a love of study in any subject, I care not how subordinate its importance or how limited its scope, is to take the first step toward making your man a scholar; while to fail to gain his interest in any [Pg 84] study is to lose the whole end of education—and what is true of the man is still more true of the child. Classical culture on the one hand and scientific culture on the other are excellent things, but, if your boy can not be made to take an interest either in classics or in science, how plain it is that such treasures are not for him, and, in the absence of the one condition which can give value to any study, how idle and inconsequent all questions in regard to the relative merits of these studies appear! On the other hand, a love of study once gained, all studies are alike good.

And as with the pupil, so with the teacher. No teaching is of any real value that does not come directly from the intelligence, and heart of the teacher, and thus appeals to the intelligence and heart of the pupil. It, of course, implies more acquisition, and it requires far more energy to teach from one's own knowledge than to teach from a book, but then, just in proportion to the difficulties overcome, does the teacher raise his profession and ennoble himself. There is no nobler service than the life of a true teacher; but the mere task-master has no right to the teacher's name, and can never attain the teacher's reward. [Pg 85]

IV.

THE RADIOMETER:

A FRESH EVIDENCE OF A MOLECULAR UNIVERSE.

A Lecture delivered in the Sanders Theatre of Harvard University, March 6, 1878.

No one who is not familiar with the history of physical science can appreciate how very modern are those grand conceptions which add so much to the loftiness of scientific studies; and, of the many who, on one of our starlit nights, look up into the depths of space, and are awed by the thoughts of that immensity which come crowding upon the mind, there are few, I imagine, who realize the fact that almost all the knowledge which gives such great sublimity to that sight is the result of comparatively recent scientific investigation; and that the most elementary student can now gain conceptions of the immensity of the universe of which the fathers of astronomy never dreamed. And how very grand are the familiar astronomical facts which the sight of the starry [Pg 86] heavens suggests!

Those brilliant points are all suns like the one which forms the center of our system, and around which our earth revolves; yet so inconceivably remote, that, although moving through space with an incredible velocity, they have not materially changed their relative position since recorded observations began. Compared with their distance, the distance of our own sun—92,000,000 miles—seems as nothing; yet how inconceivable even that distance is when we endeavor to mete it out with our terrestrial standards! For if, when Copernicus—the great father of modern astronomy—died, in 1543, just at the close of the Protestant Reformation, a messenger had started for the sun, and traveled ever since with the velocity of a railroad train—thirty miles an hour—he would not yet have reached his destination!

Evidently, then, no standards, which, like our ordinary measures, bear a simple or at least a conceivable relation to the dimensions of our own bodies, can help us to stretch a line in such a universe. We must seek for some magnitude which is commensurate with these immensities of space; and, in the wonderfully rapid motion of light, astronomy furnishes us with a suitable standard. By the eclipses of Jupiter's satellites the astronomers have determined that this mysterious effluence reaches us from the sun in eight minutes and a half, and therefore must [Pg 87] travel through space with the incredible velocity—shall I dare to name it?—of 186,000 miles in a second of time! Yet, inconceivably rapid as this motion is, capable of girdling the earth nearly eight times in a single second, the very nearest of the fixed stars, α Centauri, is so remote that the light by which it will be seen in the southern heavens to-night, near that magnificent constellation, the Southern Cross, must have started on its journey three years and a half ago. But this light comes from merely the threshold of the stellar universe; and the telescope reveals to us stars so distant that, had they been blotted out of existence when history began, the tidings of the event could not yet have reached the earth!

Compare now with these grand conceptions the popular belief of only a few centuries back. Where we look into the infinite depths, our Puritan forefathers saw only a solid dome hemming in the earth and skies, and through whose opened doors the rain descended. They regarded the sun and moon merely as great luminaries set in this firmament to rule the day and night, and to their understandings the stars served no better purpose than the spangles which glitter on the azure ceiling of many a modern church. The great work of Copernicus, "De Orbium Cœlestium Revolutionibus," which was destined, ultimately, to overthrow the crude cosmography which [Pg 88] Christianity had inherited from Judaism, was not published until just at the close of the author's life in 1543, the date before mentioned. The telescope, which was required to fully convince the world of its previous error, was not invented until more than half a century later, and it was not until 1835 that Struve detected the parallax of α Lyræ. The measurement of this parallax, together with Bessel's determination of the parallax of 61 Cygni, and Henderson's that of α Centauri, at about the same time, gave us our first accurate knowledge of the distances of the fixed stars.

To the thought I have endeavored to express, I must add another, before I can draw the lesson which I wish to teach. Great scientific truths become popularized very slowly, and, after they have been thoroughly worked out by the investigators, it is often many years before they become a part of the current knowledge of mankind. It was fully a century after Copernicus died, with his great volume—still wet from the press of Nuremberg—in his hands, before the Copernican theory was generally accepted even by the learned; and the intolerant spirit with which this work was received and the persecution which Galileo encountered more than half a century later were due solely to the circumstance that the new theory tended to subvert the popular faith in the cosmography of the Church. In modern times, with the many popular expositors of science, the [Pg 89] diffusion of new truth is more rapid; but even now there is always a long interval after any great discovery in abstract science before the new conception is translated into the language of common life, so that it can be apprehended by the mass even of educated men.

I have thus dwelt on what must be familiar facts in the past history of astronomy, because they illustrate and will help you to realize the present condition of a much younger branch of physical science; for, in the transition period I have described, there exists now a conception which opens a vision into the microcosmos beneath us as extensive and as grand as that which the Copernican theory revealed into the macrocosmos above us.

The conception to which I refer will be at once suggested to every scientific scholar by the word *molecule*. This word is a Latin diminutive, which means, primarily, a small mass of matter; and, although heretofore often applied in mechanics to the indefinitely small particles of a body between which the attractive or repulsive forces might be supposed to act, it has only recently acquired the exact significance with which we now use it.

In attempting to discover the original usage of the word molecule, I was surprised to find that it [Pg 90] was apparently first introduced into science by the great French naturalist, Buffon, who employed the term in a very peculiar sense. Buffon does not seem to have been troubled with the problem which so engrosses our modern naturalists—how the vegetable and animal kingdoms were developed into their present condition—but he was greatly exercised by an equally difficult problem, which seems to have been lost sight of in the present controversy, and which is just as obscure to-day as it was in Buffon's time, at the close of the last century, and that is, Why species are so persistent in Nature; why the acorn always grows into the oak, and why every creature always produces of its kind. And, if you will reflect upon it, I am sure you will conclude that this last is by far the more fundamental problem of the two, and one which necessarily includes the first. That, of two eggs, in which no anatomist can discover any structural difference, the one should, in a few short years, *develop* an intelligence like Newton's, while the other soon ends in a Guinea-pig, is certainly a greater mystery than that, in the course of unnumbered ages, monkeys, by insensible gradations, should *grow* into men.

In order to explain the remarkable constancy of species, Buffon advanced a theory which, when freed from a good deal that was fanciful, may be expressed thus: The attributes of every species, [Pg 91] whether of plants or of animals, reside in their ultimate particles, or, to use a more philosophical but less familiar word, *inhere* in these particles, which Buffon names *organic molecules*. According to Buffon, the oak owes all the peculiarities of its organization to the special oak molecules of which it consists; and so all the differences in the vegetable or animal kingdom, from the lowest to the highest species, depend on fundamental peculiarities with which their respective molecules were primarily endowed. There must, of course, be as many kinds of molecules as there are different species of living beings; but, while the molecules of the same species were supposed to be exactly alike, and to have a strong affinity or attraction for each other, those of different species were assumed to be inherently distinct and to have no such affinities. Buffon further assumed that these molecules of organic nature were diffused more or less widely through the atmosphere and through the soil, and that the acorn grew to the oak simply because, consisting itself of oak molecules, it could draw only oak molecules from the surrounding media.

With our present knowledge of the chemical constitution of organic beings, we can find a great deal that is both fantastic and absurd in this theory of Buffon; but it must be remembered that the science of chemistry is almost wholly a growth of the present century, while Buffon died in [Pg 92] 1788; and, if we look at the theory solely from the standpoint of his knowledge, we shall find in it much that was worthy of this great man. Indeed, in our time, the essential features of the theory of Buffon have been transferred from natural history to chemistry almost unchanged.

According to our modern chemistry, the qualities of every substance reside or inhere in its molecules. Take this lump of sugar. It has certain qualities with which every one is familiar. Are those qualities attributes of the lump or of its parts? Certainly of its parts; for, if we break up the lump, the smallest particles will still taste sweet and show all the characteristics of sugar. Could we, then, carry on this subdivision indefinitely, provided only we had senses or tests delicate enough to recognize the qualities of sugar in the resulting particles? To this question, modern chemistry answers decidedly, No! You would before long reach the smallest mass that can have the qualities of sugar. You would have no difficulty in breaking up these masses, but you would then obtain, not smaller particles of sugar, but particles of those utterly different substances which we call carbon, oxygen, and hydrogen—in a word, particles of the elementary substances of which sugar consists. These ultimate particles of sugar we call the molecules of sugar, and [Pg 93] thus we come to the present chemical definition of a molecule, "*The smallest particles of a substance in which its qualities inhere*," which, as you see, is a reproduction of Buffon's idea, although applied to matter and not to organism.

A lump of sugar, then, has its peculiar qualities because it is an aggregate of molecules which have those qualities, and a lump of salt differs from a lump of sugar simply because the molecules of salt differ from those of sugar, and so with every other substance. There are as many kinds of molecules in Nature as there are different substances, but all the molecules of the same substance are absolutely alike in every respect.

Thus far, as you see, we are merely reviving in a different association the old ideas of Buffon. But just at this point comes in a new conception, which gives far greater grandeur to our modern theory: for we conceive that those smallest particles in which the qualities of a substance inhere are definite bodies or systems of bodies moving in space, and that *a lump of sugar is a universe of* *moving worlds*.

If on a clear night you direct a telescope to one of the many star-clusters of our northern heavens, you will have presented to the eye as good a diagram as we can at present draw of what we suppose would, under certain circumstances, be seen in a lump of sugar if we could look into [Pg 94] the molecular universe with the same facility with which the telescope penetrates the depths of space.

Do you tell me that the absurdities of Buffon were wisdom when compared with such wild speculations as these? The criticism is simply what I expected, and I must remind you that, as I intimated at the outset, this conception of modern science is in the transition period of which I then spoke, and, although very familiar to scientific scholars, has not yet been grasped by the popular mind. I can further only add that, wild as it may appear, the idea is the growth of legitimate scientific investigation, and express my conviction that it will soon become as much a part of the popular belief as those grand conceptions of astronomy to which I have referred.

Do you rejoin that we can see the suns in a stellar cluster, but can not even begin to see the molecules? I must again remind you that, in fact, you only see points of light in the field of the telescope, and that your knowledge that these points are immensely distant suns is an inference of astronomical science; and, further, that our knowledge—if I may so call our confident belief—that the lump of sugar is an aggregate of moving molecules is an equally legitimate inference of molecular mechanics, a science which, although so much newer, is as positive a field of study as astronomy. Moreover, sight is not the only avenue to knowledge; and, although our material [Pg 95] limitations forbid us to expect that the microscope will ever be able to penetrate the molecular universe, yet we feel assured that we have been able by strictly experimental methods to weigh molecular masses and measure molecular magnitudes with as much accuracy as those of the fixed stars.

Of all forms of matter the gas has the simplest molecular structure, and, as might be anticipated, our knowledge of molecular magnitudes is as yet chiefly confined to materials of this class. I have given below some of the results which have been obtained in regard to the molecular magnitudes of hydrogen gas, one of the best studied of this class of substances; and, although the vast numbers are as inconceivable as are those of astronomy, they can not fail to impress you with the reality of the magnitudes they represent. I take hydrogen gas for my illustration rather than air, because our atmosphere is a mixture of two gases, oxygen and nitrogen, and therefore its condition is less simple than that of a perfectly homogeneous material like hydrogen. The molecular dimensions of other substances, although varying very greatly in their relative values, are of the same order of magnitude as these.[A]

Dimension of Hydrogen Molecules calculated for Temperature of Melting Ice, and for the Mean [Pg 96] *Height of the Barometer of the Sea Level:*

> Mean velocity, 6,099 feet a second.
> Mean path, 31 ten-millionths of an inch.
> Collisions, 17,750 millions each second.
> Diameter, 438,000, side by side, measure $^1/_{100}$ of an inch.
> Mass, 14 (millions^3) weigh $^1/_{1000}$ of a grain.
> Gas-volume, 311 (millions^3) fill one cubic inch.

To explain how the values here presented were obtained would be out of place in a popular lecture,[B] but a few words in regard to two or three of the data are required to elucidate the [Pg 97] subject of this lecture.

First, then, in regard to the mass or weight of the molecules. So far as their relative values are concerned, chemistry gives us the means of determining the molecular weights with very great accuracy; but when we attempt to estimate their weights in fractions of a grain—the smallest of our common standards—we can not expect precision, simply because the magnitudes compared are of such a different order; and the same is true of most of the other absolute dimensions, such as the diameter and volume of the molecules. We only regard the values given in our table as a very rough estimate, but still we have good grounds for believing that they are sufficiently accurate to give us a true idea of the order of the quantities with which we are dealing; and it will be seen that, although the numbers required to express the relations to our ordinary standards are so large, these molecular magnitudes are no more removed from us on the one side than are those of astronomy on the other.

Passing next to the velocity of the molecular motion, we find in that a quantity which, although large, is commensurate with the velocity of sound, the velocity of a rifle-ball, and the velocities of [Pg 98] many other motions with which we are familiar. We are, therefore, not comparing, as before, quantities of an utterly different order, and we have confidence that we have been able to determine the value within very narrow limits of error. But how surprising the result is! Those molecules of hydrogen are constantly moving to and fro with this great velocity, and not only are the molecules of all aëriform substances moving at similar, although differing rates, but the same is equally true of the molecules of every substance, whatever may be its state of aggregation.

The gas is the simplest molecular condition of matter, because in this state the molecules are so far separated from each other that their motions are not influenced by mutual attractions. Hence, in accordance with the well-known laws of motion, gas molecules must always move in straight lines and with a constant velocity until they collide with each other or strike against the walls of the containing vessel, when, in consequence of their elasticity, they at once rebound and start on a new path with a new velocity. In these collisions, however, there is no loss of motion, for, as the molecules have the same weight and are perfectly elastic, they simply change velocities, and whatever one may lose the other must gain.

But, if the velocity changes in this way, you may ask, What meaning has the definite value given [Pg 99] in our table? The answer is, that this is the mean value of the velocity of all the molecules in a mass of hydrogen gas under the assumed conditions; and, by the principle just stated, the mean value can not be changed by the collisions of the molecules among themselves, however great may be the change in the motion of the individuals.

In both liquids and solids the molecular motions are undoubtedly as active as in a gas, but they must be greatly influenced by the mutual attractions which hold the particles together, and hence the conditions are far more complicated, and present a problem which we have been able to solve only very imperfectly, and with which, fortunately, we have not at present to deal.

Limiting, then, our study to the molecular condition of a gas, picture to yourselves what must be the condition of our atmosphere, with its molecules flying about in all directions. Conceive what a molecular storm must be raging about us, and how it must beat against our bodies and against every exposed surface. The molecules of our atmosphere move, on an average, nearly four (3·8) times slower than those of hydrogen under the same conditions; but then they weigh, on an average, fourteen and a half times more than hydrogen molecules, and therefore strike with as great energy. And do not think that the effect of these blows is insignificant because the [Pg 100] molecular projectiles are so small; they make up by their number for what they want in size.

Consider, for example, a cubic yard of air, which, if measured at the freezing-point, weighs considerably over two pounds. That cubic yard of material contains over two pounds of molecules, which are moving with an average velocity of 1,605 feet a second, and this motion is equivalent, in every respect, to that of a cannon-ball of equal weight rushing along its path at the same tremendous rate. Of course, this is true of every cubic yard of air at the same temperature; and, if the motion of the molecules of the atmosphere around us could by any means be turned into one and the same direction, the result would be a hurricane sweeping over the earth with this velocity—that is, at the rate of 1,094 miles an hour—whose destructive violence not even the Pyramids could withstand.

Living as we do in the midst of a molecular tornado capable of such effects, our safety lies wholly in the circumstance that the storm beats equally in all directions at the same time, and the force is thus so exactly balanced that we are wholly unconscious of the tumult. Not even the aspen-leaf is stirred, nor the most delicate membrane broken; but let us remove the air from one of the surfaces of such a membrane, and then the power of the molecular storm becomes evident, as in [Pg 101] the familiar experiments with an air-pump.

As has already been intimated, the values of the velocities both of hydrogen and of air molecules given above were measured at a definite temperature, 32° of our Fahrenheit thermometer, the freezing point of water; and this introduces a very important point bearing on our subject, namely, that the molecular velocities vary very greatly with the temperature. Indeed, according to our theory, this very molecular motion constitutes that state or condition of matter which we call temperature. A hot body is one whose molecules are moving comparatively rapidly, and a cold body one in which they are moving comparatively slowly. Without, however, entering into further details, which would involve the whole mechanical theory of heat, let me call your attention to a single consequence of the principle I have stated.

When we heat hydrogen, air, or any mass of gas, we simply increase the velocity of its moving molecules. When we cool the gas, we simply lessen the velocity of the same molecules. Take a current of air which enters a room through a furnace. In passing it comes in contact with heated iron, and, as we say, is heated. But, as we view the process, the molecules of the air, while in contact with the hot iron, collide with the very rapidly oscillating metallic molecules, and fly back as a billiard-ball would under similar circumstances, with a greatly increased velocity, and it is [Pg 102] this more rapid motion which alone constitutes the higher temperature.

Consider, next, what must be the effect on the surface. A moment's reflection will show that the normal pressure exerted by the molecular storm, always raging in the atmosphere, is due not only to the impact of the molecules, but also to the reaction caused by their rebound. When the molecules rebound, they are, as it were, driven away from the surface in virtue of the inherent elasticity both of the surface and of the molecules. Now, what takes place when one mass of matter is driven away from another—when a cannon-ball is driven out of a gun, for example? Why, the gun *kicks*! And so every surface from which molecules rebound must *kick*; and, if the velocity is not changed by the collision, one half of the pressure caused by the molecular bombardment is due to the recoil. From a heated surface, as we have said, the molecules rebound with an increased velocity, and hence the recoil must be proportionally increased, determining a greater pressure against the surface.

According to this theory, then, we should expect that the air would press unequally against surfaces at different temperatures, and that, other things being equal, the pressure exerted would be greater the higher the temperature of the surface. Such a result, of course, is wholly [Pg 103] contrary to common experience, which tells us that a uniform mass of air presses equally in all directions and against all surfaces of the same area, whatever may be their condition. It would seem, then, at first sight, as if we had here met with a conspicuous case in which our theory fails. But further study will convince us that the result is just what we should expect in a dense atmosphere like that in which we dwell; and, in order that this may become evident, let me next call your attention to another class of molecular magnitudes.

It must seem strange indeed that we should be able to measure molecular velocities; but the next point I have to bring to your notice is stranger yet, for we are confident that we have been able to determine with approximate accuracy for each kind of gas molecule the average number of times one of these little bodies runs against its neighbors in a second, assuming, of course, that the conditions of the gas are given. Knowing, now, the molecular velocity and the number of collisions a second, we can readily calculate the mean path of the molecule—that is, the average distance it moves, under the same conditions, between two successive collisions. Of course, for any one molecule, this path must be constantly varying; since, while at one time the molecule may find a clear coast and make a long run, the very next time it may hardly start before its [Pg 104]
course is arrested. Still, taking a mass of gas under constant conditions, the doctrine of averages shows that the mean path must have a definite value, and an illustration will give an idea of the manner in which we have been able to estimate it.

The nauseous, smelling gas we call sulphide of hydrogen has a density only a little greater than that of air, and its molecules must therefore move with very nearly as great velocity as the average air molecule—that is to say, about fourteen hundred and eighty feet a second; and we might therefore expect that, on opening a jar of the gas, its molecules would spread instantly through the surrounding atmosphere. But, so far from this, if the air is quiet, so that the gas is not transported by currents, a very considerable time will elapse before the characteristic odor is perceived on the opposite side of an ordinary room. The reason is obvious: the molecules must elbow their way through the crowd of air molecules which already occupy the space, and can therefore advance only slowly; and it is obvious that, the oftener they come into collision with their neighbors, the slower their progress must be. Knowing, then, the mean velocity of the molecular motion, and being able to measure by appropriate means *the rate of diffusion*, as it is called, we have the data from which we can calculate both the number of collisions in a second [Pg 105]
and also the mean path between two successive collisions. The results, as we must expect, are of the same order as the other molecular magnitudes. But, inconceivably short as the free[C] path of a molecule certainly is, it is still, in the case of hydrogen gas, 136 times the diameter of the moving body, which would certainly be regarded among men as quite ample elbow-room.

Although, in this lecture, I have as yet had no occasion to mention the radiometer, I have by no means forgotten my main subject, and everything which has been said has had a direct bearing on the theory of this remarkable instrument; and still, before you can understand the great interest with which it is regarded, we must follow out another line of thought, converging on the same point.

One of the most remarkable results of modern science is the discovery that all energy at work on the surface of this planet comes from the sun. Most of you probably saw, at our Centennial Exhibition, that great artificial cascade in Machinery Hall, and were impressed with the power of [Pg 106]
the steam-pump which could keep flowing such a mass of water. But, also, when you stood before the falls at Niagara, did you realize the fact that the enormous floods of water which you saw surging over those cliffs were in like manner supplied by an all-powerful pump, and that pump the sun? And not only is this true, but it is equally true that every drop of water that falls, every wave that beats, every wind that blows, every creature that moves on the surface of the earth, one and all, are animated by that mysterious effluence we call the sunbeam. I say mysterious effluence; for how that power is transmitted over those 92,000,000 miles between the earth and the sun is still one of the greatest mysteries of Nature.

In the science of optics, as is well known, the phenomena of light are explained by the assumption that the energy is transmitted in waves through a medium which fills all space called the luminiferous ether, and there is no question that this theory of Nature, known in science as the Undulatory Theory of Light, is, as a working hypothesis, one of the most comprehensive and searching which the human mind has ever framed. It has both correlated known facts and pointed the way to remarkable discoveries. But, the moment we attempt to apply it to the problem before us, it demands conditions which tax even a philosopher's credulity. [Pg 107]

As sad experience on the ocean only too frequently teaches, energy can be transmitted by waves as well as in any other way. But every mechanic will tell you that the transmission of energy, whatever be the means employed, implies certain well-known conditions. Assume that the energy is to be used to turn the spindles of a cotton mill. The engineer can tell you just how many horse-power he must supply for every working-day, and it is equally true that a definite amount of energy must come from the sun to do each day's work on the surface of the globe. Further, the engineer will also tell you that, in order to transmit the power from his turbine or his steam-engine, he must have shafts and pulleys and belts of adequate strength, and he knows in every case what is the lowest limit of safety. In like manner, the medium through which the energy which runs the world is transmitted must be strong enough to do the immense work put upon it; and, if the energy is transmitted by waves, this implies that the medium must have an enormously great elasticity, an elasticity vastly greater than that of the best-tempered steel.

But turn now to the astronomers, and learn what they have to tell us in regard to the assumed luminiferous ether through which all this energy is supposed to be transmitted. Our planet is rushing in its orbit around the sun at an average rate of over 1,000 miles a minute, and makes its [Pg 108] annual journey of some 550,000,000 miles in 365 days, 6 hours, 9 seconds, and $\frac{6}{10}$ of a second. Mark the tenths; for astronomical observations are so accurate that, if the length of the year varied permanently by the tenth of a second, we should know it; and you can readily understand that, if there were a medium in space which offered as much resistance to the motion of the earth as would gossamer threads to a race-horse, the planet could never come up to time, year after year, to the tenth of a second.

How, then, can we save our theory by which we set so much, and rightly, because it has helped us so effectively in studying Nature? If we may be allowed such an extravagant solecism, let us suppose that the engineer of our previous illustration was the hero of a fairy tale. He has built a mill, set a steam-engine in the basement, arranged his spindles above, and is connecting the pulleys by the usual belts, when some stern necessity requires him to transmit all the energy with cobwebs. Of course, a good fairy comes to his aid, and what does she do? Simply makes the cobwebs indefinitely strong. So the physicists, not to be outdone by any fairies, make their ether indefinitely elastic, and their theory lands them just here, with a medium filling all space, thousands of times more elastic than steel, and thousands on thousands of times less dense than hydrogen gas. There must be a fallacy somewhere, and I strongly suspect it is to be found in our [Pg 109] ordinary materialistic notions of causation, which involve the old metaphysical dogma, "*nulla actio in distans*," and which in our day have culminated in the famous apothegm of the German materialist, "Kein Phosphor kein Gedanke."

But it is not my purpose to discuss the doctrines of causation, and I have dwelt on the difficulty, which this subject presents in connection with the undulatory theory, solely because I wished you to appreciate the great interest with which scientific men have looked for some direct manifestation of the mechanical action of light. It is true that the ether waves must have dimensions similar to those of the molecules discussed above, and we must expect, therefore, that they would act primarily on the molecules and not on masses of matter. But still the well-known principles of wave motion have led competent physicists to maintain that a more or less considerable pressure ought to be exerted by the ether waves on the surfaces against which they beat, as a partial resultant of the molecular tremors first imparted. Already, in the last century, attempts were made to discover some evidence of such action, and in various experiments the sun's direct rays were concentrated on films, delicately suspended and carefully protected from all other extraneous influences, but without any apparent effect; and thus the question remained [Pg 110] until about three years ago, when the scientific world were startled by the announcement of Mr. Crookes, of London, that, on suspending a small piece of blackened alder pith in the very perfect vacuum which can now be obtained with the mercury pump, invented by Sprengel, he had seen this light body actually repelled by the sun's rays; and they were still more startled, when, after a few further experiments, he presented us with the instrument he called a radiometer, in which the sun's rays do the no inconsiderable work of turning a small wheel. Let us examine for a moment the construction of this remarkable instrument.

The moving part of the radiometer is a small horizontal wheel, to the ends of whose arms are fastened vertical vanes, usually of mica, and blackened on one side. A glass cap forms the hub, and by the glass-blower's art the wheel is inclosed in a glass bulb, so that the cap rests on the point of a cambric needle; and the wheel is so delicately balanced on this pivot that it turns with the greatest freedom. From the interior of the bulb the air is now exhausted by means of the Sprengel pump, until less than $\frac{1}{1000}$ of the original quantity is left, and the only opening is then hermetically sealed. If, now, the sun's light or even the light from a candle shines on the vanes, the blackened surfaces—which are coated with lampblack—are repelled, and, these being [Pg 111] symmetrically placed around the wheel, the several forces conspire to produce the rapid motion which results. The effect has all the appearance of a direct mechanical action exerted by the light, and for some time was so regarded by Mr. Crookes and other eminent physicists, although in his published papers it should be added that Mr. Crookes carefully abstained from speculating on the subject—aiming, as he has since said, to keep himself unbiased by any theory, while he accumulated the facts upon which a satisfactory explanation might be based.

Singularly, however, the first aspects of the new phenomena proved to be wholly deceptive, and the motion, so far from being an effect of the direct mechanical action of the waves of light, is now believed to be a new and very striking manifestation of molecular motion. To this opinion Mr. Crookes himself has come, and, in a recent article, he writes: "Twelve months' research, however, has thrown much light on these actions, and the explanation afforded by the dynamical theory of gases makes what was a year ago obscure and contradictory now reasonable and intelligible."

As is frequently the case in Nature, the chief effect is here obscured by various subordinate phenomena, and it is not surprising that a great difference of opinion should have arisen in regard to the cause of the motion. This would not be an appropriate place to describe the [Pg 112] numerous investigations occasioned by the controversy, many of which show in a most striking manner how easily experimental evidence may be honestly misinterpreted in support of a preconceived opinion. I will, however, venture to trespass further on your patience, so far as to describe the few experiments by which, very early in the controversy, I satisfied my own mind on the subject.

When, two years ago, I had for the first time an opportunity of experimenting with a radiometer, the opinion was still prevalent that the motion of the wheel was a direct mechanical effect of the waves of light, and, therefore, that the impulses came from the outside of the instrument, the waves passing freely through the glass envelope. At the outset, this opinion did not seem to me to be reasonable, or in harmony with well-known facts; for, knowing how great must be the molecular disturbance caused by the sun's rays, as shown by their heating power, I could not believe that a residual action, such as has been referred to, would first appear in these delicate phenomena observed by Mr. Crookes, and should only be manifested in the vacuum of a mercury pump.

On examining the instrument, my attention was at once arrested by the lampblack coating on the alternate surfaces of the vanes; and, from the remarkable power of lampblack to absorb radiant heat, it was evident at once that, whatever other effects the rays from the sun or from a flame [Pg 113] might cause, they must necessarily determine a constant difference of temperature between the two surfaces of the vanes, and the thought at once occurred that, after all, the motion might be a direct result of this difference of temperature—in other words, that the radiometer might be a small heat engine, whose motions, like those of every other heat engine, depend on the difference of temperature between its parts.

But, if this were true, the effect ought to be proportional solely to the heating power of the rays, and a very easy means of roughly testing this question was at hand. It is well known that an aqueous solution of alum, although transmitting light as freely as the purest water, powerfully absorbs those rays, of any source, which have the chief heating power. Accordingly, I interposed what we call an alum cell in the path of the rays shining on the radiometer, when, although the light on the vanes was as bright as before, the motion was almost completely arrested.

This experiment, however, was not conclusive, as it might still be said that the *heat*-giving rays acted *mechanically*, and it must be admitted that the chief part of the energy in the rays, even from the most brilliant luminous sources, always takes the form of heat. But, if the action is mechanical, the reaction must be against the medium through which the rays are transmitted, [Pg 114] while, if the radiometer is simply a heat engine, the action and reaction must be, ultimately at least, between the heater and the cooler, which in this case are respectively the blackened surfaces of the vanes and the glass walls of the inclosing bulb; and here, again, a very easy method of testing the actual condition at once suggested itself.

If the motion of the radiometer wheel is an effect of mechanical impulses transmitted in the direction of the beam of light, it was certainly to be expected that the beam would act on the lustrous as well as on the blackened mica surfaces, however large might be the difference in the resultants producing mechanical motion, in consequence of the great absorbing power of the lampblack. Moreover, since the instrument is so constructed that, of two vanes on opposite sides of the wheel, one always presents a blackened and the other a lustrous surface to an incident beam, we should further expect to find in the motion of the wheel a differential phenomenon, due to the unequal action of the light on these surfaces. On the other hand, if the radiometer is a heat engine, and the reaction takes place between the heated blackened surfaces of the vanes and the colder glass, it is evident that the total effect will be simply the sum of the effects at the several surfaces.

In order to investigate the question thus presented, I placed the radiometer before a common kerosene lamp, and observed, with a stop-watch, the number of seconds that elapsed during ten [Pg 115] revolutions of the little wheel. Finding that this number was absolutely constant, I next screened one half of the bulb, so that only the blackened faces were exposed to the light as the wheel turned them into the beam. Again, I several times observed the number of seconds during ten turns, which, although equally constant, was greater than before. Lastly, I screened the blackened surfaces so that, as the wheel turned, only the lustrous surfaces of mica were exposed to the light, when, to my surprise, the wheel continued to turn in the same direction as before, although much more slowly. It appeared as if the lustrous surfaces were attracted by the light. Again I observed the time of ten revolutions, and here I have collected my results, reducing them, in the last column, so as to show the corresponding number of revolutions in the same time:

CONDITIONS.	**Time of ten revolutions.**	**No. of revolutions in same time.**
Both faces exposed	8 seconds.	319
Blackened faces only	11 "	232
Mica faces only	29 "	88

It will be noticed that 88 + 232 equals very nearly 319. Evidently the effect, so far from being differential, is concurrent. Hence, the action which causes the motion must take place between the parts of the instrument, and can not be a direct effect of impulses imparted by ether waves; [Pg 116] or else we are driven to the most improbable alternative, that lampblack and mica should have such a remarkable selective power that the impulses imparted by the light should exert a repulsive force at one surface and an attractive force at the other. Were there, however, such an improbable effect, it must be independent of the thickness of the mica vanes; while, on the other hand, if, as seemed to us now most probable, the whole effect depended on the difference of temperature between the lampblack and the mica, and if the light produced an effect on the mica surface only because, the mica plate being diathermous to a very considerable extent, the lampblack became heated through the plate more than the plate itself, then it would follow that, if we used a thicker mica plate, which would absorb more of the heat, we ought to obtain a marked difference of effect. Accordingly, we repeated the experiment with an equally sensitive radiometer, which we made for the purpose, with comparatively thick vanes, and with this the effect of a beam of light on the mica surface was absolutely null, the wheel revolving in the same time, whether these faces were protected or not.

But one thing was now wanting to make the demonstration complete. A heat engine is reversible, and if the motion of the radiometer depended on the circumstance that the temperature of the [Pg 117] blackened faces of the vanes was higher than that of the glass, then by reversing the conditions we ought to reverse the motion. Accordingly, I carefully heated the glass bulb over a lamp, until it was as hot as the hand would bear, and then placed the instrument in a cold room, trusting to the great radiating power of lampblack to maintain the temperature of the blackened surfaces of the vanes below that of the glass. Immediately the wheel began to turn in the opposite direction, and continued to turn until the temperature of the glass came into equilibrium with the surrounding objects.

These early experiments have since been confirmed to the fullest extent, and no physicist at the present day can reasonably doubt that the radiometer is a very beautiful example of a heat engine, and it is the first that has been made to work continuously by the heat of the sunbeam. But it is one thing to show that the instrument is a heat engine, and quite another thing to explain in detail the manner in which it acts. In regard to the last point, there is still room for much difference of opinion, although physicists are generally agreed in referring the action to the residual gas that is left in the bulb. As for myself, I became strongly persuaded—after experimenting with more than one hundred of these instruments, made under my own eye, with every variation of condition I could suggest—*that the effect was due to the same cause which* [Pg 118] *determines gas pressure*, and, according to the dynamical theory of gases, this amounts to saying that the effect is due to molecular motion. I have not time, however, to describe either my own experiments on which this opinion was first based, or the far more thorough investigations since made by others, which have served to strengthen the first impression.[D] But, after our previous discussions, a few words will suffice to show how the molecular theory explains the new phenomena.

Although the air in the bulb has been so nearly exhausted that less than the one-thousandth part remains, yet it must be borne in mind that the number of molecules left behind is by no means inconsiderable. As will be seen by referring to our table, there must still be no less than 311,000 million million in every cubic inch. Moreover, the absolute pressure which this residual gas exerts is a very appreciable quantity. It is simply the one-thousandth of the normal pressure of the atmosphere, that is, of $14\frac{7}{10}$ pounds on a square inch, which is equivalent to a little over one hundred grains on the same area. Now, the area of the blackened surfaces of the vanes of an ordinary radiometer measures just about a square inch, and the wheel is mounted so delicately that a constant pressure of one-tenth of a grain would be sufficient to produce rapid motion. So [Pg 119] that a difference of pressure on the opposite faces of the vanes, equal to one one-thousandth of the whole amount, is all that we need account for; and, as can easily be calculated, a difference of temperature of less than half a degree Fahrenheit would cause all this difference in the pressure of the rarefied air.

But you may ask, How can such a difference of pressure exist on different surfaces exposed to one and the same medium? and your question is a perfectly legitimate one; for it is just here that the new phenomena seem to belie all our previous experience. If, however, you followed me in my very partial exposition of the mechanical theory of gases, you will easily see that on this theory it is a more difficult question to explain why such a difference of pressure does not manifest itself in every gas medium and under all conditions between any two surfaces having different temperatures.

We saw that gas pressure is a double effect, caused both by the impact of molecules and by the recoil of the surface attending their rebound. We also saw that when molecules strike a heated surface they rebound with increased velocity, and hence produce an increased pressure against the surface, the greater the higher the temperature. According to this theory, then, we should expect to find the same atmosphere pressing unequally on equal surfaces if at different [Pg 120] temperatures; and the difference in the pressure on the lampblack and mica surfaces of the vanes, which the motion of the radiometer wheel necessarily implies, is therefore simply the normal effect of the mechanical condition of every gas medium. The real difficulty is, to explain why we must exhaust the air so perfectly before the effect manifests itself.

The new theory is equal to the emergency. As has been already pointed out, in the ordinary state of the air the amplitude of the molecular motion is exceedingly small, not over a few ten-millionths of an inch—a very small fraction, therefore, of the height of the inequalities on the lampblack surfaces of the vanes of a radiometer. Under such circumstances, evidently the molecules would not leave the heated surface, but simply bound back and forth between the vanes and the surrounding mass of dense air, which, being almost absolutely a non-conductor of heat, must act essentially like an elastic solid wall confining the vanes on either side. For the time being, and until replaced by convection currents, the oscillating molecules are as much a part of the vanes as our atmosphere is a part of the earth; and on this system, as a whole, the homogeneous dense air which surrounds it must press equally from all directions. In proportion, however, as the air is exhausted, the molecules find more room and the amplitude of the [Pg 121] molecular motion is increased, and, when a very high degree of exhaustion is reached, the air particles no longer bound back and forth on the vanes without change of condition, but they either bound off entirely like a ball from a cannon, or else, having transferred a portion of their momentum, return with diminished velocity, and in either case the force of the reaction is felt.[E]

Thus it appears that we have been able to show by very definite experimental evidence that the radiometer is a heat engine. We have also been able to show that such a difference of temperature as the radiation must produce in the air in *direct* contact with the opposite faces of the vanes of the radiometer would determine a difference of tension, which is sufficient to account for the motion of the wheel. Finally, we have shown, as fully as is possible in a popular lecture, that, according to the mechanical theory of gases, such a difference of tension would have its normal effect only in a highly rarefied atmosphere, and thus we have brought the new phenomena into harmony with the general principles of molecular mechanics previously established. [Pg 122]

More than this can not be said of the steam-engine, although, of course, in the older engine the measurements on which the theory is based are vastly more accurate and complete. But the moment we attempt to go beyond the general principles of heat engines, of which the steam-engine is such a conspicuous illustration, and explain how the heat is transformed into motion, we have to resort to the molecular theory just as in the case of the radiometer; and the motion of the steam-engine seems to us less wonderful than that of the radiometer only because it is more familiar and more completely harmonized with the rest of our knowledge. Moreover, the very molecular theory which we call upon to explain the steam-engine involves consequences which, as we have seen, have been first realized in the radiometer; and thus it is that this new instrument, although disappointing the first expectations of its discoverer, has furnished a very striking confirmation of this wonderful theory. Indeed, the confirmation is so remote and yet so close, so unexpected and yet so strong, that the new phenomena almost seem to be a direct manifestation of the molecular motion which our theory assumes; and when a new discovery thus confirms the accuracy of a previous generalization, and gives us additional reason to believe that the glimpses we have gained into the order of Nature are trustworthy, it excites, with reason, among scientific scholars the warmest interest. [Pg 123]

And when we consider the vast scope of the molecular theory, the order on order of existences which it opens to the imagination, how can we fail to be impressed with the position in which it places man midway between the molecular cosmos on the one side and the stellar cosmos on the other—a position in which he is able, in some measure at least, to study and interpret both? [Pg 124]

Since the time to which we referred at the beginning of this lecture, when man's dwelling-place was looked at as the center of a creation which was solely subservient to his wants, there has been a reaction to the opposite extreme, and we have heard much of the utter insignificance of the earth in a universe among whose immensities all human belongings are but as a drop in the ocean. When now, however, we learn from Sir William Thomson that the drop of water in our comparison is itself a universe, consisting of units so small that, were the drop magnified to the size of the earth, these units would not exceed in magnitude a cricket-ball,[F] and when, on studying chemistry, we still further learn that these units are not single masses but systems of atoms, we may leave the illusions of the imagination from the one side to correct those from the other, and all will teach us the great lesson that man's place in Nature is not to be estimated by relations of magnitude, but by the intelligence which makes the whole creation his own. [Pg 125]

But, if it is man's privilege to follow both the atoms and the stars in their courses, he finds that, while thus exercising the highest attributes of his nature, he is ever in the presence of an immeasurably superior intelligence, before which he must bow and adore, and thus come to him both the assurance and the pledge of a kinship in which his only real glory can be found.

[Pg 126]

V.

MEMOIR OF THOMAS GRAHAM.

Reprinted from the "Proceedings of the American Academy of Arts and Sciences," Vol. VIII, May 24, 1870.

It would be difficult to find in the history of science a character more simple, more noble, or more symmetrical in all its parts than that of Thomas Graham, and he will always be remembered as one of the most eminent of those great students of nature who have rendered our Saxon race illustrious. He was born of Scotch parents in Glasgow in the year 1805, and in that city, where he received his education, all his early life was passed. In 1837 he went to London as Professor of Chemistry in the newly established London University, now called University College, and he occupied this chair until the year 1855, when he succeeded Sir John Herschel as Master of the Royal Mint, a post which he held to the close of his life. His death, on the 16th of September last (1869), at the age of sixty, was caused by no active disease, but was simply the wearing out of a constitution enfeebled in youth by privations voluntarily and courageously encountered that he might devote his life to scientific study. As with all earnest students, that life was uneventful, if judged by ordinary standards; and the records of his discoveries form the only materials for his biography. [Pg 127]

Although one of the most successful investigators of physical science, the late Master of the Mint had not that felicity of language or that copiousness of illustration which added so much to the popular reputation of his distinguished contemporary, Faraday; but his influence on the progress of science was not less marked or less important. Both of these eminent men were for a long period of years best known to the English public as teachers of chemistry, but their investigations were chiefly limited to physical problems; yet, although both cultivated the border ground between chemistry and physics, they followed wholly different lines of research. While Faraday was so successfully developing the principles of electrical action, Graham with equal success was investigating the laws of molecular motion. Each followed with wonderful constancy, as well as skill, a single line of study from first to last, and to this concentration of power their great discoveries are largely due. [Pg 128]

One of the earliest and most important of Graham's investigations, and the one which gave the direction to his subsequent course of study, was that on the diffusion of gases. It had already been recognized that impenetrability in its ordinary sense is not, as was formerly supposed, a universal quality of matter. Dalton had not only recognized that aëriform bodies exhibit a positive tendency to mix, or to penetrate through each other, even in opposition to the force of gravity, but had made this quality of gases the subject of experimental investigation. He inferred, as the result of his inquiry, "that different gases afford no resistance to each other; but that one gas spreads or expands into the space occupied by another gas, as it would rush into a vacuum; at least, that the resistance which the particles of one gas offer to those of another is of a very imperfect kind, to be compared to the resistance which stones in the channel of a stream oppose to the flow of running water." But, although this theory of Dalton was essentially correct and involved the whole truth, yet it was supported by no sufficient evidence, and he failed to perceive the simple law which underlies this whole class of phenomena.

Graham, "on entering on this inquiry, found that gases diffuse into the atmosphere with different degrees of ease and rapidity." This was first observed by allowing each gas to diffuse from a bottle into the air through a narrow tube in opposition to the solicitation of gravity. Afterward an [Pg 129] observation of Doebereiner on the escape of hydrogen gas by a fissure or crack in a glass receiver caused him to vary the conditions of his experiments, and led to the invention of the well-known "diffusion tube." In this simple apparatus a thin septum of plaster of Paris is used to separate the diffusing gases, which, while it arrests in a great measure all direct currents between the two media, does not interfere with the molecular motion. Much later, Graham found in prepared graphite a material far better adapted to this purpose than the plaster, and he used septa of this mineral to confirm his early results, in answer to certain ill-considered criticisms in Bunsen's work on gasometry. These septa he was in the habit of calling his "atomic filters."

By means of the diffusion tube, Graham was able to measure accurately the relative times of diffusion of different gases, and he found that *equal volumes of any two gases interpenetrate each other in times which are inversely proportional to the square roots of their respective densities*; and this fundamental law was the greatest discovery of our late foreign associate. It is now universally recognized as one of the few great cardinal principles which form the basis of physical science.

It can be shown, on the principles of pneumatics, that gases should rush into a vacuum with [Pg 130] velocities corresponding to the numbers which have been found to express their diffusion times; and, in a series of experiments on what he calls the "*effusion*" of gases, Graham confirmed by trial this deduction of theory. In these experiments a measured volume of the gas was allowed to find its way into the vacuous jar through a minute aperture in a thin metallic plate, and he carefully distinguished between this class of phenomena and the flowing of gases through capillary tubes into a vacuum, in which case, however short the tube, the effects of friction materially modify the result. This last class of phenomena Graham likewise investigated, and designated by the term "transpiration."

While, however, it thus appears that the results of Graham's investigation were in strict accordance with Dalton's theory, it must also be evident that Graham was the first to observe the exact numerical relation which obtains in this class of phenomena, and that all-important circumstance entitles him to be regarded as the discoverer of the law of diffusion. The law, however, at first enunciated, was purely empirical, and Graham himself says that something more must be assumed than that gases are vacua to each other, in order to explain all the phenomena observed; and according to his original view this representation of the process was only a convenient mode of expressing the final result. Such has proved to be the case. [Pg 131]

Like other great men, Graham built better than he knew. In the progress of physical science during the last twenty-five years, two principles have become more and more conspicuous, until at last they have completely revolutionized the philosophy of chemistry. In the first place, it has appeared that a host of chemical as well as of physical facts are coördinated by the assumption that all substances in the state of gas have the same molecular volume, or, in other words, contain the same number of molecules in a given space; and in the second place, it has become evident that the phenomena of heat are simply the manifestations of molecular motion. According to this view, the temperature of a body is the *vis viva* of its molecules; and, since all molecules at a given temperature have the same *vis viva*, it follows that the molecules must move with velocities which are inversely proportional to the square roots of the molecular weights. Moreover, since the molecular volumes are equal, and the molecular weights therefore proportional to the densities of the aëriform bodies in which the molecules are the active units, it also follows that the velocities of the molecules in any two gases are inversely proportional to the square roots of their respective densities. Thus the simple numerical relations first observed in the phenomena of diffusion are the direct result of molecular motion; and it is now seen that [Pg 132] Graham's empirical law is included under the fundamental laws of motion. Thus Graham's investigation has become the basis of the new science of molecular mechanics, and his measurements of the rates of diffusion prove to be the measures of molecular velocities.

From the study of diffusion Graham passed by a natural transition to the investigation of a class of phenomena which, although closely allied to the first as to the effects produced, differ wholly in their essential nature. Here also he followed in the footsteps of Dalton. This distinguished chemist had noticed that a bubble of air separated by a film of water from an atmosphere of carbonic anhydride gradually expanded until it burst. In like manner a moist bladder, half filled with air and tied, if suspended in an atmosphere of the same material, becomes in time greatly distended by the insinuation of this gas through its substance. This effect can not be the result of simple diffusion, for it is to be remembered that the thinnest film of water, or of any liquid, is absolutely impermeable to a gas as such, and, moreover, only the carbonic anhydride passes through the film, very little or none of the air escaping outward. The result depends, first, upon the solution of the carbonic anhydride by the water on one surface of the film; secondly, on the [Pg 133] evaporation into the air, from the other surface, of the gas thus absorbed. Similar experiments were made by Drs. Mitchell and Faust, and others, in which gases passed through a film of India-rubber, entering into a partial combination with the material on one surface, and escaping from it on the other.

Graham not only considerably extended our knowledge of this class of phenomena, but also gave us a satisfactory explanation of the mode in which these remarkable results are produced. He recognized in these cases the action of a feeble chemical force, insufficient to produce a definite compound, but still capable of determining a more or less perfect union, as in the case of simple solution. He also distinguished the influence of mass in causing the formation or decomposition of such weak chemical compounds. The conditions of the phenomena under consideration are simply these:

First. A material for the septum capable of forming a feeble chemical union with the gas to be transferred.

Secondly. An excess of the gas on one side of the film and a deficiency on the other.

Thirdly. Such a temperature that the unstable compound may form at the surface, where the aëriform constituent is present in large mass, while it decomposes at the opposite surface, where the quantity is less abundant.

One of the most remarkable results of Graham's study of this peculiar mode of transfer of [Pg 134] aëriform matter through the very substance of solid bodies was an ingenious method of separating the oxygen from the atmosphere. The apparatus consisted simply of a bag of India-rubber kept distended by an interior framework, while it was exhausted by a Sprengel pump. Under these circumstances the selective affinity of the caoutchouc determines such a difference in the rate of transfer of the two constituents of the atmosphere that the amount of oxygen in the transpired air rises to forty per cent., and by repeating the process nearly pure oxygen may be obtained. It was at first hoped that this method might find a valuable application in the arts, but in this Graham was disappointed; for the same result has since been effected by purely chemical methods, which are both cheaper and more rapid.

These experiments on India-rubber naturally led to the study of similar effects produced with metallic septa, which, although to some extent previously observed in passing gases through heated metallic tubes, had been only imperfectly understood. Thus, when a stream of hydrogen or carbonic oxide is passed through a red-hot iron tube, a no inconsiderable portion of the gas escapes through the walls. The same is true to a still greater degree when hydrogen is passed through a red-hot tube of platinum, and Graham showed that, through the walls of a tube of [Pg 135] palladium, hydrogen gas passes, under the same conditions, almost as rapidly as water through a sieve. Moreover, our distinguished associate proved that this rapid transfer of gas through these dense metallic septa was due, as in the case of the India-rubber, to an actual chemical combination of its material with the metal, formed at the surface, where the gas is in excess, and as rapidly decomposed on the opposite face of the septum. He not only recognized as belonging to this class of phenomena the very great absorption of hydrogen by platinum plate and sponge in the familiar experiment of the Doebereiner lamp, but also showed that this gas is a definite constituent of meteoric iron—a fact of great interest from its bearing on the meteoric theory.

We are thus led to Graham's last important discovery, which was the justification of the theory we have been considering, and the crowning of this long line of investigation. As may be anticipated from what has been said, the most marked example of that order of chemical compounds, to which the metallic transpiration of aëriform matter we have been considering is due, is the compound of palladium with hydrogen. Graham showed that, when a plate of this metal is made the negative pole in the electrolysis of water, it absorbs nearly one thousand times its volume of hydrogen gas—a quantity approximatively equivalent to one atom of hydrogen to [Pg 136] each atom of palladium. He further showed that the metal thus becomes so profoundly altered as to indicate that the product of this union is a definite compound. Not only is the volume of the metal increased, but its tenacity and conducting power for electricity are diminished, and it acquires a slight susceptibility to magnetism, which the pure metal does not possess. The chemical qualities of this product are also remarkable. It precipitates mercury from a solution of its chloride, and in general acts as a strong reducing agent. Exposed to the action of chlorine, bromine, or iodine, the hydrogen leaves the palladium and enters into direct union with these elements. Moreover, although the compound is readily decomposed by heat, the gas can not be expelled from the metal by simple mechanical means.

These facts recall the similar relations frequently observed between the qualities of an alloy and those of the constituent metals, and suggest the inference made by Graham, that palladium charged with hydrogen is a compound of the same class—a conclusion which harmonizes with the theory long held by many chemists, that hydrogen gas is the vapor of a very volatile metal. This element, however, when combined with palladium, is in a peculiarly active state, which sustains somewhat the same relation to the familiar gas that ozone bears to ordinary oxygen. Hence Graham distinguished this condition of hydrogen by the term "hydrogenium." Shortly before his [Pg 137]
death a medal was struck at the Royal Mint from the hydrogen palladium alloy in honor of its discovery; but, although this discovery attracted public attention chiefly on account of the singular chemical relations of hydrogen, which it brought so prominently to notice, it will be remembered in the history of science rather as the beautiful termination of a life-long investigation, of which the medal was the appropriate seal.

Simultaneously with the experiments on *gases*, whose results we have endeavored to present in the preceding pages, Graham carried forward a parallel line of investigation of an allied class of phenomena, which may be regarded as the manifestations of molecular motion in *liquid* bodies. The phenomena of diffusion reappear in liquids, and Graham carefully observed the times in which equal weights of various salts dissolved in water diffused from an open-mouth bottle into a large volume of pure water, in which the bottle was immersed. He was not, however, able to correlate the results of these experiments by such a simple law as that which obtains with gases. It appeared, nevertheless, that the rate of diffusion differs very greatly for the different soluble salts, having some relation to the chemical composition of the salt which he was unable to discover. But he found it possible to divide the salts into groups of equi-diffusive substances, and [Pg 138]
he showed that the rate of diffusion of the several groups bear to one another simple numerical ratios.

More important results were obtained from the study of a class of phenomena corresponding to the transpiration of gases through India-rubber or metallic septa. These phenomena, as manifested in the transfer of liquids and of salts in solution through bladder or a similar membrane, had previously been frequently studied under the names of exosmose and endosmose, but to Graham we owe the first satisfactory explanation. As in the case of gases, he referred these effects to the influence of chemical force, combination taking place on one surface of the membrane and the compound breaking up on the other, the difference depending, as in the previous instance, on the influence of mass. He also swept away the arbitrary distinctions made by previous experimenters, showed that this whole class of phenomena are essentially similar, and called this manifestation of power simply "osmose."

While studying osmotic action, Graham was led to one of his most important generalizations—the recognition of the crystalline and amorphous states as fundamental distinctions in chemistry. Bodies in the first state he called crystalloids; those in the last state, colloids (resembling glue). That there is a difference in structure between crystalloids, like sugar or felspar, and colloids, [Pg 139]
like barley candy or glass, has of course always been evident to the most superficial observer; but Graham was the first to recognize in these external differences two fundamentally distinct conditions of matter not peculiar to certain substances, but underlying all chemical differences, and appearing to a greater or less degree in every substance. He showed that the power of diffusion through liquids depends very much on these fundamental differences of condition—sugar, one of the least diffusible of the crystalloids, diffusing fourteen times more rapidly than caromel, the corresponding colloid. He also showed that, in accordance with the general chemical rule, while colloids readily combine with crystalloids, bodies in the same condition manifest little or no tendency to chemical union. Hence, in osmose, where the membranes employed are invariably colloidal, the osmotic action is confined almost entirely to crystalloids, since they alone are capable of entering into that combination with the material of the septum on which the whole action depends.

On the above principles Graham based a simple method of separating crystalloids from colloids, which he calls "dialysis," and which was a most valuable addition to the means of chemical analysis. A shallow tray, prepared by stretching parchment paper (an insoluble colloid) over a gutta-percha hoop, is the only apparatus required. The solution to be "dialyzed" is poured into [Pg 140]
this tray, which is then floated on pure water, whose volume should be eight or ten times greater than that of the solution. Under these conditions the crystalloids will diffuse through the porus septum into the water, leaving the colloids on the tray, and in the course of a few days a more or less complete separation of the two classes of bodies will have taken place. In this way arsenious acid and similar crystalloids may be separated from the colloidal materials with which, in the case of poisoning, they are usually found mixed in the animal juices or tissues.

But, besides having these practical applications, the method of dialysis in the hands of Graham yielded the most startling results, developing an almost entirely new class of bodies, as the colloidal forms of our most familiar substances, and justifying the conclusion that the colloidal as well as the crystalline condition is an almost universal attribute of matter. Thus, he was able to obtain solutions in water of the colloidal states of aluminic, ferric, chromic, stannic, metastannic, titanic, molybdic, tungstic, and silicic hydrates, all of which gelatinize under definite conditions like a solution of glue. The wonderful nature of these facts can be thoroughly appreciated only by those familiar with the subject, but all may understand the surprise with which the chemist saw such hard, insoluble bodies as flint dissolved abundantly in water and converted into soft jellies. [Pg 141] These facts are, without doubt, the most important contributions of Dr. Graham to pure chemistry.

In this sketch of the scientific career of our late associate, we have followed the logical, rather than the chronological, order of events, hoping thus to render the relations of the different parts of his work more intelligible. It must be remembered, however, that the two lines of investigation we have distinguished were in fact inter-woven, and that the beautiful harmony which his completed life presents was the result, not of a preconceived plan, but of a constant devotion to truth, and a childlike faith, which unhesitatingly pressed forward whenever nature pointed out the way.

Although the investigations of the phenomena connected with the molecular motion in gases and liquids were by far the most important of Dr. Graham's labors, he also contributed to chemistry many researches which can not be included under this head. Of these, which we may regard as his detached efforts, the most important was his investigation of the hydrates and other salts of phosphorus. It is true that the interpretation he gave of the results has been materially modified by the modern chemical philosophy, yet the facts which he established form an important part of the basis on which that philosophy rests. [Pg 142] Indeed, it seems as if he almost anticipated the later doctrines of types and polybasic acids, and in none of his work did he show more discriminating observation or acute reasoning. A subsequent investigation on the condition of water in several crystalline salts and in the hydrates of sulphuric acid is equally remarkable. Lastly, Graham also made interesting observations on the combination of alcohol with salts, on the process of etherification, on the slow oxidation of phosphorus, and on the spontaneous inflammability of phosphureted hydrogen. It would not, however, be appropriate in this place to do more than enumerate the subjects of these less important studies; and we have therefore only aimed in this sketch to give a general view of the character of the field which this eminent student of nature chiefly cultivated, and to show how abundant was the harvest of truth which we owe to his faithful toil.

Graham was not a voluminous writer. His scientific papers were all very brief, but comprehensive, and his "Elements of Chemistry" was his only large work. This was an admirable exposition of chemical physics, as well as of pure chemistry, and gave a more philosophical account of the theory of the galvanic battery than had previously appeared. Our late associate was fortunate in receiving during life a generous recognition of the value of his labors. His [Pg 143] membership was sought by almost all the chief scientific societies of the world, and he enjoyed to a high degree the confidence and esteem of his associates. Indeed, he was singularly elevated above the petty jealousies and belittling quarrels which so often mar the beauty of a student's life, while the great loveliness and kindliness of his nature closely endeared him to his friends.

In concluding, we must not forget to mention that most genial trait of Graham's character, his sympathy with young men, which gave him great influence as a teacher in the college with which he was long associated. There are many now prominent in the scientific world who have found in his encouragement the strongest incentive to perseverance, and in his approval and friendship the best reward of success. [Pg 144]

VI.

MEMOIR OF WILLIAM HALLOWES MILLER.

Reprinted from the "Proceedings of the American Academy of Arts and Sciences," Vol. XVI, May 24, 1881.

William Hallowes Miller, who was elected Foreign Honorary Member of this Academy in the place of C. F. Naumann, May 26, 1874, died at his residence in Cambridge, England, on the 20th of May, 1880, at the age of seventy-nine, having been born at Velindre, in Wales, April 5, 1801. His life was singularly uneventful, even for a scholar. Graduating with mathematical honors at Cambridge in 1826, he became a fellow of his college (St. John's) in 1829, and was elected Professor of Mineralogy in the University in 1832. Under the influence of the calm and elegant associations of this ancient English university, Miller passed a long and tranquil life—crowded with useful labors, honored by the respect and love of his associates, and blessed by congenial [Pg 145] family ties. This quiet student-life was exactly suited to his nature, which shunned the bustle and unrest of our modern world. For relaxation, even, he loved to seek the retired valleys of the Eastern Alps; and the description which he once gave to the writer, of himself sitting at the side of his wife amid the grand scenery, intent on developing crystallographic formulæ, while the accomplished artist traced the magnificent outlines of the Dolomite mountains, was a beautiful idyl of science.

Miller's activities, however, were not confined to the University. In 1838 he became a Fellow of the Royal Society, and in 1856 he was appointed its Foreign Secretary—a post for which he was eminently fitted, and which he filled for many years. In 1843 he was selected one of a committee to superintend the construction of the new Parliamentary standards of length and weight, to replace those which had been lost in the fire which consumed the Houses of Parliament in 1834, and to Professor Miller was confided the construction of the new standard of weight. His work on this important committee, described in an extended paper published in the "Philosophical Transactions" for 1856, was a model of conscientious investigation and scientific accuracy. Professor Miller was subsequently a member of a new Royal Commission for "examining into and reporting on the state of the secondary standards, and for considering every question which [Pg 146] could affect the primary, secondary, and local standards"; and in 1870 he was appointed a member of the "Commission Internationale du Mètre." His services on this commission were of great value, and it has been said that "there was no member whose opinions had greater weight in influencing a decision upon any intricate and delicate question."

Valuable, however, as were Professor Miller's public services on these various commissions, his chief work was at the University. His teacher, Dr. William Whewell—afterward the Master of Trinity College—was his immediate predecessor in the Professorship of Mineralogy at Cambridge. This great scholar, whose encyclopædic mind could not long be confined in so narrow a field, held the professorship only four years; but during this period he devoted himself with his usual enthusiasm to the study of crystallography, and he accomplished a most important work in attracting to the same study young Miller, who brought his mathematical training to its elucidation. It was the privilege of Professor Miller to accomplish a unique work, for the like of which a more advanced science, with its multiplicity of details, will offer few opportunities.

The foundations of crystallography had been laid long before Miller's time. Haüy is usually regarded as the founder of the science; for he first discovered the importance of cleavage, and [Pg 147] classed the known facts under a definite system. Taking cleavage as his guide, and assuming that the forms of cleavage were not only the *primitive forms* of crystals as a whole, but also the forms of their *integrant molecules*, he endeavored to show that all secondary forms might be derived from a few primary forms, regarded as elements of nature, by means of *decrements* of molecules at their edges. In like manner he showed that all the forms of a given mineral, like fluor-spar or calcite, might be built up from the integrant molecules by skillfully placing together the primitive forms. Haüy's dissection of crystals, in a manner which appeared to lead to their ultimate crystalline elements, gained for his system great popular attention and applause. The system was developed with great perspicuity and completeness in a work remarkable for the vivacity of its style and the felicity of its illustration. Moreover, a simple mathematical expression was given to the system, and the notation which Haüy invented to express the relation of the secondary to the primary forms, as modified and improved by Lèvy, is still used by the French mineralogists.

The system of Haüy, however, was highly artificial, and only prepared the way for a simpler and more general expression of the facts. The German crystallographer, Weiss, seems to be the first [Pg 148] to have recognized the truth that the decrements of Haüy were merely a mechanical mode of representing the fact that all the secondary faces of a crystal make intercepts on the edges of the primitive form which are simple multiples of each other; and, this general conception once gained, it was soon seen that these ratios could be as simply measured on the axes of symmetry of the crystal as on the edges of the fundamental forms; and, moreover, that, when crystal forms are viewed in their relation to these axes, a more general law becomes evident, and the artificial distinction between primary and secondary forms disappears.

Thus became slowly evolved the conception of a crystal as a group of similar planes symmetrically disposed around certain definite and obvious systems of axes, and so placed that the intercepts, or parameters, on these axes bore to each other a simple numerical ratio. Representing by $a : b : c$ the ratio of the intercepts of a plane on the three axes of a crystal of a given substance, then the intercepts of every other plane of this, or of any other crystal of the same substance, conform to the general proportion $m\,a : n\,b : p\,c$, in which m, n, p are three simple whole numbers. This simple notation, devised by Weiss, expressed the fundamental law of crystallography; and the conception of a crystal as a system of planes, symmetrically distributed according to this law, was a great advance beyond the decrements of Haüy, an advance not [Pg 149] unlike that of astronomy from the system of vortices to the law of gravitation. Yet, as the mechanism of vortices was a natural prelude to the law of Newton, so the decrements of Haüy prepared the way for the wider views of the German crystallographers.

Whether Weiss or Mohs contributed most to advance crystallography to its more philosophical stage, it is not important here to inquire. Each of these eminent scholars did an important work in developing and diffusing the larger ideas, and in showing by their investigations that the facts of nature corresponded to the new conceptions. But to Carl Friedrich Naumann, Professor at the time in the "Bergakademie zu Freiberg," belongs the merit of first developing a complete system of theoretical crystallography based on the laws of symmetry and axial ratios. His "Lehrbuch der reinen und angewandten Krystallographie," published in two volumes at Leipzig in 1830, was a remarkable production, and seemed to grasp the whole theory of the external forms of crystals. Naumann used the obvious and direct methods of analytical geometry to express the quantitative relations between the parts of a crystal; and, although his methods are often unnecessarily prolix and his notation awkward, his formulæ are well adapted to calculation, and easily intelligible to persons moderately disciplined in mathematics. [Pg 150]

But, however comprehensive and perfect in its details, the system of Naumann was cumbrous, and lacked elegance of mathematical form. This arose chiefly from the fact that the old methods of analytical geometry were unsuited to the problems of crystallography; but it resulted also from a habit of the German mind to dwell on details and give importance to systems of classification.

To Naumann the six crystalline systems were as much realities of nature as were the forms of the integrant molecules to Haüy, and he failed to grasp the larger thought which includes all partial systems in one comprehensive plan.

Our late colleague, Professor Miller, on the other hand, had that power of mathematical generalization which enabled him to properly subordinate the parts to the whole, and to develop a system of mathematical crystallography of such simplicity and beauty of form that it leaves little to be desired. This was the great work of his life, and a work worthy of the university which had produced the "Principia." It was published in 1839, under the title, "A Treatise on Crystallography"; and in 1863 the substance of the work was reproduced in a more perfect form, still more condensed and generalized, in a thin volume of only eighty-six pages, which the author modestly called, "A Tract on Crystallography."

Miller began his study of crystallography with the same materials as Naumann; but, in addition, he adopted the beautiful method of Franz Ernst Neumann of referring the faces of a crystal to the surface of a circumscribed sphere by means of radii drawn perpendicular to the faces. The points where the radii meet the spherical surface are the poles of the faces, and the arcs of great circles connecting these poles may obviously be used as a measure of the angles between the crystal faces. This invention of Neumann's was the germ of Miller's system of crystallography, for it enabled the English mathematician to apply the elegant and compendious methods of spherical trigonometry to the solution of crystallographic problems; and Professor Miller always expressed his great indebtedness to Neumann, not only for this simple mode of defining the position of the faces of a crystal, but also for his method of representing the relative position of the poles of the faces on a plane surface by a beautiful application of the methods of stereo-graphic and gnomonic projection. This method of representing a crystal shows very clearly the relations of the parts, and was undoubtedly of great aid to Miller in assisting him to generalize his deductions. [Pg 151]

From the outset, Professor Miller apprehended more clearly than any previous writer the all-embracing scope of the great law of crystallography. He opens his treatise with its enunciation, and, from this law as the fundamental principle of the subject, the whole of his system of crystallography is logically developed. Beyond this, all that is peculiar to Miller's system is involved in two or three general theorems. The rest of his treatise consists of deductions from these principles and their application to particular cases. [Pg 152]

One of the most important of these principles, and one which in the treatise is involved in the enunciation of the fundamental law of crystallography, is in its essence nothing but an analytical device. As we have already stated, Weiss had shown that, if $a : b : c$ represent the ratio of the intercepts of any plane of a crystal on the three axes x, y, and z, respectively, the intercepts of any other possible plane must satisfy the proportion—

$$A : B : C = m\,a : n\,b : p\,c,$$

in which m, n, and p are simple whole numbers. The irrational values a, b, and c are fundamental magnitudes for every crystalline substance;[G] and Miller called these relative magnitudes the parameters of the crystals, while he called the whole numbers, m, n, and p, the indices of the respective planes. But, instead of writing the proportion which expresses the law of crystallography as above, he gave to it a slightly different form, thus: [Pg 153]

$$A : B : C = \frac{1}{h}a : \frac{1}{k}b : \frac{1}{l}c,$$

and used in his system for the indices of a plane the values $h : k : l$, which are also in the ratio of whole numbers, and usually of simpler whole numbers than $m : n : p$. This seems a small difference; for $h\ k\ l$ in the last proportion are obviously the reciprocals of $m\ n\ p$ in the first; but the difference, small as it is, causes a wonderful simplification of the formulæ which express the relations between the parts of a crystal. From the last proportion we derive at once

$$\frac{1}{h}\cdot\frac{a}{A} = \frac{1}{k}\cdot\frac{b}{B} = \frac{1}{l}\cdot\frac{c}{C},$$

which is the form in which Miller stated his fundamental law.

If P represents the "pole" of a face whose "indices" are $h\ k\ l$, that is, represents the point where the radius drawn normal to the face meets the surface of the sphere circumscribed around the crystal (the sphere of projection, as it is called), and if X, Y, Z represent the points where the axes of the crystal meet the same spherical surface,[H] then it is evident that $X\,Y$, $X\,Z$, and $Y\,Z$ are the arcs of great circles, which measure the inclination of the axes to each other, and that $P\,X$, $P\,Y$, and $P\,Z$ are arcs of other great circles, which measure the inclination of the plane ($h\ k\ l$) on planes normal to the respective axes; and, also, that these several arcs form the sides of spherical triangles thus drawn on the sphere of projection. Now, it is very easily shown that [Pg 154]

$$\frac{a}{h}\cos P\,X = \frac{b}{k}\cos P\,Y = \frac{c}{l}\cos P\,Z,$$

and by means of this theorem we are able to reduce a great many problems of crystallography to the solution of spherical triangles.

Another very large class of problems in crystallography is based on the relation of faces in a zone; that is, of faces which are all parallel to one line called the zone axis, and whose mutual intersections, therefore, are all parallel to each other. If, now, $h\ k\ l$ and $p\ q\ r$ are the indices of any two planes of a zone (not parallel to each other), any other plane in the same zone must fulfill the condition expressed by the simple equation

$$\mathrm{u}\,u + \mathrm{v}\,v + \mathrm{w}\,w = o,$$

where $u\ v$ and w are the indices of the third plane, and u v w have the values

$$\mathrm{u} = k\,r - l\,q \qquad \mathrm{v} = l\,p - h\,r \qquad \mathrm{w} = h\,q - k\,p.$$

Since $h\ k\ l$ and $p\ q\ r$ are whole numbers, it is evident that u v w must also be whole numbers, and [Pg 155] these quantities are called the indices of the zone. The three whole numbers which are the indices of a plane when written in succession serve as a very convenient symbol of that plane, and represent to the crystallographer all its relations; and in like manner Miller used the indices of a zone inclosed in brackets as the symbol of that zone. Thus 123, 531, 010 are symbols of planes, and [111], [213], [001] symbols of zones.

An additional theorem enables us to calculate the symbols of a fourth plane in a zone when the angular distances between the four planes and the symbols of three of them are known, but this problem can not be made intelligible with a few words.

The few propositions to which we have referred involve all that is essential and peculiar to the system of Professor Miller. These given, and the rest could be at once developed by any scholar who was familiar with the facts of crystallography; and the circumstance that its essential features can be so briefly stated is sufficient to show how exceedingly simple the system is. At the same time, it is wonderfully comprehensive, and the student who has mastered it feels that it presents to him in one grand view the entire scheme of crystal forms, and that it greatly helps him to comprehend the scheme as a whole, and not simply as the sum of certain distinct parts. So [Pg 156] felt Professor Miller himself; and, while he regarded the six systems of crystals of the German crystallographers as natural divisions of the field, he considered that they were bounded by artificial lines which have no deeper significance than the boundary lines on a map. How great the unfolding of the science from Haüy to Miller, and yet now we can see the great fundamental ideas shining through the obscurity from the first! What we now call the parameters of a crystal were to Haüy the fundamental dimensions of his "integrant molecules," our indices were his "decrements," and our conceptions of symmetry his "fundamental forms." There has been nothing peculiar, however, in the growth of crystallography. This growth has followed the usual order of science, and here as elsewhere the early, gross, material conceptions have been the stepping-stones by which men rose to higher things. In sciences like chemistry, which are obviously still in the earlier stages of their development, it would be well if students would bear in mind this truth of history, and not attach undue importance to structural formulæ and similar mechanical devices, which, although useful for aiding the memory, are simply hindrances to progress as soon as the necessity of such assistance is passed. And, when the life of a great master of science has ended, it is well to look back over the road he has traveled, and, while we take courage in his [Pg 157] success, consider well the lesson which his experience has to teach; and, as progress in this world's knowledge has ever been from the gross to the spiritual, may we not rejoice as those who have a great hope?

Although the exceeding merit of the "Treatise on Crystallography" casts into the shade all that was subordinate, we must not omit to mention that Professor Miller published an early work on hydrostatics, and numerous shorter papers on mineralogy and physics, which were all valuable, and constantly contained important additions to knowledge. Moreover, the "New Edition of Phillips's Mineralogy," which he published in 1852 in connection with H. J. Brooke, owed its chief value to a mass of crystallographic observations which he had made with his usual accuracy and patience during many years, and there tabulated in his concise manner. As has been said by one of his associates in the Royal Society, "it is a monument to Miller's name, although he almost expunged that name from it."[I] It is due to Professor Miller's memory that his works should be collated, and especially that by a suitable commentary his "Tract on Crystallography" should be made accessible to the great body of the students of physical science, who have not, as a rule, the [Pg 158] ability or training which enables them to apprehend a generalization when solely expressed in mathematical terms. The very merits of Professor Miller's book as a scientific work render it very difficult to the average student, although it only involves the simplest forms of algebra and trigonometry.

Independence, breadth, accuracy, simplicity, humility, courtesy, are luminous words which express the character of Professor Miller. In his genial presence the young student felt encouraged to express his immature thoughts, which were sure to be treated with consideration, while from a wealth of knowledge the great master made the error evident by making the truth resplendent. It was the greatest satisfaction to the inexperienced investigator when his observations had been confirmed by Professor Miller, and he was never made to feel discouraged when his mistakes were corrected. The writer of this notice regards it as one of the great privileges of his youth, and one of the most important elements of his education, to have been the recipient of the courtesies and counsel of three great English men of science, who have always been "his own ideal knights," and these noble knights were Faraday, Graham, and Miller.

[Pg 159]

VII.

WILLIAM BARTON ROGERS.

William Barton Rogers was born at Philadelphia, on the 7th of December, 1804. His father, Patrick Kerr Rogers, was a native of Newton Stewart, in the north of Ireland; but while a student at Trinity College, Dublin, becoming an object of suspicion on account of his sympathy with the Rebellion of 1798, he emigrated to this country, and finished his education in the University of Pennsylvania, at Philadelphia, where he received the degree of Doctor of Medicine.

Here he married Hannah Blythe, a Scotch lady—who was at the time living with her aunt, Mrs. Ramsay—and settled himself in his profession in a house on Ninth Street, opposite to the University; and in this house William B. Rogers was born. He was the second of four sons—James, William, Henry, and Robert—all of whom became distinguished as men of science. [Pg 160]

Patrick Kerr Rogers, finding that his prospects of medical practice in Philadelphia had been lessened in consequence of a protracted absence in Ireland, made necessary by the death of his father, removed to Baltimore; but soon afterward accepted the Professorship of Chemistry and Physics in William and Mary College, Virginia, made vacant by the resignation of the late Robert Hare; and it is a fact worthy of notice that, while he succeeded Dr. Hare at William and Mary College, his eldest son, James, succeeded Dr. Hare at the University of Pennsylvania. At William and Mary College the four brothers Rogers were educated; and on the death of the father, at Ellicott Mills, in 1828, William B. Rogers succeeded to the professorship thus made vacant.

He had already earned a reputation as a teacher by a course of lectures before the Maryland Institute in Baltimore during the previous year, and after his appointment at once entered on his career as a scientific investigator. At this period he published a paper on "Dew," and, in connection with his brother Henry, another paper on the "Voltaic Battery"—both subjects directly connected with his professorship. But his attention was early directed to questions of chemical geology; and he wrote, while at William and Mary College, a series of articles for the "Farmer's Register" on the "Green Sands and Marls of Eastern Virginia," and their value as fertilizers. Next [Pg 161] we find the young professor going before the Legislature of Virginia, and, while modestly presenting his own discoveries, making them the occasion for urging upon that body the importance of a systematic geological survey for developing the resources of the State. So great was the scientific reputation that Professor Rogers early acquired by such services, that in 1835 he was called to fill the important Professorship of Natural Philosophy and Geology in the University of Virginia; and during the same year he was appointed State Geologist of Virginia, and began those important investigations which will always associate his name with American geology.

Professor Rogers remained at the head of the Geological Survey of Virginia until it was discontinued, in 1842, and published a series of very valuable annual reports. As was anticipated, the survey led to a large accumulation of material, and to numerous discoveries of great local importance. As this was one of the earliest geological surveys undertaken in the United States, its directors had in great measure to devise the methods and lay out the plans of investigation which have since become general. This is not the place, however, for such details; but there are four or five general results of Professor Rogers's geological work at this period which have exerted a [Pg 162] permanent influence on geological science, and which should therefore be briefly noticed. Some of these results were first published in the "American Journal of Science"; others were originally presented to the Association of American Geologists and Naturalists, and published in its "Transactions." Professor Rogers took a great interest in the organization of this association in 1840, presided over its meeting in 1845, and again, two years later, when it was expanded into the American Association for the Advancement of Science.

In connection with his brother Robert, Professor William B. Rogers was the first to investigate the solvent action of water—especially when charged with carbonic acid—on various minerals and rocks; and by showing the extent of this action in nature, and its influence in the formation of mineral deposits of various kinds, he was one of the first to observe and interpret the important class of facts which are the basis of chemical geology.

Another important result of Professor Rogers's geological work was to show that the condition of any coal-bed stands in a close genetic relation to the amount of disturbance to which the enclosing strata have been submitted, the coal becoming harder and containing less volatile matter as the evidence of disturbance increases. This generalization, which seems to us now [Pg 163] almost self-evident—understanding, as we do, more of the history of the formation of coal—was with Professor Rogers an induction from a great mass of observed facts.

By far, however, the most memorable contribution of Professor Rogers to geology was that made in connection with Henry D. Rogers, in a paper entitled "The Laws of Structure of the more Disturbed Zones of the Earth's Crust," presented by the two brothers at the meeting of the Association of American Geologists and Naturalists, held at Boston in 1842. This paper was the first presentation of what may be called in brief the "Wave Theory of Mountain Chains." This theory was deduced by the brothers Rogers from an extended study of the Appalachian Chain in Pennsylvania and Virginia, and was supported by numerous geological sections and by a great mass of facts. The hypothesis which they offered as an explanation of the origin of the great mountain waves may not be generally received; but the general fact, that the structure of mountain chains is alike in all the essential features which the brothers Rogers first pointed out, has been confirmed by the observations of Murchison in the Ural, of Darwin in the Andes, and of the Swiss geologists in the Alps. "In the Appalachians the wave structure is very simple, and the same is true in all corrugated districts where the crust movements have been simple, and have [Pg 164] acted in one direction only. But where the elevating forces have acted in different directions at different times, causing interference of waves like a chopped sea, as in the Swiss Alps and the mountains of Wales or Cumberland, the undulations are disguised, and are with extreme difficulty made out." The wave theory of mountain chains was the first important contribution to dynamical and structural geology which had been brought forward in this country. It excited at the time great interest, as well from the novelty of the views as from the eloquence with which they were set forth; and to-day it is still regarded as one of the most important advances in orographic geology.

A marked feature of mountain regions is that rupturing of the strata called faults; and another of the striking geological generalizations of the brothers Rogers is what may be called the law of the distribution of faults. They showed that faults do not occur on gentle waves, but in the most compressed flexures of the mountain chains, which in the act of moving have snapped or given way at the summit where the bend is sharpest, the less inclined side being shoved up on the plane of the fault, this plane being generally parallel to, if it does not coincide with, the axis plane; and, further, that "the direction of these faults generally follows the run of the line of elevation of the mountains, the length and vertical displacement depending on the strength of the [Pg 165] disturbing force."

The last of the general geological results to which we referred above was published under the name of William B. Rogers only. It was based on the observed positions of more than fifty thermal springs in the Appalachian belt, occurring in an area of about fifteen thousand square miles, which were shown to issue from anticlinal axes and faults, or from points very near such lines; and in connection with these springs it was further shown that there was a great preponderance of nitrogen in the gases which the waters held in solution.

It must be remembered that, during the time when this geological work was accomplished, Professor Rogers was an active teacher in the University of Virginia, giving through a large part of the year almost daily lectures either on physics or geology. Those who met him in his after-life in various relations in Boston, and were often charmed by his wonderful power of scientific exposition, can readily understand the effect he must have produced, when in the prime of manhood, upon the enthusiastic youths who were brought under his influence. His lecture-room was always thronged. As one of his former students writes, "All the aisles would be filled, and even the windows crowded from the outside. In one instance I remember the crowd had assembled long before the hour named for the lecture, and so filled the hall that the professor [Pg 166] could only gain admittance through a side entrance leading from the rear of the hall through the apparatus-room. These facts show how he was regarded by the students of the University of Virginia. His manner of presenting the commonest subject in science—clothing his thoughts, as he always did, with a marvelous fluency and clearness of expression and beauty of diction—caused the warmest admiration, and often aroused the excitable nature of Southern youths to the exhibition of enthusiastic demonstrations of approbation. Throughout Virginia, and indeed the entire South, his former students are scattered, who even now regard it as one of the highest privileges of their lives to have attended his lectures."

Such was the impression which Professor Rogers left at the University of Virginia, that, when he returned, thirty-five years later, to aid in the celebration of the semi-centennial, he was met with a perfect ovation. Although the memories of the civil war, which had intervened, and Professor Rogers's known sympathies with the Northern cause, might well have damped enthusiasm, yet the presence of the highly honored teacher was sufficient to rekindle the former admiration; and, in the language of a contemporary Virginia newspaper, "the old students beheld before them the same William B. Rogers who thirty-five years before had held them spellbound in his class of [Pg 167] natural philosophy; and, as the great orator warmed up, these men forgot their age; they were again young, and showed their enthusiasm as wildly as when, in days of yore, enraptured by his eloquence, they made the lecture-room of the University ring with their applause."

Besides his geological papers, Professor Rogers published, while at the University of Virginia, a number of important chemical contributions, relating chiefly to new and improved methods in chemical analysis and research. These papers were published in connection with his youngest brother, Robert E. Rogers, now become his colleague as Professor of Chemistry and Materia Medica in the University; and such were the singularly intimate relations between the brothers that it is often impossible to dissociate their scientific work. Among these were papers "On a New Process for obtaining Pure Chlorine"; "A New Process for obtaining Formic Acid, Aldehyde, etc."; "On the Oxidation of the Diamond in the Liquid Way"; "On New Instruments and Processes for the Analysis of the Carbonates"; "On the Absorption of Carbonic Acid by Liquids"; besides the extended investigation "On the Decomposition of Minerals and Rocks by Carbonated and Meteoric Waters," to which we have referred above. There was also at this time a large amount [Pg 168] of chemical work constantly on hand in connection with the Geological Survey, such as analyses of mineral waters, ores, and the like. Moreover, while at the University of Virginia, Professor Rogers published a short treatise on "The Strength of Materials," and a volume on "The Elements of Mechanics,"—books which, though long out of print, were very useful text-books in their day, and are marked by the clearness of style and felicity of explanation for which the author was so distinguished.

The year 1853 formed a turning-point in Professor Rogers's life. Four years previously he had married Miss Emma Savage, daughter of Hon. James Savage, of Boston, the well-known author of the "New England Genealogical Dictionary," and President of the Massachusetts Historical Society. This connection proved to be the crowning blessing of his life. Mrs. Rogers, by her energy, her intelligence, her cheerful equanimity, her unfailing sympathy, became the promoter of his labors, the ornament and solace of his middle life, and the devoted companion and support of his declining years. Immediately after his marriage, June 20, 1849, he visited Europe with his wife, and was present at the meeting of the British Association for the Advancement of Science, held that year at Birmingham, where he was received with great warmth, and made a most marked impression. Returning home in the autumn, Professor Rogers resumed his work at the [Pg 169] University of Virginia; but the new family relations which had been established led in 1853 to the transfer of his residence to Boston, where a quite different, but even a more important, sphere of usefulness surrounded him. His wide scientific reputation, as well as his family connection, assured him a warm welcome in the most cultivated circles of Boston society, where his strength of character, his power of imparting knowledge, and his genial manners, soon commanded universal respect and admiration. He at once took an active part in the various scientific interests of the city. From 1845 he had been a Fellow of this Academy;[J] and after taking up his residence among us he was a frequent attendant at our meetings, often took part in our proceedings, became a member of our Council, and from 1863 to 1869 acted as our Corresponding Secretary. He took a similar interest in the Boston Society of Natural History. He was a member, and for many years the President, of the Thursday Evening Scientific Club, to which he imparted new life and vigor, and which was rendered by him an important field of influence. The members who were associated with him in that club will never forget those masterly expositions of recent advances in physical science; and will remember that, while he made clear their technical [Pg 170] importance to the wealthy business men around him, he never failed to impress his auditors with the worth and dignity of scientific culture.

During the earlier years of his residence in Boston, Professor Rogers occupied himself with a number of scientific problems, chiefly physical. He studied the variations of ozone (or of what was then regarded as ozone) in the atmosphere at the time when this subject was exciting great attention. He was greatly interested in the improvements of the Ruhmkorff Coil made by Mr. E. S. Ritchie; and in this connection published a paper on the "Actinism of the Electric Discharge in Vacuum Tubes." A study of the phenomena of binocular vision led to a paper entitled "Experiments disproving by the Binocular Combination of Visual Spectra Brewster's Theory of Successive Combinations of Corresponding Points." A paper discussing the phenomena of smoke rings and rotating rings in liquids appeared in the "American Journal of Science" for 1858, with the description of a very simple but effective apparatus by which the phenomena would be readily reproduced. In this paper Professor Rogers anticipated some of the later results of Helmholtz and Sir William Thomson. In the same year an ingenious illustration of the properties of sonorous flames was exhibited to the Thursday Evening Club above mentioned, in which [Pg 171] Professor Rogers anticipated Count Schafgottsch in the invention of a beautiful optical proof of the discontinuity of the singing hydrogen flame.

In 1861 Professor Rogers accepted from Governor Andrew the office of Inspector of Gas and Gas-Meters for the State of Massachusetts, and organized a system of inspection in which he aimed to apply the latest scientific knowledge to this work; and in a visit he again made to Europe in 1864 he presented, at the meeting of the British Association at Bath, a paper entitled "An Account of Apparatus and Processes for Chemical and Photometrical Testing of Illuminating Gas."

During this period he gave several courses of lectures before the Lowell Institute of Boston, which were listened to with the greatest enthusiasm, and served very greatly to extend Professor Rogers's reputation in this community. Night after night, crowded audiences, consisting chiefly of teachers and working-people, were spellbound by his wonderful power of exposition and illustration. There was a great deal more in Professor Rogers's presentation of a subject than felicity of expression, beauty of language, choice of epithets, or significance of gesture. He had a power of marshaling facts, and bringing them all to bear on the point he desired to illustrate, which rendered the relations of his subject as clear as day. In listening to this powerful oratory, [Pg 172] one only felt that it might have had, if not a more useful, still a more ambitious aim; for less power has moved senates and determined the destinies of empires.

The interest in Professor Rogers's lectures was not excited solely, however, by the charm of his eloquence; for, although such was the felicity of his presentations, and such the vividness of his descriptions, that he could often dispense with the material aids so essential to most teachers, yet when the means of illustration were at his command he showed his power quite as much in the adaptation of experiments as in the choice of language. He well knew that experiments, to be effective, must be simple and to the point; and he also knew how to impress his audience with the beauty of the phenomena and with the grandeur of the powers of nature. He always seemed to enjoy any elegant or striking illustration of a physical principle even more than his auditors, and it was delightful to see the enthusiasm which he felt over the simplest phenomena of science when presented in a novel way.

We come now to the crowning and greatest work of Professor Rogers's life, the founding of the Massachusetts Institute of Technology—an achievement so important in its results, so far-reaching in its prospects, and so complete in its details, that it overshadows all else. A great [Pg 173] preacher has said that "every man's life is a plan of God's." The faithful workman can only make the best use of the opportunities which every day offers; but he may be confident that work faithfully done will not be for naught, and must trustingly leave the issue to a higher power. Little did young Rogers think, when he began to teach in Virginia, that he was to be the founder of a great institution in the State of Massachusetts; and yet we can now see that the whole work of his life was a preparation for this noble destiny. The very eloquence he so early acquired was to be his great tool; his work on the Geological Survey gave him a national reputation which was an essential condition of success; his life at the University of Virginia, where he was untrammeled by the traditions of the older universities, enabled him to mature the practical methods of scientific teaching which were to commend the future institution to a working community; and, most of all, the force of character and large humanity developed by his varied experience with the world were to give him the power, even in the conservative State of his late adoption, to mold legislators and men of affairs to his wise designs.

It would be out of place, as it would be unnecessary, to dwell in this connection on the various stages in the development of the Institute of Technology. The facts are very generally known in [Pg 174] this community, and the story has been already well told. The conception was by no means a sudden inspiration, but was slowly matured out of a far more general and less specific plan, originating in a committee of large-minded citizens of Boston, who, in 1859, and again in 1860, petitioned the Legislature of Massachusetts to set apart a small portion of the land reclaimed from the Back Bay "for the use of such scientific, industrial, and fine art institutions as may associate together for the public good." The large scheme failed; but from the failure arose two institutions which are the honor and pride of Boston—the Museum of Fine Arts and the Institute of Technology. In the further development of the Museum of Fine Arts, Professor Rogers had only a secondary influence; but one of his memorials to the Legislature contains a most eloquent statement, often quoted, of the value of the fine arts in education, which attests at once the breadth of his culture and the largeness of his sympathies.

Although the committee of gentlemen above referred to had failed to carry out their general plan, yet the discussions to which it gave rise had developed such an interest in the establishment of an institution to be devoted to industrial science and education that they determined upon taking the preliminary steps toward the organization of such an institution. A sub-committee was [Pg 175] charged with preparing a plan; and the result was a document, written by Professor Rogers, entitled "Objects and Plan of an Institute of Technology." That document gave birth to the Massachusetts Institute of Technology, for it enlisted sufficient interest to authorize the committee to go forward. A charter with a conditional grant of land was obtained from the Legislature in 1861, and the institution was definitely organized, and Professor Rogers appointed President, April 8, 1862. Still, the final plans were not matured, and it was not until May 30, 1864, that the government of the new institution adopted the report prepared by its president, entitled "Scope and Plan of the School of Industrial Science of the Massachusetts Institute of Technology," which Dr. Runkle has called the "intellectual charter" of the institution, and which he states "has been followed in all essential points to this very day." In striking confirmation of what we have written above, Dr. Runkle further says:

"In this document we see more clearly the breadth, depth, and variety of Professor Rogers's scientific knowledge, and his large experience in college teaching and discipline. It needed just this combination of acquirements and experience to put his conceptions into working shape, to group together those studies and exercises which naturally and properly belong to each [Pg 176] professional course, and thus enable others to see the guiding-lines which must direct and limit their work in its relations to the demands of other departments....

"The experimental element in our school—a feature which has been widely recognized as characteristic—is undoubtedly due to the stress and distinctness given to it in the 'Scope and Plan.' In our discipline we must also give credit to the tact and large-heartedness of Professor Rogers—in the fact that we are entirely free from all petty rules and regulations relating to conduct, free from all antagonism between teachers and students."

The associates of Professor Rogers in this Academy—many of them his associates also in the Institute of Technology, or in the Society of Arts, which was so important a feature of the organization—will remember with what admiration they watched the indefatigable care with which its ever active president fostered the young life of the institution he had created. They know how, during the earlier years, he bore the whole weight of the responsibility of the trust he had voluntarily and unselfishly assumed for the public good; how, while by his personal influence obtaining means for the daily support of the school, he gave a great part of the instruction, and extended a personal regard to every individual student committed to his charge. They recall with what wisdom, skill, tact, and patience he directed the increasing means and expanding scope of [Pg 177] the now vigorous institution, overcoming obstacles, reconciling differences, and ingratiating public favor. They will never forget how, when the great depression succeeded the unhealthy business activity caused by the civil war, during which the institution had its rise, the powerful influence of its great leader was able to conduct it safely through the financial storm. They greatly grieved when, in the autumn of 1868, the great man who had accomplished so much, but on whom so much depended, his nerves fatigued by care and overwork, was obliged to transfer the leadership to a younger man; and ten years later were correspondingly rejoiced to see the honored chief come again to the front, with his mental power unimpaired, and with adequate strength to use his well-earned influence to secure those endowments which the increased life of the institution required; and they rejoiced with him when he was able to transfer to a worthy successor the completed edifice, well established and equipped—an enduring monument to the nobility of character and the consecration of talents. They have been present also on that last occasion, and have united in the acclamation which bestowed on him the title "Founder and Father perpetual, by a patent indefeasible." They have heard his feeling but modest response, and have been rejoicing though tearful witnesses when, after the final seal of commendation was [Pg 178] set, he fell back, and the great work was done.

We honor the successful teacher, we honor the investigator of Nature's laws, we honor the upright director of affairs—and our late associate had all these claims to our regard; but we honor most of all the noble manhood—and of such make are the founders of great institutions. In comparison, how empty are the ordinary titles of distinction of which most men are proud! It seems now almost trivial to add that our associate was decorated with a Doctor's degree, both by his own university and also by the University at Cambridge; that he was sought as a member by many learned societies; that he was twice called to preside over the annual meetings of the American Association for the Advancement of Science; and that, at the death of Professor Henry, he was the one man of the country to whom all pointed as the President of the National Academy of Science. This last honor, however, was one on which it is a satisfaction to dwell for a moment, because it gave satisfaction to Professor Rogers, and the office was one which he greatly adorned, and for which his unusual oratorical abilities were so well suited. He was a most admirable presiding officer of a learned society. His breadth of soul and urbanity of manner insensibly resolved the discords which often disturb the harmonies of scientific truth. He had the [Pg 179] delicate tact so to introduce a speaker as to win in advance the attention of the audience, without intruding his own personality; and when a paper was read, and the discussion closed, he would sum up the argument with such clearness, and throw around the subject such a glow of light, that abstruse results of scientific investigation were made clear to the general comprehension, and a recognition gained for the author which the shrinking investigator could never have secured for himself. To Professor Rogers the truth was always beautiful, and he could make it radiant.

It is also a pleasure to record, in conclusion, that Professor Rogers's declining years were passed in great comfort and tranquillity, amidst all the amenities of life; that to the last he had the companionship of her whom he so greatly loved; and that increasing infirmities were guarded and the accidents of age warded off with a watchfulness that only the tenderest love can keep. We delight to remember him in that pleasant summer home at Newport, which he made so fully in reality as in name the "Morning-side," that we never thought of him as old, and to believe that the morning glow which he so often watched spreading above the eastern ocean was the promise of the fuller day on which he has entered. [Pg 180]

VIII.

JEAN-BAPTISTE-ANDRÉ DUMAS.[K]

Jean-Baptiste-André Dumas was born at Alais, in the south of France, July 14, 1800. His father belonged to an ancient family, was a man of culture, and held the position as clerk to the municipality of Alais. The son was educated at the college of his native place, and appears to have been destined by his parents for the naval service. But the anarchy and bloodshed which attended the downfall of the First Empire produced such an aversion to a military life that his parents abandoned their plan, and apprenticed him to an apothecary of the town. He remained in this situation, however, but a short time; for, owing to the same sad causes, he had formed an earnest desire to leave his home, and, his parents yielding to his wish, he traveled on foot to Geneva in 1816, where he had relatives who gave him a friendly welcome, and where he found [Pg 181] employment in the pharmacy of Le Royer.

At that time Geneva was the center of much scientific activity, and young Dumas, while discharging his duties in the pharmacy, had the opportunity of attending lectures on botany by M. de Candolle, on physics by M. Pictet, and on chemistry by M. Gaspard de la Rive; and from these lectures he acquired an earnest zeal for scientific investigation. The laboratory of the pharmacy gave him the necessary opportunities for experimenting, and an observation which he made of the definite proportions of water contained in various commercial salts, although yielding no new results, gained for him the attention and friendship of De la Rive. Soon after we find the young philosopher attempting to deduce the volumes of the atoms in solid and liquid bodies by carefully determining their specific gravities, and thus anticipating a method which thirty years later was more fully developed by Hermann Kopp.

About this time young Dumas had the good fortune to render an important service to one of the most distinguished physicians of Geneva, whose name is associated with the beneficial uses of iodine in cases of goitre. It had occurred to Dr. Coindet that burned sponge, then generally used as a remedy for that disease, might owe its efficacy to the presence of a small amount of iodine; [Pg 182] and on referring the question to Dumas, the young chemist not only proved the presence of iodine in the sponge, but also indicated the best method of administering what proved to be almost a specific remedy. It was in connection with this investigation that Dumas's name first appears in public. The discovery produced a great sensation, and for many years the manufacture of iodine preparations brought both wealth and reputation to the pharmacy of Le Royer.

Soon after, Dumas formed an intimacy with Dr. J. L. Prévost, then recently returned from pursuing his studies in Edinburgh and Dublin, and was induced to undertake a series of physiological investigations, which for a time withdrew him from his strictly chemical studies. Several valuable papers on physiological subjects were published by Prévost and Dumas, which attracted the notice of Alexander von Humboldt, who on visiting Geneva, in 1822, sought out Dumas and awakened in him a desire to seek a wider field of activity than his present position opened to him. In consequence he removed to Paris in 1823, where the reputation he had so deservedly earned at Geneva won for him a cordial reception at what was then the chief center of scientific study in Europe. La Place, Berthollet, Vauquelin, Gay-Lussac, Thenard, Alexandre Brongniart, Cuvier, Geoffroy St. Hilaire, Arago, Ampère, and Poisson, all manifested their [Pg 183] interest in the young investigator. Dumas was soon appointed Répétiteur de Chimie at the École Polytechnique, and also Lecturer at the Athenæum, an institution founded and maintained by public subscription, for the purpose of exciting popular interest in literature and science; and from this beginning his advancement to the highest position which a man of science can occupy in France was extremely rapid.

In 1826 he married Mdlle. Herminie Brongniart, the eldest daughter of Alexandre Brongniart, the illustrious geologist, an alliance which not only brought him great happiness, and at the time greatly advanced his social position, but also in after years made his house one of the chief resorts of the scientific society of Paris. The many who have shared its generous hospitality will appreciate how greatly, for more than half a century, Madame Dumas has aided the work and extended the influence of her noble husband.

In 1828-'29 Dumas united with Théodore Olivier and Eugène Péclet in founding the École Centrale des Arts et Manufactures, an institution which met with great success, and in which, as Professor of Chemistry, Dumas rendered most efficient service for many years; and in 1878 had the very good fortune to aid in celebrating the fiftieth anniversary of his own foundation, and to see it acknowledged as among the most important and efficient scientific institutions of the [Pg 184] world. In 1832 Dumas succeeded Gay-Lussac as Professor at the Sorbonne; in 1835 he succeeded Thenard at the École Polytechnique; and in 1839 he succeeded Deyeux at the École de Médecine. Thus before the age of forty he filled successively, and for some time simultaneously, all the important professorships of chemistry in Paris except one. This exception was that of the College of France, with which he was never permanently connected, although it was there that he delivered his famous course on the History of Chemical Philosophy, when temporarily supplying the place of Thenard.

Dumas early recognized the importance of laboratory instruction in chemistry, for which there were no facilities at Paris when he first came to what was then the center of the world's science; and in 1832 founded a laboratory for research at his own expense. This laboratory, first established at the Polytechnic School, was removed to the Rue Cuvier in 1839, where it remained until broken up by the Revolution of 1848. The laboratory was small, and Dumas would receive only a few advanced students, and these on terms wholly gratuitous. Among these students were Piria, Stas, Melsens, Leblanc, Lalande, and Lewy, with whose aid he carried on many of his important investigations. By the Revolution of 1848 Dumas's activities were for a time diverted [Pg 185] into political channels; but under the Second Empire his laboratory was re-established at the Sorbonne, and in 1868 was removed to the École Centrale.

The political episode of Dumas's life was the natural result of an active mind with wide sympathies, which recognizes in the pressing demands of society its highest duty. The political and social upheaval of 1848 seemed at the time to endanger the stability in France of everything which a cultivated and learned man holds most dear; and Dumas was not one to consider his own preferences when he felt he could aid in averting the calamities which threatened his country. Immediately after the Revolution of February, he accepted a seat in the Legislative Assembly offered him by the electors of the Arrondissement of Valenciennes. Shortly afterward the President of the Republic called him to fill the office of Minister of Agriculture and Commerce. During the Second Empire he was elevated to the rank of Senator, and shortly after his entrance into the Senate he became Vice-President of the High Council of Education. In order to reform the abuses into which many of the higher educational institutions of Paris had fallen, be accepted a place in the Municipal Council of Paris, over which he subsequently presided from 1859 to 1870.

In 1868 Dumas was appointed Master of the Mint of France; but he retained the office only [Pg 186] during a short time, for with the fall of the Second Empire, in 1870, his political career came to an abrupt termination. The Senate had ceased to exist, and in the stormy days which followed, the Municipal Council had naturally changed its complexion; and even at the Mint, the man who had held such a conspicuous position under the Imperial government was obliged to vacate his place. Some years previously he had resigned his professorships because his official positions were incompatible with his relations as teacher, and now, at the age of seventy, he found himself for the first time relieved from the daily routine of official duties, and free to devote his leisure to the noble work of encouraging research, and thus promoting the advancement of science. He had reached an age when active investigation was almost an impossibility, but his commanding position gave him the opportunity of exerting a most powerful influence, and this he used with great effect. In early life he had been elected, in 1832, a member of the Academy of Sciences in succession to Serullas; in 1868 he had succeeded Flourens as its Permanent Secretary; and in 1875 he was elected a member of the French Academy as successor to Guizot, a distinction rarely attained by a man of science.

It was, however, as Permanent Secretary of the Academy of Sciences that Dumas exerted during the last years of his life his greatest influence. [Pg 187] He was the central figure and the ruling spirit of this distinguished body. No important commission was complete without him, and on all public occasions he was the orator of the body, always graceful, always eloquent. In announcing Dumas's death to the Academy, M. Rolland, the presiding officer, said:

"Vous savez la part considérable que Dumas prenait à vos travaux et vous avez bien souvent admiré, comme moi, la haute intelligence et la tact infini avec lesquels il savait imprimer à nos discussions les formes modérées et courtoises inhérentes à sa nature et à son caractère. Sous ce rapport aussi la perte de Dumas est irréparable et crée dans l'Académie un vide bien difficile à combler. Aussi, longtemps encore nous chercherons, à la place qu'il occupait au Bureau avec tant d'autorité, la figure sympathique et vénérée de notre bienaimé Secrétaire perpétuel."

And while Dumas was still occupying his conspicuous position in the Academy, one of the most distinguished of his German contemporaries[L] wrote of him: "An ever-ready interpreter of the researches of others, he always heightens the value of what he communicates by adding from the [Pg 188] rich stores of his own experience, thus often conveying lights not noticed even by the authors of those researches."

When the writer last saw Dumas, in the winter of 1881-'82, the great chemist had still all the vivacity of youth, and it was difficult to realize his age. He took a lively interest in all questions of chemical philosophy, which he discussed with great earnestness and warmth. There was the same fire and the same exuberance of fancy which had enchanted me in his lectures thirty years before. At an age when most men hold speculation in small esteem, I was much struck with his criticism of a contemporary, who, he said, had no imagination, although he spoke with the highest praise of his experimental skill. At that time Dumas showed no signs of impaired strength. But during the following year his health began to fail, and he died on the 11th of April, at Cannes, where he had sought a retreat from the severity of the winter climate of Paris.

Dumas was one of the few men whose greatness can not be estimated from a single point of view. He was not only eminent as an investigator of nature, but even more eminent as a teacher and an administrator. Beginning the study of chemistry at the culmination of the epoch of the Lavoisierian system, and regarding, as he always did, the author of that system with the greatest [Pg 189] admiration, he nevertheless was the first to discover the weak point in its armor and inflict the wound which led to its overthrow. Without attempting to detail Dumas's numerous contributions to chemical knowledge, we will here only refer to three important investigations, which produced a marked influence in the progress of chemical science.

While still in Geneva, Dumas, as has been said, made numerous determinations of the densities of allied substances, with a view to discovering the relations of what he called their molecular or atomic volumes; and it is no wonder to us that the problem proved too complex to be solved at that time. After his removal to Paris he took up the much simpler problem which the relations of the molecular volumes of aëriform substances present, and his paper "On Some Points of the Atomic Theory," which was published in the "Annales de Chimie et de Physique" for 1826, had an important influence in developing our modern chemical philosophy. Gay-Lussac had previously observed, not only that the relative weights of the several factors and products concerned in a chemical process bear to each other definite proportions, but also that, when the materials are aëriform, the relative volumes preserve an equally definite and still simpler ratio. Moreover, on [Pg 190] the physical side, Avogadro, and afterward Ampère, had conceived the theory, that in the state of gas all molecules must have the same volume. It was Dumas who first saw that these principles furnished an important means of verifying the molecular and atomic weights.

"I am engaged," he writes, "in a series of experiments intended to fix the atomic weights of a considerable number of bodies, by determining their density in the state of gas or vapor. There remains in this case but one hypothesis to be made, which is accepted by all physicists. It consists in supposing that, in all elastic fluids observed under the same conditions, the molecules are placed at equal distances, i. e., that they are present in them in equal numbers. An immediate consequence of this mode of looking at the question has already been the subject of a learned discussion on the part of Ampère"—and Avogadro, as the author subsequently adds—"to which, however, chemists, with the exception perhaps of M. Gay-Lussac, appear to have given as yet but little attention. It consists in the necessity of considering the molecules of the simplest gases as capable of a further division—a division occurring in the moment of combination, and varying with the nature of the compound."

Here, it is obvious, are the very conceptions which form the basis of our modern chemical [Pg 191] philosophy; and at first we are surprised that they did not lead Dumas at once to the full realization of the consequences which the doctrine of equal molecular volumes involves in the interpretation of the constitution of chemical compounds, and to the clear distinction between "the physically smallest particles" and "the chemically smallest particles," or the molecules and the atoms, as we now call the physical and the chemical units. This distinction is implied throughout Dumas's paper already quoted, and is illustrated by a striking example in the introduction to his treatise on "Chemistry applied to the Arts," published two years later; but the ground was not yet prepared to receive the seed, and more than a quarter of a century must pass before the full harvest of this fruitful hypothesis could be reaped.

There were, however, two important incidental results of this investigation from which chemical science immediately profited. One was a simple method of determining with accuracy the vapor densities of volatile substances which has since been known by Dumas's name. The other was a radical change in the formula of the silicates. On the authority of Berzelius, who based his opinion chiefly on the analogy between the silicates and the sulphates, the formula SiO_3, had [Pg 192] been accepted as representing the constitution of silica. But from the density of both the chloride and the fluoride of silicon Dumas concluded that the formula was SiO_2, a conclusion which is now seen to be in complete harmony with the scheme of allied compounds. To Berzelius, however, the new views appeared wholly out of harmony with the system of chemistry which he had so greatly assisted in developing, and he opposed them with the whole weight of his powerful influence, and so far succeeded as to prevent their general adoption for many years. Still, "the new mode of looking at the constitution of silicic acid slowly but surely gained ground, and it is now so firmly rooted in our convictions, that the younger generation of chemists will scarcely understand the pertinacity with which this innovation was resisted."[M]

But if this investigation of gas and vapor densities brought a great strain upon the dualistic system, the second of the three great investigations of Dumas, to which we have referred, led to its complete overthrow. The experimental results of this investigation would not be regarded at the present day as remarkable, and can not be compared either in breadth or intricacy with the results of numerous investigations of a similar character which have since been made. The most important of these results were the substitution products obtained by the action of chlorine gas [Pg 193] on acetic acid. They were published in a series of papers entitled "Sur les Types Chimiques," and the capital point made was that chlorine could be substituted in acetic acid for a large part of the hydrogen without destroying the acid relations of the product; and the inference was, that the qualities of a compound substance depend not simply on the nature of the elements of which it consists, but also on the manner or type according to which these elements are combined.

To the chemists of the present day these results and inferences seem so natural that it is difficult to understand the spirit with which they were received forty years ago. But it must be remembered that at that time the conceptions of chemists were wholly molded in the dualistic system. It was thought that chemical action depended upon the antagonism between metals and metalloids, bases and acids, acid salts and basic salts, and that the qualities of the products resulted from the blending of such opposite virtues. That chlorine should unite with hydrogen was natural, for no two substances could be more unlike; but that chlorine should supply the place of hydrogen in a chemical compound was a conception which the dualists scouted as absurd. Even Liebig, the "father of organic chemistry," warmly controverted the interpretation [Pg 194] which Dumas had given to the facts he had discovered. Liebig himself had successfully investigated the chemical relations of a large class of organic products. He had, however, worked on the lines of the dualistic system, showing that organic substances might be classed with similar inorganic substances, if we assume that certain groups of atoms, which he called "compound radicals," might take the place of elementary substances. In the edition of the organic part of Turner's "Chemistry" bearing his name, organic chemistry is defined as the "chemistry of compound radicals," and the formulas of organic compounds are represented on the dualistic system. Liebig's conceptions were therefore naturally opposed to those advanced by Dumas; but it is pleasant to know that the controversy which arose never disturbed the friendly relations between these two noble men of science, who could approach the same truth from different sides, and yet have faith that each was working for the same great end. In his commemorative address on Pelouze, Dumas expresses toward Liebig sentiments of affectionate regard, and Liebig dedicates to Dumas, with equal warmth, the German edition of his "Letters on Chemistry."

By the second investigation, as by the first, although Dumas gave a most fruitful conception to chemistry, he only took the first step in developing it. His conception of chemical types was very [Pg 195] indefinite, and Laurent wrote of it, a few years later: "Dumas's theory is too general; by its poetic coloring, it lends itself to false interpretations; it is a programme of which we await the realization." Laurent himself helped toward this realization, and in his early death left the work to his associate and friend Gerhardt, who pushed it forward with great zeal, classifying chemical compounds according to the four types of hydrochloric acid, water, ammonia, and marsh-gas. Hofmann, Williamson, Wurtz, and many others, greatly aided in this work by realizing many of the possibilities which these types suggested; and thus modern Structural Chemistry gradually grew up, in which the types of Dumas and Gerhardt have been in their turn superseded by the larger views which the doctrine of quantivalence has opened out to the scientific imagination. It is a singular fact, however, that, while the growth began in France, the harvest has been chiefly reaped by Germans; and that, although in its inception the movement was strongly opposed in Germany, its legitimate conclusions are now repudiated by the most influential school of French chemists.

The third great investigation of Dumas was his revision of the atomic weights of many of the chemical elements, and in none of his work did he show greater experimental skill. His [Pg 196] determination of the atomic weight of oxygen by the synthesis of water, and of that of carbon by the synthesis of carbonic dioxide, are models of quantitative experimental work. To this investigation, as to all his other work, Dumas was directed by his vivid scientific imagination. In his teaching, from the first, he had aimed to exhibit the relations of the elementary substances by classing them in groups of allied bodies; and at the meeting of the British Association in 1851 he had delighted the chemical section by the eloquence and force with which he exhibited such relations, especially triads of elementary substances; such as chlorine, bromine, and iodine; oxygen, sulphur, and selenium; phosphorus, arsenic, and antimony; calcium, barium, and strontium: in which not only the atomic weight, but also the qualities of the middle member of the triad, were the mean of those of the other two members. Later, he came to regard these triads as parts of more extended series, in each of which the atomic weights increased from the first to the last element of the series, by determinate, but not always by equal differences, the values being, if not exact multiples of the hydrogen atom according to the hypothesis of Prout, at least multiples of one half or one quarter of that weight. There can be no doubt that these speculations [Pg 197] were more fanciful than sound, and that Dumas did not do full justice to earlier theories of the same kind; but with him these speculations were merely the ornaments, not the substance of his work, and they led him to fix more accurately the constants of chemistry, and thus to lay a trustworthy foundation upon which the superstructure of science could safely be built.

That exuberance of fancy to which we have referred made Dumas one of the most successful of teachers, and one of the most fascinating of lecturers. It was the privilege of the writer to attend the larger part of two of his courses of lectures given in Paris, in the winters of 1848 and 1851, and he remembers distinctly the impression produced. Besides the well-arranged material and the carefully prepared experiment, there was an elegance and pomp of circumstance which added greatly to the effect. The large theatre of the Sorbonne was filled to overflowing long before the hour. The lecturer always entered at the exact moment, in full evening dress, and held to the end of a two hours' lecture the unflagging attention of his audience. The manipulations were entirely left to the care of a number of assistants, who brought each experiment to a conclusion at the exact moment when the illustration was required. An elegance of diction, an [Pg 198] appropriateness of illustration, and a beauty of exposition, which could not be excelled, were displayed throughout, and the enthusiasm of a French audience added to the animation of the scene.

To the writer the lectures of Dumas were brought in contrast to those of Faraday. Both were perfect of their kind, but very different. Faraday's method was far more simple and natural, and he excelled Dumas in bringing home to young minds abstruse truths by the logic of well-arranged consecutive experiment. With Dumas there was no attempt to popularize science; he excelled in clearness and elegance of exposition. He exhausted the subject which he treated, and was able to throw a glow of interest around details which by most teachers would have been made dry and profitless.

Two volumes of Dumas's lectures have been published; one comprises his course on the "Philosophy of Chemistry," delivered at the College of France in 1836; the other contains only a single lecture, accompanied by notes, entitled "The Balance of Organic Life," which was delivered at the Medical School of Paris, August 20, 1841. In both these volumes will be found the beauty of exposition and the elegance of diction of which we have spoken, and they are models of literary style. But of course the sympathetic enthusiasm of the great man's presence can not be reproduced by written words. [Pg 199]

The lecture on "The Balance of Organic Life" was probably the most remarkable of Dumas's literary efforts. It dealt simply with the relations which the vegetable sustains to the animal kingdom through the atmosphere, which, though now so familiar, were then not generally understood; and the late Dr. Jeffries Wyman, who heard the lecture, always spoke of it with the greatest enthusiasm.

As might be expected, Dumas's oratory found an ample field in the Chamber of Deputies and in the Senate; and whether setting forth a project of recasting the copper coinage or a law of drainage, or ridiculing the absurd theories of homœopathy, he riveted the attention of his colleagues as completely as he had entranced the students at the Sorbonne.

In the early part of his life, Dumas was a voluminous writer, and in 1828 published the "Traité de Chimie appliquée aux Arts," in eight large octavo volumes, with an atlas of plates in quarto. But besides this extended treatise, the two volumes of lectures just referred to are his only important literary works. He published numerous papers in scientific journals, which, as we have seen, produced a most marked effect on the growth of chemical science. But the number of his monographs is not large compared with those of many of his contemporaries, and his work is to be judged by its importance and influence rather than by the extent of the field which it covers. [Pg 200]

In his capacity of President of the Municipal Council at Paris, of Minister of Agricultural Commerce, of Vice-President of the High Council of Education, and of Perpetual Secretary of the Academy of Sciences, Dumas had abundant opportunity for the exercise of his administrative ability, and no one has questioned his great powers in this direction; but in regard to his political career we could not expect the same unanimity of opinion. That he was a liberal under Louis Philippe, and a reactionist under Louis Napoleon, may possibly be reconciled with a fixed political faith and an unswerving aim for the public good; but his scheme for "civilian billeting" (by which wealthy people having rooms to spare in their houses would have been compelled to billet artisans employed in public works) leads one to infer that his statesmanship was not equal to his science. Nevertheless, there can be no question about his large-hearted charity. He instituted the "Crédit Foncier," which flourishes in great prosperity to this day; he also founded the "Caisse de Rétraite pour la Vieillesse," and several other agricultural charities, which, though less successful, afford great assistance to aged workmen. Louis Napoleon used to say in jest that the whole of the War Minister's budget would not have been enough to realize M. Dumas's [Pg 201] benevolent schemes; and once, half-dazzled, half-amused, by one of the chemist's vast sanitary projects, he called him "the poet of hygiene."

It was to be expected that a man working with such eminent success in so many spheres of activity, and at one of the chief centers of the world's culture, should be loaded with medals, and marks of distinction of every kind. It would be idle to enumerate the orders of knighthood, or the learned societies, to which he belonged, for, so far from their honoring him, he honored them in accepting their membership. It is a pleasure, however, to remember that he lived to realize his highest ambitions and to enjoy the fruits of his well-earned renown. France has added his name in the Pantheon

"AUX GRANDS HOMMES LA PATRIE RECONNAISSANTE." [Pg 202]

IX.

THE GREEK QUESTION.[N]

The question whether the college faculty ought to continue to insist on a limited study of the ancient Greek language, as an essential prerequisite of receiving the A. B. degree, has been under consideration at Cambridge for a long time; and, since the opinions of those with whom I naturally sympathize have been so greatly misrepresented in the desultory discussion which has followed Mr. Adams's Phi Beta Kappa oration, I am glad of the opportunity to say a few words on the "Greek question."

This question is by no means a new one. For the last ten years it has been under discussion at most, if not at all, of the great universities of the world; and, among others, the University of [Pg 203] Berlin, which stands in the very front rank, has already conceded to what we may call the new culture all that can reasonably be asked.

Let me begin by asserting that the responsible advocates of an expansion of the old academic system do not wish in the least degree to diminish the study of the Greek language, the Greek literature, or the Greek art. On the contrary, they wish to encourage such studies by every legitimate means. For myself I believe that the old classical culture is the best culture yet known for the literary professions; and among the literary professions I include both law and divinity. Fifty years ago I should have said that it was the only culture worthy of the recognition of a university. But we live in the present, not in the past, and a half-century has wholly changed the relations of human knowledge. Regard the change with favor or disfavor, as you please, the fact remains that the natural sciences have become the chief factors of our modern civilization; and—which is the important point in this connection—they have given rise to new professions that more and more every year are opening occupations to our educated men. The professions of the chemist, of the mining engineer, and of the electrician, which have entirely grown up during the lifetime of many here present, are just as "learned" as the older professions, and are recognized as such by every university. Moreover, the old profession of medicine, which, when, as formerly, [Pg 204] wholly ruled by authority or traditions, might have been classed with the literary professions, has come to rest on a purely scientific basis.

In a word, the distinction between the literary and the scientific professions has become definite and wide, and can no longer be ignored in our systems of education. Now, while they would accord to their classical associates the right to decide what is the best culture for a literary calling, the scientific experts claim an equal right to decide what is the best culture for a scientific calling. Ever since the revival of Greek learning in Europe the literary scholars have been working out an admirable system of education. In this system most of us have been trained. I would pay it all honor, and I would here bear my testimony to the acknowledged facts that in no departments of our own university have the methods of teaching been so much improved during the last few years as in the classical. I should resist as firmly as my classical colleagues any attempt to emasculate the well-tried methods of literary culture, and I have no sympathy whatever with the opinion that the study of the modern languages as polite accomplishments can in any degree take the place of the critical study of the great languages of antiquity. To compare German literature with the Greek, or, what is worse, French literature with the Latin, as means [Pg 205] of culture, implies, as it seems to me, a forgetfulness of the true spirit of literary culture.

But literature and science are very different things, and "what is one man's meat may be another man's poison," and the scientific teachers claim the right to direct the training of their own men. It is not their aim to educate men to clothe thought in beautiful and suggestive language, to weave argument into correct and persuasive forms, or to kindle enthusiasm by eloquence. But it is their object to prepare men to unravel the mysteries of the universe, to probe the secrets of disease, to direct the forces of nature, and to develop the resources of this earth. These last aims may be less spiritual, lower on your arbitrary intellectual scale, if you please, than the first; but they are none the less legitimate aims which society demands of educated men: and all we claim is that the astronomers, the physicists, the chemists, the biologists, the physicians, and the engineers, who have shown that they are able to answer these demands of society, should be intrusted with the training of those who are to follow them in the same work.

Now, such is the artificial condition of our schools, and so completely are they ruled by prescription, that, when we attempt to lay out a proper course of training for the scientific [Pg 206] professions, we are met at the very outset by the Greek question. Greek is a requisition for admission to college, and the only schools in which a scientific training can be had do not teach

Greek, and, what is more, can not be expected to teach it.

This brings us to the root of the whole difficulty with which the teachers of natural science have been contending, and which is the cause of the present movement. We can not obtain any proper scientific training from the classical schools, and the present requisitions for admission to college practically exclude students prepared at any others. At Cambridge we have vainly tried to secure some small measure of scientific training in the classical schools: first, by establishing summer courses in practical science especially designed for training teachers, and chiefly resorted to by such persons; and, secondly, by introducing some science requisitions into the admission examinations. But the attempt has been an utter failure. The science requisitions have been simply "crammed," and the result has been worse than useless; because, instead of securing any training in the methods of science, it has in most cases given a distaste for the whole subject. True science-teaching is so utterly foreign to all their methods that the requisitions have merely hampered the classical schools, and the sooner they are abandoned the better. Both the methods [Pg 207] and the spirit of literary and scientific culture are so completely at variance that we can not expect them to be successfully united in the same preparatory school.

We look, therefore, to entirely different schools for the two kinds of preparation for the university which modern society demands—schools, which for the want of better distinctive names, we may call classical and scientific schools. In the classical school the aim should be, as it has always been, literary culture, and the end should be that power of clothing thought in words which awakens thought. Of course, the results of natural science must to a certain extent be taught; for even literary men can not afford to be wholly ignorant of the great powers that move the world. But the natural sciences should be studied as useful knowledge, not as a discipline, and such teaching should not be permitted in the least degree to interfere with the serious business of the place. In the scientific school, on the other hand, while language must be taught, it should be taught as a means, not as an end. The educated man of science must command at least French and German—and for the present a limited amount of Latin—as well as his mother-tongue, because science is cosmopolitan. But these languages should be acquired as tools, and studied no further than they are essential to the one great end in view, that knowledge which is the essential condition of the power of observing, interpreting, and ruling natural phenomena. [Pg 208]

In such a course as this it is obvious that the study of Greek would have no place, even if there were time to devote to it, and we can not alter the appointed span of human life, even out of respect to this most honored and worthy representative of the highest literary culture. Of course, no one will question that the scholar who can command both the literary and scientific culture will be thereby so much the stronger and more useful man; and certainly let us give every opportunity to the "double firsts" to cultivate all their abilities, and so the more efficiently to benefit the world. But such powers are rare, and the great body of the scientific professions must be made up of men who can only do well the special class of work in which they have been trained; and, if you make certain formal and arbitrary requisitions, like a small amount of Greek, obstacles in the way of their advancement, or of that social recognition to which they feel themselves entitled as educated men, those requisitions must necessarily be slighted, and your policy will give rise to that cry of "fetich" of which recently we have heard so much.

Now, all the schools which prepare students for Harvard College are classical schools. We do not wish to alter these schools in any respect, unless to make them more thorough in their special [Pg 209] work. As I have already said, the small amount of study of natural science which we have forced upon them has proved to be a wretched failure, and the sooner this hindrance is got out of their way the better. We do not wish to alter the studies of such schools as the Boston and Roxbury Latin Schools, the Exeter and Andover Academies, the St. Paul's and the St. Mark's Schools, and the other great feeders of the college. No—not in the least degree! We do not ask for any change which in our opinion will diminish the number of those coming to the college with a classical preparation by a single man. We look for our scientific recruits to wholly different and entirely new sources. For, although we think that there are many students now coming to us through the classical schools who would run a better chance of becoming useful men if they were trained from the beginning in a different way, yet such is the social prestige of the old classical schools and of the old classical culture that, whatever new relations might be established, the class of students which alone we now have would, I am confident, all continue to come through the old channels.

This is not a mere opinion; for only a very few men avail themselves of the limited option which we now permit at the entrance examinations—nine, at least, out of ten, offering what is called maximum in classics. [Pg 210]

We look, then, for no change in the classical schools. Our only expectation is to affiliate the college with a wholly different class of schools, which will send us a wholly different class of students, with wholly different aims, and trained according to a wholly different method. At the outset we shall look to the best of our New England high-schools for a limited supply of scientific students, and hope by constant pressure to improve the methods of teaching in these schools, as our literary colleagues have within ten years vastly improved the methods in the classical schools. In time we hope to bring about the establishment of special academies which will do for science-culture what Exeter and St. Paul's are doing for classical culture. We expect to establish a set of requisitions just as difficult as the classical requisitions—only they will be requisitions which have a different motive, a different spirit, and a different aim; and all we ask is, that they should be regarded as the equivalents of the classical requisitions so far as college standing is concerned. We do not at once expect to draw many students through these new channels. To improve methods of teaching and build up new schools is a work of years. But we have the greatest confidence that in time we shall thus be able to increase very greatly both the clientage and the usefulness of the university.

Is this heresy? Is this revolution? Is it not rather the scientific method seeking to work out the [Pg 211] best results in education as elsewhere by careful observation and cautious experimenting, unterrified by authority or superstition? Certainly, the philologist must respect our method; for of all the conquests of natural science none is more remarkable than its conquest of the philologists themselves. They have adopted the scientific methods as well as the scientific spirit of investigation; but, while thus widening and classifying their knowledge, they have rendered the critical study of language more abstruse and more difficult; and this is the chief reason why the time of preparation for our college has been so greatly extended during the last twenty-five years. Nominally, the classical schools cover no more ground than formerly, but they cultivate that ground in a vastly more thorough and scientific way.

These increased requirements of modern literary culture suggest another consideration, which we can barely mention on this occasion. How long will the condition of our new country permit its youths to remain in pupilage until the age of twenty-three or twenty-four; on an average at least three years later than in any of the older countries of the civilized world? It is all very well that every educated man should have a certain acquaintance with what have been called the "humanities." But when your system comes to its present results, and demands of the physician, [Pg 212] the chemist, and the engineer—whose birthright is a certain social status, which by accident you temporarily control—that he shall pass fully four years of the training period of his life upon technicalities, which, however important to a literary man, are worthless in his future calling, is it not plain that your conservatism has become an artificial barrier which the progress of society must sooner or later sweep away? Is it not the part of wisdom, however much pain it may cost, to sacrifice your traditional preferences gracefully when you can direct the impending change, and not to wait until the rush of the stream can not be controlled? [Pg 213]

X.

FURTHER REMARKS ON THE GREEK QUESTION.

In a former essay I endeavored to make prominent the essential difference between a system of education based on scientific culture and the generally prevailing system which is based on linguistic training. I maintained that there is not only a difference of subject-matter, but a difference of method, a difference of spirit, and a difference of aim; and I argued that, as the conditions of success under the two modes of culture are so unlike, there was no danger, even with the amplest freedom, that the study of the physical sciences would supplant or seriously interfere with linguistic studies. But, although the drift of my argument was plain, this essay has been quoted in order to show that not only Greek, but also all linguistic study, would be neglected by the students of natural science as soon as it ceased to be useful in their profession; [Pg 214] and my attempt to point out a basis of agreement and co-operation has been made the occasion of reiterating the extreme doctrine that there can be no liberal education not based on the study of language. It has been thus assumed that scientific culture can not supply such a basis, and in this whole discussion the value of the study of Nature in education, except in so far as this study may yield a fund of useful knowledge, has been entirely ignored by the advocates of the old system. Not only has there been no recognition of the value of the study of material forms and physical phenomena as a mode of liberal culture, but it has been assumed throughout that—to use the now familiar form of words—"no sense for conduct" and "no sense for beauty" can be acquired except through that special type of linguistic training that has so long limited elementary education. Those who demand a place for science-culture certainly have not shown the same contemptuous spirit; and I venture to suggest that, if classical students were as familiar with the methods of natural science as are the students of Nature with philological and archæological study, they would be more charitable to those who differ with them on this subject.

There are, of course, two distinct elements in a liberal education: the one the acquisition of useful knowledge, the other a training or culture of the intellectual faculties. The first should be made [Pg 215] as broad as possible, the second, in the present state of knowledge, must unfortunately be greatly restricted. While in the passage referred to I have claimed that, in a system of education based upon science, languages should be studied simply as tools, Mr. Matthew Arnold, in a lecture which he has recently repeatedly delivered in this country, and whose constant refrain was the phrases I have already quoted, has claimed that, although scholars must use the results of science as so much literary material, they need have nothing to do with its methods. In my view, both positions are essentially sound. It has been said that the Greek departments in our colleges could do without the scientific students much better than scientific scholars could do without Greek, and this remark admits of an evident rejoinder. Certainly in this age no professional man can afford to be ignorant of the results of science, and he will constantly be led into error if he does not know something of its methods. It is perfectly well known that very few of the investigators, who have coined the scientific terms derived from the Greek, so often referred to, could read a page of Herodotus or Homer in the original; and it is equally true that Mr. Matthew

Arnold, and his compeer, Lord Tennyson, who have shown such large knowledge of the results of science, could not interpret the complex relations in which the simplest phenomena of Nature are [Pg 216] presented to the observer. The greater number of the students of Nature can only know the beauties of Greek literature as they are feebly presented in translations, and so the greater number of literary students can only know of the wonders of Nature as they are inadequately described in popular works on science. If it requires years of study to enable a student to master the meaning of a Greek sentence, can we expect that in less time a student shall be able to unravel the intricacies of natural phenomena? It has been said that no Greek scholarship is possible for a student who begins the study of that language in college. Is it supposed that scientific scholarship is any more possible under such conditions?

In order to teach successfully the *results* of science to college students, I have no desire that they should have any preliminary preparation. It has been my duty for more than thirty years to present the elements of chemistry to the youngest class in one of our colleges, and I have never had any reason to complain of their want of interest in the subject. Indeed, I regard it as a great privilege to be the first to point out to enthusiastic young men the wonderful vistas which modern science has opened to our view. So far as their temporary interest is concerned, I should greatly prefer that they had never studied the subject before coming to college. But even enthusiastic [Pg 217] interest in popular lectures is not scientific culture. A few men in every class always have been, and will continue to be, so far interested as to make the cultivation of science the business of their lives. But such men always labor under the disadvantages resulting from a want of early training, and these obstacles repel a large number whose natural tastes and abilities would otherwise have fitted them for a scientific calling. The change from one system of culture to another, at the age of eighteen, has all the disadvantages of changing a profession late in life. Nevertheless, the college will always continue to educate a number of men of science in this way. Most of these men become teachers, and no one questions that their previous linguistic training makes them all the more forcible expositors of scientific truth. It is not for such persons that I desire any change. I am, however, most anxious that the university should do its part in educating that important class of men who are to direct the industries and develop the material resources of our country. Such men can be led to appreciate, and will give time to acquire, an elegant use of language, but they will not devote four or five years of their lives to purely linguistic training, and, if we do not open our doors to them, they will be forced to content themselves with such education as high-schools, or, at best, technical schools, can offer. But, [Pg 218] while they will thus lose the broader knowledge and larger scope which a university education affords, the university will also lose their sympathy and powerful support. Such students are now wholly repelled from the university, and, under a more liberal policy, they would form an important and clear addition to our numbers, and—as I have said in another place—without diminishing by a single man the number of those who come to college through the classical schools.

But there is another class of young men with whom a system of education based on the study of Nature would, as I am convinced, be more successful than the prevailing system of linguistic culture: I refer to those who now come to college, some of them through the influence of family tradition, some of them through the expectation of social advantage, and a still larger number on account of the attractions of college-life. Many of these are men who, with poor verbal memories, or want of aptitude for recognizing abstract relations, can never become classical scholars with any exertion that they can be expected to make, but who can often be educated with success through their perceptive faculties. These men are the dunces of the classical department, they add nothing to its strength, and in every classical school are a hindrance to the better students; but some of them may become able and useful men, if their interest can be aroused in objective [Pg 219] realities. Of our present students, it is only this class that the proposed changes would really affect. Those who have tastes and aptitudes for linguistic studies would continue to come through the old channels, and of such only can classical scholars be made.

I know very well it is said that, although the classical department would be glad to be rid of this undesirable element, yet the change could not be made without endangering the continuance of the study of Greek in many of our classical schools. But can the university be justified in continuing a requisition which is recognized to be opposed to the best interests of an important class of its patrons? And certainly it is not necessary to protect the study of Greek in this country by any such questionable means. I have a great deal more faith myself in the value of classical scholarship than many of my classical colleagues appear to possess. Never has one word of disparagement been heard from me. I honor true classical scholarship as much as I despise the counterfeit. To maintain that the class of classical dunces, to whom I have referred, appreciate the beauties of classical literature or derive any real advantage from the study is, in my opinion, to maintain a manifest absurdity. Fully as much do the convicts in a tread-mill enjoy the beauties [Pg 220] of the legal code under which they are compelled to work; and if, as Chief-Justice Coleridge has recently maintained, in his speech at New Haven, classical scholarship is the best preparation for the highest distinctions in church and state, certainly its continuance does not depend on the minimum requisition in Greek of this university.[O] The "new culture," although a much "younger industry," does not ask for any such artificial protection. It only asks for an opportunity to show what it can accomplish, and this opportunity it has never yet had. Even if the largest liberty were granted, those who seek to promote a genuine education, based on natural science, would labor under the greatest disadvantages. Not only is the apparatus required for the new culture far more expensive than that of an ordinary classical school, but also more personal attention must be given to each scholar, and the ordinary labor-saving methods of the class-room are wholly inapplicable. In the face of such obstacles as these conditions present, the new culture can advance only very gradually; and, amid the rivalry of the old system, it can only succeed by maintaining a very high degree of efficiency. The new way will certainly not offer any easier [Pg 221] mode of admission to college than the old; and when it is remembered that the classical system has the control of all the endowed secondary schools, the prestige of past success, and the support of the most powerful social influence, it is difficult to understand on what the opposition to the free development of the "new education" is based. Are not gentlemen, who have been talking of a revolution in education, taking counsel of their fears rather than of their better judgment; and are they not forgetting that the teachers of natural science have the same interest in upholding the principles of sound education as have their classical colleagues? Certainly there can be no question that, in the future as in the past, they will ever seek to maintain the integrity of all the great departments of the university unimpaired. It has happened before this that the judgment, even of intelligent men, has been warped by their class relations or supposed interests; but as, in this country, the learned class has no control of government patronage, we may at least hope that the discussion of the Greek question will never assume with us the great bitterness that a similar controversy has aroused in Germany.

There has been a great deal said in this discussion about the "humanities," and it has been assumed that, while the analysis of the Greek verb is "humanizing," the analysis of the [Pg 222] phenomena of Nature is "materializing." I can discover nothing humanizing in the one or the other, except through the spirit with which they are studied, and I know by experience that the spirit with which the study of the Latin and Greek grammars is often enforced is most demoralizing. Those who have been born with a facility for language may laugh at this statement; but a boy who has been held up to ridicule for the want of a good verbal memory, denied him by his Creator, long remembers the depressing effect produced, if not the malignity aroused, by the cruelty. Many are the men, now eminent in literature as well as science, who have experienced the tyranny of a classical school, so graphically described in the Autobiography of Anthony Trollope; and many are the boys who might have been highly educated if their perceptive faculties had been cultivated, whose career as scholars has been cut short by the same tyranny.

Again, a great deal has been said about specialization at an early age, as if the study of Nature were specializing while the study of Latin metres and Greek accents was liberalizing. But how could specialization be more strikingly illustrated than by a system which limits a boy's attention between the ages of twelve and twenty to linguistic studies to the almost entire exclusion of a [Pg 223] knowledge of that universe in which his life is to be passed, and which so limits his intellectual training that his powers of observation are left undeveloped, his judgments in respect to material relations unformed, and even his natural conceptions of truth distorted? Now, although a special culture which has such mischievous results as these may be necessary in order to command that power over language which marks the highest literary excellence, and although a university should foster this culture by all legitimate means, yet to enforce it upon every boy who aspires to be a scholar, whatever may be his natural talents, is as cruel as the Chinese practice of cramping the feet of women in order to conform to a traditional ideal of beauty. Indeed, an instructor in natural science has very much the same difficulty in training classical scholars to observe that a dancing-master would have in teaching a class of Chinese girls to waltz.

Again, it has been said that while the opportunities for scientific culture in college are ample, no one will oppose such a modification of the requisitions for admission as the conditions of this culture demand, provided only we label the product of such culture with a descriptive name. Call the product of your scientific culture Bachelors of Science, we have been told, and you may [Pg 224] arrange the requisites of admission to your own courses as you choose. I am forced to say that this argument, however specious, is neither ingenuous nor charitable. If you will label the product of a purely linguistic culture with an equally descriptive name; if, following the French usage, you will call such graduates Bachelors of Letters, we shall not object to the term Bachelors of Science; or, without making so great an innovation, I, for one, should have no objection to a distinction between Bachelors of Arts in Letters and Bachelors of Arts in Science. But it is perfectly well understood that in this community the degree of Bachelor of Arts is for most men the one essential condition of admission to the noble fraternity of scholars, to what has been called the "Guild of the Learned." To refuse this degree to a certain class of our graduates is to exclude them from such associations and from the privileges which they afford; and this is just what is intended. Hence I say that the argument is not ingenuous, and it is not charitable because it implies that a class of men who profess to love the truth as their lives are seeking to appear under false colors. To cite examples from my own profession only, I have always maintained that such men as Davy, Dalton, and Faraday were as truly learned, as highly cultivated, and as capable of expressing their thoughts in appropriate language, as the most eminent of their [Pg 225] literary compeers, and I shall continue to maintain this proposition before our American community, and I have no question that sooner or later my claim will be allowed, and the doors of the "Guild of the Learned" will be opened to all scholars who have acquired by cultivation the same power which these great men held in such a pre-eminent degree by gift of Nature.

Lastly, I am persuaded that in a large body politic like this it is unwise, and in the long run futile, to attempt to protect any special form of culture at the expense of another. If one member suffers, all the members suffer with it; and what is for the interest of the whole is in the long run always for the interest of every part. I would welcome every form of culture which has vindicated its efficiency and its value, and in so doing I feel that I should best promote the interests of the special department which I have in charge. [Pg 226]

XI.

SCIENTIFIC CULTURE;

ITS SPIRIT, ITS AIM, AND ITS METHODS.[P]

I assume that most of those whom I address are teachers, and that you have been drawn here by a desire to be instructed in the best methods of teaching physical science. It has therefore seemed to me that I might render a real service, in this introductory address, by giving the results of my own experience and reflection on this subject; and my thoughts have been recently especially directed to this topic by the discussion in regard to the requisites for admission, which during the past year have actively engaged the attention of the faculty of this college.

At the very outset of this discussion we must be careful to make a clear distinction between instruction and education—between the acquisition of knowledge and the cultivation of the [Pg 227] faculties of the mind. Our knowledge should be as broad as possible, but, in the short space of human life, it is not, as a rule, practicable to cultivate, for effective usefulness, the intellectual powers in more than one direction.

Let me illustrate what I mean from that department of knowledge which is at once the most fundamental and the most essential. I refer to the study of language. No person can be regarded as thoroughly educated who has not the power of speaking and writing his mother-tongue accurately, elegantly, and forcibly; and scholars of the present day must also command, to a considerable extent, both the French and the German languages. These three languages, at least, are the necessary tools of the American scholar, whatever may be the special field of his scholarship, and his end is gained if he has acquired thorough command of these tools. But if he goes further, and studies the philology of these languages, their structure, their derivation, their literature, the study may occupy a lifetime, and be made the basis of severe intellectual training. More frequently, and as most scholars think more effectually, such linguistic training is obtained by the study of the ancient languages, especially the Latin and the Greek, and no one questions [Pg 228] the value and efficiency of this form of mental discipline. But obviously such a preparation is not necessary for the use of the modern languages as tools, or in order to acquire a knowledge of ancient history, of the modes of ancient life, or the results of ancient thought. In recent discussions a great deal has been said about the value of classical learning, and it has been argued that no man could be regarded as thoroughly educated who had never heard of Homer or Virgil, of Marathon or Cannæ, of the Acropolis of Athens or the Forum of Rome. Certainly not. But all this knowledge can be acquired without spending six years in learning to read the Latin and Greek authors in the original, or in writing Latin hexameters or Greek iambics. The discipline acquired by this long study is undoubtedly of the highest value, but its value depends upon the intellectual training which is the essential result, and not upon the knowledge of ancient life and thought, which is merely an incident.

Now, this same distinction, which I have endeavored to illustrate on familiar ground, must not be forgotten in considering the relations of physical science to education. Physical science may also be studied from two wholly different points of view: First, to acquire a knowledge of facts and principles, which are among the most important factors of modern life; secondly, as a means of [Pg 229] developing and training some of the most important intellectual faculties of the mind—for example, the powers of observation, of conception, and of inductive reasoning.

The experimental sciences must often be studied chiefly from the first point of view. If no man can be regarded as thoroughly educated who is ignorant of the outlines of Roman and Greek history: one who knows nothing of the principles of the steam-engine, or of the electric telegraph, is certainly equally deficient. I do not question that in our high-schools the physical sciences must be taught, for the most part, as funds of useful knowledge, and in regard to such teaching I have only a few remarks to make. Assuming that information is the end to be attained, the best method of securing the desired result is to present the facts in such a way as will interest the scholar, and thus secure the retention of these facts by his memory. I think it a very serious mistake to attempt to teach such subjects by *memoriter* recitations from a text-book, however well prepared. This method at once makes the subject a task; and, if in addition the preparation for an examination is the great end in view, it is wonderful how small is the residuum after the work is done. Such subjects can always be made intensely interesting if presented by lectures, with the [Pg 230] requisite illustrations, and I do not believe that the cramming process required to pass an examination adds much to the knowledge previously gained. Many teachers, finding that the parrot-like learning of a text-book is unprofitable, attempt to make the exercise more valuable by means of problems—usually simple arithmetical problems—depending upon principles of physics or chemistry. And there can be no doubt that such problems do serve to enforce the principles they illustrate; but I am afraid they also more frequently, by disgusting the student, stand in the way of the acquisition of the desired knowledge.

It must not be forgotten, in studying the results of science, that the facts are never fully learned unless the learner is made to understand the evidence on which the facts rest. The child who reads in his physical geography that the world revolves on its axis, learns what to him is a mere form of words, until he connects this astronomical fact with his own observation that the sun rises in the east and sets in the west; and so the scholar who reads that water is composed of oxygen and hydrogen has acquired no real knowledge until he has seen the evidence on which this fundamental conclusion rests. Let, then, the sciences be taught as they have been in schools, as important parts of useful knowledge, but let them so be taught as to engage the interest of the scholar, and to direct his attention to the phenomena of Nature. [Pg 231]

All this, however, is not scientific culture, in the sense in which I have constantly used the term, and does not afford any special training for the intellectual faculties. For myself, I do not desire any study of natural history, chemistry, or physics from this point of view as a preparation for college; simply because, with the large apparatus of the university, all these subjects can be presented more effectively, and be made more interesting, than is possible in the schools. What I desire to see accomplished by our schools is a training in physical science, comparable in extent and efficiency with that which they now accomplish in the ancient languages. And this brings me to another topic, namely, scientific culture as a system of mental training.

Before attempting to state in what scientific culture consists, we shall do well, even at the expense of some repetition, to show that what often passes for scientific culture is far different from the system of education which we have so constantly advocated. The acquisition of scientific knowledge, however extensive, does not in itself constitute scientific culture, nor is the power of reproducing such knowledge, at a competitive examination, any test of real scientific power. Nevertheless, the examination papers which have been published by the universities of England [Pg 232] and of this country show that this is the sole test of scientific scholarship on which most of these universities rely, in awarding their highest honors to students in physical science. The power of so mastering a subject as to be able to reproduce any portion of it with accuracy, completeness, and elegance, at a written examination, is the normal result of literary, not of scientific, culture, and the power is of the same order, whether the subject-matter be philology, literature, art, or science. Indeed, scientific are, as a rule, much less adapted than literary subjects to the cultivation of this power. Moreover, it is also true that scholars, having attained to a very high degree of scholarship, may not possess this power of stating clearly and concisely the knowledge they actually possess. We have all of us known eminent men, possessing in a very high degree the power of investigating Nature, who have been wholly unable to state clearly the knowledge they have themselves discovered. Great harm has been done to the cause of scientific culture by attempting to adapt the well-tried methods of literary scholarship to scientific subjects: for, as I have said in another place, competitive examinations are no test of real attainment in physical science.

Let me not be understood as disparaging the retentive memory and power of concentration which enable the student to reproduce acquired information with accuracy, rapidity, and elegance. This [Pg 233] is a power of the very highest order, and is the result of the cultivation to a high degree of many of the noblest faculties of the mill. And I wish to enforce is, that success in such examinations is no indication of scientific culture, properly so called.

What, then, are the tests of true scientific scholarship? The answer can be made perfectly plain and intelligible. The real test is the power to study and interpret natural phenomena. As in classical scholarship the true test of attainment is the power to interpret the delicate shades of meaning expressed by the classical authors, so in science the true test is the power to read and interpret Nature; and this last power, like the other, can as a rule only be acquired by careful and systematic training. As some men have a remarkable facility for acquiring languages, so also there are men who seem to be born investigators of Nature; but by most men such powers can only be acquired through a careful training and exercise of the faculties of the mind, on which success depends. No man would be regarded as a classical scholar, however broad and extended his knowledge, if that knowledge had been acquired solely by reading English translations of the classical authors, however excellent. So, no man can be regarded as a scientific scholar whose [Pg 234] knowledge of Nature has been solely derived from books. In either case the real scholar must have been to the fountain-head and drawn his knowledge from the original sources. In order, then, to discover how scientific culture must be gained, we must consider the conditions on which the successful study and interpretation of Nature depend.

Of the powers of the mind called into exercise in the investigation of Nature, the most obvious and fundamental is the power of observation. By power of observation is not meant simply the ability to see, to hear, to taste, or to smell with delicacy, but the power of so concentrating the attention on what we observe as to form a definite and lasting impression on the mind. There are undoubtedly great differences among men in the acuteness of their sensations, but successful observation depends far less upon the acuteness of the senses than on the faculty of the mind which clearly distinguishes and remembers what is seen and heard. We say of a man that he walks through the world with his eyes shut, meaning that, although the objects around him produce their normal impression on the retina of his eye, he pays no attention to what he sees. The power of the naturalist to distinguish slight differences of form or feature in natural objects is simply the result of a habit, acquired through long experience, of paying attention to what he [Pg 235] sees, and the want of this power in students who have been trained solely by literary studies is most marked.

An assistant, who was at the time conducting a class in mineralogy, once said to me: "What am I to do? One of my class can not see the difference between this piece of blende and this piece of quartz" (showing me two specimens which bore a certain superficial resemblance in color and general aspect). My answer was, "Let him look until he can see the difference." And, after a while, he did see the difference. The difficulty was not lack of vision, but want of attention.

The power of observation, then, is simply the power of fixing the attention upon our sensations, and this power of fixing the attention is the one essential condition of scholarship in all departments of learning. It is a power which ought to be cultivated at an early age, and in a system of scientific culture the sciences of mineralogy and botany afford the best field for its culture, and I should therefore place them among the earliest studies of a scientific course. Minerals and plants may be profitably studied in the youngest classes of our secondary schools, but they should be studied solely from specimens, which the scholar should examine until he can distinguish all the characteristics of form, feature, or structure. I am told that in many of our secondary schools both mineralogy and botany are studied with great success and interest in the [Pg 236] manner I have indicated. But a mistake is frequently made in attempting to do too much. With mineralogy or botany as classificatory sciences, our secondary schools should have nothing to do. The discrimination between many, even of the commonest, species of minerals or plants depends upon delicate distinctions which are quite beyond the grasp of young minds, and the study of botany frequently loses all its value, through the ambition of the teacher to embrace so much of systematic botany as will enable scholars "to analyze plants."

If a child, twelve or fourteen years of age, is made to observe the characteristic qualities of a few common minerals so as to enable it to recognize them in the rocks, and is likewise led to examine the structure of a few familiar flowers, not only will a new power have been acquired, but a new interest will have been added to life.

Of course, the faculty of observation thus early exercised in childhood only attains the highest degree of development after long experience and continued practice. The acuteness which practice gives is frequently very remarkable, and rude men often surprise us by the extent to which their power of observation has been cultivated in certain special directions. The sailor who [Pg 237] recognizes the outlines of to him a well-known coast, where the ordinary traveler sees nothing but a bank of clouds, or the miner who recognizes in the rock indications of valuable ores, are illustrations which may give a clearer conception of the nature of the power we have been attempting to describe.

Naturally following the power of observation in the order of education is the power of conception with the cognate power of abstraction; that is, the power of forming in the mind distinct and accurate images of objects, and relations, which have been previously apprehended either by direct observation, or through description; and also the power of confining the attention to certain features which these images may present to the exclusion of all others. This is a power which depends very greatly on the imagination and is capable of being cultivated to a very high degree. There is no study which is so well suited to the training both of the powers of conception and of abstraction as the study of geometry.

To this end the study of geometry should be begun at an early period in school-life, and it should be studied at first not as a series of propositions logically connected, but as a description of the properties and relations of lines, surfaces, and solids—what has sometimes been called "the science of form." A text-book prepared on this idea by Mr. G. A. Hill forms an admirable [Pg 238] introduction to the study.

I esteem very highly the system of geometry of Euclid, either in its original form or as it has been modified by modern writers, as a means of developing the logical faculty. The completeness of the proof of the successive propositions and their mutual dependence by means of which, as on a series of steps, we mount from simple axiomatic truths to the most complex relations, furnish an admirable discipline for the reasoning power; but too often the whole value of this discipline is lost by the failure of the pupil to form a clear conception of the very relations about which he is reasoning, and the study becomes an exercise of the memory and nothing more. Often have I seen a conscientious and faithful student draw an excellent figure, and write out an accurate demonstration, without noticing that the two were not mated; and in a recent meeting of teachers of our best secondary schools it was gravely asserted that solid geometry is the most difficult study with which the teachers had to deal. In solid geometry, however, the reasoning is no more difficult than in plane geometry, but the conceptions are far more complex, and, if the teacher insisted that the pupil should not take a single step until his conceptions were perfectly clear, all the difficulties would disappear. Of this I am fully persuaded, for I have had to encounter the [Pg 239] same difficulties over and over again in teaching crystallography. In beginning the study of geometry, of course the power of conception should be helped in every possible way. Let your pupil find out by actual measurement that the sum of the angles of a triangle is equal to two right angles, and he will easily discover the proof of the proposition himself. So, also, if he actually divides with his knife a triangular prism made from a potato or an apple into three triangular pyramids, he will find no difficulty in following the reasoning on which the measurement of the solid contents of a sphere depends. Let me assure teachers that the study of geometry, taught as I have indicated, is a most valuable introduction to the study of science. But, as it has been usually taught as a preparation for college, it is almost worthless in this respect, however valuable it may be as a logical training.

I consider practice in free-hand drawing from natural objects a most valuable means of training both the power of observation and the power of conception, besides giving a skill in delineation which is of the greatest importance to the scientific student. Accuracy of drawing requires accuracy in observation, and also the ability to seize upon those features of the object which are the most prominent and characteristic. Hence, in a course of scientific training, the importance of practice in drawing can hardly be exaggerated, and it should be made one of the most [Pg 240] important objects of school-work from an early period.

To the scientific student the powers of observation and conception are not sought as ends in themselves, but as means of studying Nature. The precise portions of this wide field to which the attention of the student shall be directed will be determined by many circumstances, and it is not our purpose in this address to lay down a plan of study. To most students the natural history subjects offer the most attractive field; but all, I think, will admit that the experimental sciences should form a considerable portion, at least, of the course of all scientific students, whatever specialty may subsequently be chosen. That on which I desire particularly to dwell is the spirit in which all these studies should be pursued; and I can best illustrate what I mean by confining my remarks to that subject in which I am most interested, and in regard to which I have the greatest experience.

In a course of scientific study, chemistry can not be dissociated from physics, and the two sciences ought to be studied to a great extent in connection with each other. Not only does the philosophy of chemistry rest upon physical conceptions; but, moreover, chemical methods involve physical principles. There is, however, a distinction to be made; for, while some of the departments of physics are best studied as a preparation for chemistry, there are other subjects [Pg 241] which are best deferred until the student has some knowledge of chemical facts. Among the preliminary subjects we should mention elementary mechanics, including hydrostatics and pneumatics, and also thermotics; while electricity, acoustics, and optics, including the large subject of radiant energy, may well be deferred until after the study of chemistry.

In the study both of chemistry and physics there are of course two definite objects to be kept in view: In the first place, a knowledge of the facts of the science is to be acquired; in the second place, the student must learn by experience how these facts have been discovered. It would be obvious, from a moment's reflection, that a knowledge of the circumstances under which the facts of Nature are revealed to the student is essential to a complete apprehension of the facts themselves. The child who is taught that the earth moves in an elliptical orbit around the sun in one year does not in the least grasp the wonderful fact thus stated, and will not come to realize it until he connects the statement with the nightly procession of the stars in the heavens. And it is just such a connection as this which the teacher must seek to establish in all scientific teaching. In experimental science such a connection is most readily established in the mind of the student by means of a series of well-arranged experiments, which each one repeats for himself at the [Pg 242] laboratory table. Obviously, however, it is impossible, in a limited course of teaching, to go over the whole ground of chemistry and physics in this way, or even over that small portion of the ground with which the average scientific student can expect to become acquainted. Nor is this necessary; for, after one has realized the connection between phenomena and conclusion in a number of instances, the mind will fully comprehend that a similar connection exists in other cases, and will understand the limitations with which scientific conclusions are to be received.

Hence, it seems to me that, in teaching chemistry or physics, it is best to combine a course of lectures which should give a broad view of the whole ground with a course of laboratory instruction, which must necessarily be more or less restricted. Experimental lectures are, I am convinced, much the best way of presenting these subjects as systematic portions of knowledge. It is not necessary that the lectures should be formal, but it is all-important that they should be given in such a way that the interest of the student should be awakened, and that they should be fully illustrated by specimens and experiments. What we read in a book does not make one half the impression that is produced by the words of a living teacher, nor can we realize the facts unless we see the phenomena described. There is undoubtedly an advantage to be gained in [Pg 243] subsequently reviewing the subject as presented in a good text-book, and such a book may be of great use in preparation for an examination. But how far examinations are of value in enforcing the acquisition of knowledge of an experimental science is a question on which I feel a grave doubt. Certainly their value is very small if, as is too frequently the case, they lead the student to defer all effort to make his own the knowledge presented in the lectures, until a final cram.

The management of lectures, text-books, and examinations, will not, however, offer nearly so great difficulties to the teacher as the management of the parallel experimental course of laboratory teaching. In the last the methods are less well tried and demand of the teacher a very considerable amount of invention and experimental skill. To follow mechanically any text-book would result in a loss of the proper spirit with which the course should be conducted and which constitutes its chief value. No experiments are so good as those which have been devised by the teacher, or, still better, by the pupils themselves. A mere repetition of a process, according to a definite description, has no more value than a repetition of a form of words in an ordinary school recitation. The teacher must make sure that the student fully understands what he is about, and comprehends all the connections between observations and conclusions which it is his aim to [Pg 244] establish. Moreover, he must constantly encourage his students to think and work for themselves, and direct them in the methods of inductive reasoning. The failure of an experiment may be made most instructive if the student is led to discover the cause of the failure. A leak in his apparatus may be turned to a similar profit if the student is shown how to discover the leak, by carefully eliminating one part after another until the weak point is made evident.

The direction of an experimental laboratory is no easy task. The teacher must make each man's work his own, and follow his processes of thought as well as his experiments with the most careful attention. With large classes much time can be saved by going through each process on the lecture-room table and giving the directions to the class as a whole; but this does not supersede the personal attention and instruction which each student requires at the laboratory table. Moreover, in laboratory teaching the teacher must rely, as we have said, on his own resources, and but few aids can be given. There are books, however, which will help the teacher to prepare himself for his work, and I am happy to say that a book entitled "The New Physics," prepared by my colleague, Professor Trowbridge, is now being printed, which I hope will greatly promote the laboratory teaching of physics. Nichols's abridgment of Eliot and Storer's Manual [Pg 245] has long served a similar valuable purpose in chemistry, and there are many excellent works on "Qualitative Analysis," a study which is admirably adapted to develop the power of inductive reasoning.

There is, however, a danger with all laboratory manuals, which must be sedulously avoided, and the danger is generally greater the more precise the descriptions. They are apt to induce mechanical habits which are fatal to the true spirit of laboratory teaching. Not long ago I asked a student, who was working in our elementary laboratory, what he was doing. He answered that he was doing No. 24, and immediately went to find his book to see what No. 24 was. I fear that a great deal of laboratory work is done in a way which this anecdote illustrates, and, if so, it is a mere waste of time.

When teaching qualitative analysis it was always with me a constant struggle to prevent just such a result, and many of the excellent tables which have been prepared to facilitate analysis simply encourage the evil practice. It is an error to which college students, with their exclusively literary preparation, are especially liable, and I have no question that the proper conduct of our laboratories would be made much easier if the students came with a previous scientific training. [Pg 246]

Thus far I have dealt solely with generalities, and my object has been not so much to give definite directions as to make suggestions which might lead to better systems of teaching. The details of these systems may vary widely, and yet all may lead to the desired result if only the true spirit of scientific teaching is preserved, and a teacher's own system is generally the best system for him. This leads me to explain my own system of teaching chemistry—which presents some novelties that may be of interest, and, although it has been worked out in detail in the revised edition of the "New Chemistry," just published, still a few words of explanation may be of value at this time in setting forth its salient points.

Chemistry has been usually defined as the science which treats of the composition of bodies, and in most text-books the aim has been to develop the scheme of the chemical elements, and to show that, by combining these elements, all natural and artificial substances may be prepared. In the larger text-books, which aim to cover the whole ground and to describe all known substances, such a method is both natural and necessary. But, as an educational system, this mode of presenting the subject is, as a rule, profitless and uninteresting. The student becomes lost amid details which he can only very imperfectly grasp, and the great principles of the science, as well as their relations to cognate departments of knowledge, are lost sight of. Moreover, the system is [Pg 247] unphilosophical, because it presents the conclusions of chemistry before the observations on which they are based. Any one who has attempted to teach chemistry from the ordinary elementary text-books must have experienced the truth of what I have said.

A student learns a lesson about sodium and the various salts of this metal, and, after glibly reciting the words of the text-book, how much more does he know of the real relations of these bodies than he did before? Thus: "Chloride of sodium, symbol NaCl. Crystallizes in cubes. Soluble in water. Solubility only slightly increased by heat. Generally obtained by evaporation of sea-water in pans. Also found in beds in certain geological basins, from which it is extracted by mining. When acted upon by sulphuric acid, hydrochloric acid is evolved and sodic sulphate is formed, according to the following reaction," and so on. I have known a student to recite all this and a great deal more, without ever dreaming that he had been eating chloride of sodium on his food, three times a day at least, since he was born.

Now, the rational system of teaching chemistry is first to present to the scholar's mind the phenomena of Nature with which the science deals. Lead him to observe these phenomena for himself; then show him how the conclusions which together constitute that system of knowledge [Pg 248] we call chemistry have been deduced from these fundamental facts. My plan is to develop this system in the lecture-room in as much detail as the time allotted will permit; to illustrate all the points by experiment, and in addition to explain more in detail carefully selected fundamental experiments, which the student subsequently repeats in the laboratory himself. Thus I make the lecture-room instruction and the laboratory demonstration go hand in hand as complementary parts of a single course of teaching.

I begin by directing the student to observe for himself the properties of bodies by which substances are distinguished. I place in his hands a bit of roll-brimstone. He first notices the color, the hardness, the brittleness, and the electrical excitability of this material. He next determines its density, its melting-point, its point of ignition, and, if practicable, its boiling-point. Then he treats the brimstone with various solvents, and finds that, while insoluble in water or alcohol, it dissolves readily in sulphide of carbon. Afterward he evaporates the solution thus made, and obtains definite crystals, whose forms he studies, and compares with the forms of the crystals of the same material which he also makes by fusion. Lastly, he observes the remarkable change which follows when fused brimstone is heated above its melting-point, and also the peculiar plastic condition which the material assumes when the thickened mass is poured into [Pg 249] water. He will thus be led to see that the same material may assume different states, and gain a clear conception of the substance we call sulphur. After this I give the student pieces of two metals which externally resemble each other, like lead and tin, in order that, after making another series of observations and experiments, he may come to understand on what comparatively slight differences of properties the distinction between substances is frequently based. A comparison is next made of the properties of two closely-allied liquids, like methylic and ethylic alcohol; and by this time the student attains sufficient skill in experimenting to make a comparison between two aëriform substances, like oxygen gas and carbonic dioxide.

After more or less of such preliminary work, we are prepared to take up the subject-matter of chemistry. In the broad fields of Nature what portion does this science cover? Natural phenomena may obviously be divided into two great classes: First, those changes which do not involve a transformation of substance; and, secondly, those changes whose very essence consists in the change of one or more substances into other substances having distinctive properties. The science of physics deals with the phenomena of the first class; the science of chemistry with [Pg 250] those of the last. Any phenomenon of Nature which involves a change of substance is a chemical change, and in every chemical change one or more substances, called the factors, are converted into another substance or into other substances called the products. The first point to be made in teaching chemistry is, that a student should realize this statement, and a number of experiments should be shown in the lecture-room and repeated in the laboratory illustrating what is meant by a chemical change.

Here, of course, arises a difficulty in finding examples which shall be at once simple and conclusive, for in almost all natural phenomena there is a certain indefiniteness which obscures the simple process. The familiar phenomena of combustion are most striking examples of this fact, and men were not able to penetrate the mist which obscured them until within a hundred years. To find chemical processes whose whole course is obvious to an unpracticed observer, we are obliged to resort to unfamiliar phenomena.

A very simple example of a chemical process is a mixture of sulphur and zinc in atomic proportions, which, when lighted with a match, is rapidly converted into white sulphide of zinc, with appearance of flame. Another example, a mixture of sulphur and fine iron-filings, which, when moistened with a little water, rapidly changes into a black sulphide of iron. Then some [Pg 251] copper-filings, which, when heated on a saucer in the open air, slowly change into black oxide of copper. Then a bit of phosphorus, burned in dry air under a glass bell, yielding a white oxide. Next, some zinc, dissolved in diluted sulphuric acid, yielding hydrogen gas and sulphate of zinc. Then, a solution of chloride of barium added to a solution of sulphate of soda, giving a precipitate of sulphate of baryta, and leaving in solution common salt, which can be recovered by evaporating the filtrate.

In all these examples the student should be made to see and handle all the factors and all the products of each process, and the experiments should be selected so that he may become familiar with the different conditions under which substances appear, and with various kinds of chemical processes. He should also be made clearly to distinguish between the essential features of the process and the different accessories, which may be more or less accidental—such, for example, as the water used in determining the combination of iron and sulphur, or the flame which accompanies combustion.

After a clear conception has been gained of a chemical process, with its definite factors and definite products, we are prepared for the next important step. Every chemical process obeys [Pg 252] three fundamental laws:

> The Law of Conservation of Mass.
>
> The Law of Definite Proportions.
>
> The Law of Definite Volumes.

According to the first law, the sum of the weights of the products of a chemical process is always equal to the sum of the weights of the factors. This law must now be illustrated by experiments, and approximate quantitative determinations should be introduced thus early into the course of study. All that is required for this purpose is a common pair of scales, capable of weighing two or three hundred grammes, and turning with a decigramme. We use in our laboratory some platform-scales, made by the Fairbanks Company, which are inexpensive, and serve a very useful purpose.

A very satisfactory illustration of the law of conservation of mass can be obtained by inserting in a glass flask a mixture of copper-filings and sulphur in atomic proportions. The glass flask is first balanced in the scale-pan; then removed and gently heated until the ignition which spreads through the mass shows that chemical combination has taken place. The flask is lastly allowed to cool, and on reweighing is found not to have altered in weight. [Pg 253]

For a second experiment, a bit of phosphorus may, with the aid of some simple contrivance, be burned inside a tightly-corked glass flask, of sufficient volume to afford the requisite supply of oxygen. Of course, on reweighing the flask, after the chemical change has taken place, and the bottom of the flask covered with the white oxide formed, there will be no change of weight, and this experiment may be made to enforce the truth that, in this example of combustion at least, the chemical process is attended with no loss of material. Open now the flask, and air will rush in to supply the partial vacuum, proving that in the process of combustion a portion of the material of the air has united to form the white product.

Make now a third experiment as an application of the general principle which has been illustrated by the previous experiments. Burn some finely divided iron (iron reduced by hydrogen) on a scale-pan, and show that the process is attended by an increase of weight. What does this mean? Why, that some material has united with the iron to form the new product. Whence has this material come? Obviously from the air, for it could come from nowhere else. And thus, besides illustrating the first of the above laws, this experiment may be made to furnish an instructive lesson in regard to the relations of the oxygen of the atmosphere to chemical processes. [Pg 254]

The second law declares that in every chemical process the weights of the several factors and products bear each to the others a definite proportion. This law must next be made familiar by experimental illustrations. A weighed amount of oxide of silver is placed in a glass tube connected with a pneumatic trough. The tube is gently heated until the oxide is decomposed and the oxygen gas collected in a glass bottle of sufficient size. The metallic silver remaining in the tube is now reweighed, and the volume of the oxygen gas in the bottle measured, and from the volume of the gas its weight is deduced. The measurement is easily made by simply marking with a gummed label the level at which the water stands in the bottle. If, now, the bottle is removed from the pneumatic trough and the weight of water found which fills the bottle to the same height, the weight of the water in grammes will give the volume of the gas in cubic centimetres, and, knowing the weight of a cubic centimetre of oxygen, we easily calculate the weight of this gas resulting from the chemical process. We have now the weights of the oxide of silver, the silver, and the oxygen, the one factor and the two products of the chemical process, and, by comparing the results of different students making the same experiment, the constancy of the proportion will be made evident to the class. [Pg 255]

For a second illustration of the same law, the solution of zinc in dilute sulphuric acid, yielding sulphate of zinc and hydrogen gas, may be selected, and the weight of the hydrogen, estimated as in the previous example, shown to sustain a definite relation to the weight of the zinc dissolved.

Again, silver may be dissolved in nitric acid, and the weight of the nitrate of silver obtained shown to sustain a definite relation to the weight of the metal.

Or, still further, as an experiment of a wholly different class, a known weight of chloride of barium may be dissolved in water, and, after precipitation with sulphuric acid, the baric sulphate collected by filtration and weighed, when the definite relation between the weight of the precipitate and the weight of the chloride of barium will appear.

For a last experiment let the student neutralize a weighed amount of dilute hydrochloric acid with aqua ammonia, noting approximately the amount of ammonia required. Let him now evaporate the solution on a water-bath, and weigh the resulting saline product; taking next the same quantity of hydrochloric acid as before, and, having added twice the previous quantity of ammonia, let him obtain and weigh the resulting salammoniac as before. A third time let him begin with half the quantity of hydrochloric acid, and, adding as much ammonia as in the first [Pg 256] case, again repeat the process. It is obvious what the result of these experiments must be; but without telling the student what he is to expect, it will be a good exercise to ask him to draw his own inferences from the results. Of course, he must previously have so far been made acquainted with the properties of hydrochloric acid and ammonia as to know that the excess of either would escape when the saline solution is evaporated over a water-bath. But with this limited knowledge he will be able to deduce the law of definite proportions from the experimental results thus simply obtained.

The third of the fundamental laws of chemistry stated above (generally known as the law of Gay-Lussac) declares that, when two or more of the factors or products of a chemical process are aëriform, the volumes of these gaseous substances bear to each other a very simple ratio. Here, again, numerous experiments may be contrived to illustrate the law. Water, when decomposed by electricity, yields hydrogen and oxygen gases whose volumes bear to each other the ratio of two to one. When hydrochloric-acid gas is decomposed by sodium amalgam, the volume of the original gas bears to that of the residual hydrogen the ratio also of two to one. When ammonia is decomposed by chlorine, the volume of the resulting nitrogen gas is one third of that of the [Pg 257] chlorine gas employed.

Having illustrated these three general laws, attention should be directed to the fact that the nature of a chemical process and the laws which it obeys are results of observation and involve no theory whatsoever. On these facts the science of chemistry is built. The modern system of chemistry, however, assumes what is known as the molecular theory, and by means of this theory attempts to explain all these facts and show their mutual relations. Here the distinction between fact and theory must be insisted upon, and also the value of theory for classifying facts and directing observation.

A molecule is now defined, and, if the student has not studied physics sufficiently to become acquainted with the outlines of the kinetic theory of gases, this theory must be developed sufficiently to give the student a knowledge of the three great laws of Mariotte, of Charles, and of Avogadro. He must be made to understand how molecules are defined by the physicist, and how their relative weights may be inferred by a comparison of vapor densities. He should then be made to compare the relative molecular weights, deduced by physical means, with the definite proportions he has observed in chemical processes. [Pg 258] He will thus himself be led to the conclusion that these definite proportions are the proportions of the molecular weights, and that the constancy of the law arises from the fact that in every chemical process the action takes place between molecules, and that the products of the process are new molecules, preserving always, of course, their definite relative weights. The student will thus be brought to the chemical conception of the molecule as the smallest mass of any substance in which the qualities inhere, and he will come to regard a chemical process as always taking place between molecules.

Thus far nothing has been said about the composition of matter. A chemical process has been defined simply as certain factors yielding certain products, but nothing has been determined about the relations of these several substances except in so far as they are defined by the three laws illustrated above. But now it must be shown that a study of different chemical processes compels us to conclude that in some cases two or more substances unite to form a compound, while in other cases a compound is broken up into simpler parts. Thus, when copper-filings are heated in the air, it is evident that the material of the copper has united with that portion of the air we call oxygen to form the black product we call oxide of copper; and again, when oxide of silver is heated, it is evident that the resulting silver and oxygen gas were formerly portions of [Pg 259]
the material of the oxide. So, when water is decomposed by electricity, the conditions of the experiment show that the resulting oxygen and hydrogen gases must have come from the material of the water, and could have come from nothing else.

Experiments should now be multiplied until the student has a perfectly clear idea of the nature of the evidence on which our knowledge of the composition of bodies depends. The decomposition of chlorate of potash by heat, yielding chloride of potassium and oxygen gas; the decomposition of nitrate of ammonium by heat, yielding nitrous oxide and water; the decomposition of this resulting nitrous oxide, when the gas is passed over heated metallic copper; and, lastly, the decomposition already referred to, of water by electricity—are all striking experiments by which the evidence of chemical composition may be enforced.

The distinction between elementary and compound substances having been clearly defined by the course of reasoning already given in outline, the next aim should be to lead the student to comprehend how substances are analyzed and their composition expressed in percents. The reduction of oxide of copper by hydrogen gives readily the data for determining the composition of water, which is thus shown to contain in one hundred parts 11·11 per cent of hydrogen and [Pg 260]
88·89 per cent of oxygen.

Another substance whose analysis can be very readily made by the student is carbonate of magnesia. By igniting pure carbonate of magnesia in a crucible (not of course the "magnesia alba" of the shops), the proportions of carbonic acid and magnesia can be readily determined. Then, by burning magnesium ribbon, and weighing the product, the student easily finds the relative weight of magnesium and oxygen in the oxide. And, lastly, the proportion of carbon and oxygen in carbonic dioxide is easily deduced from the burning of a weighed amount of carbon. Here the result may be expressed either in percents of oxide or magnesium and carbonic dioxide, or else in percents of the elementary substances, carbon, magnesium, and oxygen.

After making a few analyses like these, the student will be prepared to comprehend the actual position of the science. All known substances have been analyzed, and the results tabulated, so that it is unnecessary to repeat the work except in special cases.

The teacher is now prepared to take a very important step in the development of the subject. If the molecule is simply a small particle of a substance in which the qualities of the substance inhere, then it follows, of course, that the composition of the molecule is the same as the [Pg 261]
composition of the substance. The percentage results of the analysis of water, or of carbonate of magnesia, indicate the composition of a molecule of water or a molecule of carbonate of magnesia. Thus, 11·11 per cent of every molecule of water consists of hydrogen, while 88·89 per cent consists of oxygen. Hence it follows that, in a chemical process, the molecules must be divided, and these elementary parts of molecules which analysis reveals are the atoms of chemistry. Moreover, as we know the weights of molecules, both by physical and chemical means, chemical analysis now gives us the weights of the atoms. We have no time to dwell on the details of this reasoning, but the general course to be followed will be evident, and it must be enforced by numerous examples.

Assuming that the student fully comprehends the distinction between molecules and atoms—that is, between the physically smallest particles and the chemically smallest particles—he is prepared to master the symbolical nomenclature of chemistry, with a very few words of explanation. The initial letters of the Latin names are selected to represent the atoms of the seventy known elementary substances, and these letters stand for the definite atomic weights which are tabulated in all chemical text-books. The symbols of the atoms are simply grouped together to form the symbols of the molecules of the various substances; the number of atoms of each kind [Pg 262]
entering into the composition of the molecule being indicated by a subscript numeral. Lastly, in order to represent chemical processes, the symbols of the molecules of the factors are written on one side and the symbols of the molecules of the products are written on the other side of an equation, the number of molecules of each substance involved being indicated by numerical coefficients.

The atomic symbols, as we have seen, stand for definite weights. In the same way, the molecular symbols stand for definite weights, which are the sums of the weights of the atoms of which each consists, and in every chemical equation the weights of the molecules represented on one side must necessarily equal the weights of the molecules represented on the other. The chemical process consists merely in the breaking up of certain molecules, and the rearrangement of the same constituent atoms to form new molecules. Again, as the molecular symbols represent definite weights, the equation also indicates that a definite proportion by weight is preserved between the several factors and products of the process represented.

Again, since every molecular symbol represents the same volume when the substance is in an aëriform condition, it follows that the relative gas volumes are proportional to the number of molecules of the aëriform substances involved in the reaction. Thus it is that these chemical equations or reactions are a constant declaration of the three great fundamental laws of chemistry. [Pg 263]

In order to enforce the above principles, a great number of examples should now be given which should be so selected as to illustrate familiar and important chemical processes, including the all-important phenomena of combustion. In each case, the student, having made the experiment, should write the equation or reaction which represents the process, and should be made to solve a sufficient number of stochio-metrical problems, involving both weights and volumes, to give him a complete mastery of the subject. Such questions as these will test the completeness of his knowledge:

Why is the symbol of water H_2O? What information does the symbol CO_2 give in regard to carbonic-dioxide gas? Write the reaction of hydrochloric acid on sodic carbonate, and state what information the equation gives in regard to the process which it represents.

Of course, such questions may be greatly multiplied, and I cite these three only to call attention to the features of the method of instruction I have been endeavoring to illustrate.

But, besides teaching the general principles of chemical science, it is important to give the student a more or less extended knowledge of chemical facts and processes—especially such as play an important part in daily life, or in the arts—and such knowledge can readily be given in this connection. Beyond this I do not deem it desirable to go in an elementary course of instruction. The way, however, is now opened to the most advanced fields of the science. A comparison of symbols and reactions leads at once to the doctrine of quantivalence, and to the results of modern structural chemistry which this doctrine involves. Among these results there is of course much that is fanciful, but there is also a very large substratum of established truth; and if the student thoroughly comprehends the symbolical language of chemistry, and understands the facts it actually represents, he will be able to realize, so far as is now possible, the truths which underlie the conventional forms. [Pg 264]

The study of the structure of molecules naturally leads to the study of their stability, and of the conditions which determine chemical changes, and thus opens the recently explored field of thermo-chemistry. To be able to predict the order and results of possible conditions of association of materials, or of chemical changes under all circumstances, is now the highest aim of our science, and we have already made very considerable progress toward this end. [Pg 265]

But I have detained you too long, and I must refer to the "New Chemistry" for a fuller exposition of this subject. My object has been gained if I have been able to make clear to you that it is possible to present the science of chemistry as a systematic body of truths independent of the mass of details with which the science is usually encumbered, and make the study a most valuable means of training the power of inductive reasoning, and thus securing the great end of scientific culture. [Pg 266]

XII.

"NOBLESSE OBLIGE."

In the former essays of this volume I have earnestly maintained that scientific culture, rightly understood, is a suitable basis for a liberal education; and I have maintained this thesis without in any way attempting to disparage that literary culture hitherto so generally regarded as the only basis on which the liberal arts could be built. While, however, I have argued that, in the present condition of the world, there is more than one basis of true scholarship, I have fully admitted that for far the larger number of scholars, including all those whose lives are to be occupied with literary pursuits, the old system of education is still the best. Moreover, I have endeavored to point out that scientific culture in no way conflicts with literary culture; that it has a different spirit, a different method, and a different aim; and I have only recommended it as suitable to those who are distinctly preparing themselves for a scientific calling; but I have maintained that for such men scientific studies, rightly followed, may lead to a broad, a noble, and in the truest sense a liberal education. [Pg 267]

I have used the term scientific culture *rightly understood* in order to mark a distinction; because a great deal that passes for scientific scholarship in the world does not imply true scientific culture. In all departments of learning, and not less in scientific than in literary studies, erudition does not necessarily imply a high degree of culture. We all value the labors of the lexicographer, and the work may be so done as to task the noblest intellectual power; but there is a higher form of literary culture than that which dictionary-making usually implies. So also in science, no amount of book-learning constitutes what we have called scientific culture rightly understood. For example, the ability to pass an examination on the facts and principles of science is no test whatever of the form of culture we are advocating. Not that we underrate the value of such tests, or of the knowledge they imply; but the ability to master a subject as presented in a text-book, and to state that knowledge in a concise and accurate form, is the normal result of literary, not of scientific culture. The power to do something well is involved in the very idea of culture, and the [Pg 268] scholar who can pass a successful written examination has acquired a power which literary culture chiefly gives, and that this power may be applied to scientific as well as literary subjects is obvious. Here is a most important distinction in connection with our subject. Culture implies the acquisition of some power of the mind in an eminent degree, and such power is constantly associated with erudition, simply because it leads to erudition. But when we see erudition without such power, as we often do in every department of scholarship, we perceive at once upon how much lower a level it stands. What very different things are classical scholarship and classical erudition; and is not the power which the great classical scholars possess of interpreting the thoughts of the classical authors, and of reproducing their life, the great element of difference between the two?

So scientific culture implies the ability to interpret Nature, to observe her phenomena, and to investigate her laws. The scholar, to whom Nature presents merely an orderly succession of facts and phenomena, knows nothing of true scientific culture. As there is a spirit in the great writers of classical antiquity which ennobles the study of the forms in which the thoughts of these [Pg 269] authors were expressed, so also is there a spirit in Nature without which facts and phenomena, however well classified, create no intellectual elevation. The last century of the world's history has been marked, more than by anything else, by the increase of our knowledge of Nature, and it will be known in history as the age of great discoveries; but valuable as the facts and principles of science certainly are, greatly as they have promoted the well-being of mankind, and important, therefore, as the knowledge of these facts and principles must be to man, yet nevertheless I should never urge the claims of physical science as a basis of liberal education if they could be defended on no other grounds than these. It is here as elsewhere "the spirit which giveth life"; and the power to interpret Nature, and to commune with the intelligence that rules the universe, is the one acquisition which, above all others, gives worth and dignity to the form of culture we have endeavored to advocate in these essays.

Those who regard science simply as utilitarianism, and who value scientific studies solely because they teach men how to build railroads, to explore mines, to extract the useful metals from their ores, or to increase the yield of agriculture, have an even more imperfect conception of what is meant by scientific culture than those to whom science is merely a valuable erudition. [Pg 270] It is true that physics and chemistry may be studied as arts rather than as sciences, and we have no desire to underrate the importance of such technical education; but the difference between the two modes of study is as wide as the difference between the artisan and the scholar. In asserting this we do not forget that the occupations of the engineer, the electrician, and the analytical chemist demand a very large amount of knowledge, judgment, and skill, and are rightly regarded as learned professions. But let it not be supposed that skill in such professions is the end or aim of scientific culture; any more than legal skill is the end or aim of literary culture. If literary scholars regard the study of science solely from this point of view, it is no wonder that they think that the tone of scholarship would be lowered if it rested solely on such a utilitarian basis; and, on the other hand, if they could once realize the sublimity of Nature, as Copernicus, Newton, Faraday, and unnumbered others have realized it, this fear that devotion to science must degrade scholarship would disappear.

We are well aware that practical men frequently regard with undisguised contempt the students of theoretical science, and that the greater number of persons seeking a scientific education must look for employment to the practical professions in which this tone too often prevails. But, [Pg 271] certainly, a narrow technical spirit prevails quite as often in the professions in which literary scholars chiefly find employment; and the new scientific professions are even more closely dependent on the discussion of theoretical and abstract principles than those which have hitherto been exclusively regarded as liberal. It is an admitted fact, as we have shown in another place, that all the great advances in practical science, all the great inventions, which during the last century have so wonderfully increased the power of man over Nature, may be traced directly to the results of theoretical study. For this reason, if on no higher ground, we have claimed that it is both the interest and the duty of the State to foster and reward scientific investigation. The time is not far distant, if it is not already at hand, when the scientific culture of a people will be one of the chief factors in determining its position among the nations of the world.

We can not leave this subject without giving prominence to another thought, which has been ever present with us while writing these pages, if not hitherto distinctly stated. Culture, as we have seen, implies power, and the possession of power also involves corresponding obligations. Among the many blessings which Christianity and its attendant civilization have brought to mankind, the recognition of this principle is most plainly marked. The principle is assumed in almost every [Pg 272] relation of life, even when not distinctly acknowledged; and happily it can rarely now be disregarded without incurring the odium of mankind. It leads the possessors of great wealth to devote no inconsiderable share of their fortunes to the public good; it stigmatizes as miserly any neglect of this obligation; and the best hope of preserving our modern civilization against the destructive agencies of socialism is to be found in the increasing recognition and enforcement of this saving grace.

But while this principle is, to a greater or less degree, acted upon in all relations of life, it is enforced by public opinion with special strictness upon those who assume to be the servants of the people. In political life the obligations it imposes are already very generally recognized; and still more strongly are they felt by the ministers of religion. The politician who uses his high position to promote his personal interests may sometimes escape his just deserts; but the clergyman who prostitutes his influence for private gains is universally condemned. So true is this, that a clergyman is debarred by his profession from many of the industries and occupations of life which are regarded as perfectly honorable callings for other men. A clergyman who speculated in stocks, or even engaged in a mercantile pursuit, would, with good reason, lose the respect of the very men who had gained their wealth by the same ways which they deny to him. [Pg 273] He may not, like the members of the elder religious fraternities, take the vow of poverty, but still he is held to a very strict rule of life; and on this is based his claim to an adequate support from the people to whom he ministers. Because "appointed to sow spiritual things," the clergy are entitled "to reap worldly things" which they have not sown nor gathered; and evil will be the days when this claim is disallowed.

Now, we hold that the profession of a scientific teacher implies an obligation not less binding than that which rests on the clergyman; and this is especially true if the teacher has been placed in a conspicuous and responsible position before the world. The teacher has been set apart as truly as the clergyman, and, if he uses the influence of his office merely as a means of accumulating wealth, he is not loyal to the profession which he has voluntarily assumed. Let me not be misunderstood. There are a thousand legitimate ways of earning a livelihood and acquiring wealth by means of the knowledge which scientific study gives; and a man has a right to use scientific knowledge for his worldly advancement as freely as any other knowledge. But the man who has accepted the post of a teacher, and receives the support to which his position entitles him, is bound to do the work of a teacher to the best of his ability, and to devote his [Pg 274] whole energies to extending the knowledge of the science which he professes to teach. It is of the utmost importance that the community should be educated up to this point, and should hold its teachers to their trusts and obligations as strictly as it does its clergy. Indeed, the scientific even more than the religious teacher requires the aid of a correct public sentiment to maintain the tone of his profession. Scientific knowledge and acumen, when centered on business relations, has often discovered direct avenues to wealth; the temptation to make use of the opportunities thus offered is of course very great, and in most of the relations of life the career so opened may be perfectly legitimate and honorable. But no one can expect to succeed in any business career without devoting his whole energy to the work, and there are conditions under which such a course would involve the betrayal of a trust. Nor are the words betrayal of a trust too strong; for it is sometimes the case that, besides neglecting his appropriate work, the scientific teacher sells the reputation of his position, and commands a higher price because he barters the good name of the institution with which he is connected.

I am well aware that there is another side to this question. In many of our colleges the professor has an inadequate support, and is expected or even invited to supplement his income by what is [Pg 275] technically called "commercial work." Of course, in such cases the man can not be blamed; but public opinion should be such as to prevent a respectable institution from offering, or a respectable professor from accepting, such a position. The workman is worthy of his hire, and the same sentiment which demands from the scientific professor a whole-hearted devotion to his work, demands also from the community for which he works an adequate support.

It is undoubtedly in consequence of the inadequate support which scientific teachers generally receive in this country that public sentiment tolerates with them practices which sober judgment must condemn; and it must be remembered that under these circumstances a teacher, if he is faithful to the routine of his office, may devote his remaining energies to commercial work, not only without any consciousness of wrong-doing, but even with the approbation of his associates. Hence, it is the more important to establish firmly in the public mind the well-founded opinion that the endowed professorships of our higher institutions of learning are offices of public trust, to be administered solely for the public good. There is no hardship in this position; since perfectly legitimate and honorable avenues are opened to the scientific scholar, on which he may expend his business energies, and, at the same time, use his scientific knowledge; and for many men [Pg 276] these avenues lead in the directions in which they can not only most effectually advance themselves in worldly prosperity, but also most benefit their fellows. Among the men of practical ability who have developed a new industry, or introduced a new invention, and who have acquired wealth thereby, are to be found some of the greatest benefactors of their race; and far would it be from me to institute a comparison between the practical men and the scholars. All we claim is that the men of affairs should resign the endowments intended for the maintenance of scholars to those whose zeal is sufficient to induce them to make gladly the sacrifices which the advancement of knowledge usually entails.

These considerations will appear still more forcible if viewed in relation to the interest of the community in scientific culture to which we have already referred. This interest has not been overlooked, and in recent years a great many projects have been discussed for what is termed the "endowment of research"; and already very considerable funds are held by learned societies of the Old World, and smaller amounts by several societies of this country, which have been devoted to this object. But although means are thus furnished to a limited extent to pay the expenses of scientific investigations, and very considerable prizes are offered for the solution of important [Pg 277] problems, yet it must be confessed that as yet the results have been meager and have not answered the expectations of the founders of the endowments; and the reason of the small fruitage is not far to seek. A certain order of scientific results can be purchased like other professional work for a price which is to some extent proportionate to the skill required to obtain them. Such, for example, are the daily observations at an astronomical or a meteorological station; such also are chemical analyses and assays of various kinds; such, again, is much of the routine work of a physical laboratory. But the highest order of scientific results, such as leave a permanent impress on the records of science—like Newton's law of gravitation, Young's theory of light, Faraday's theory of electricity, or Bunsen's methods of spectrum analysis—can no more be had to order than could "Paradise Lost" or "In Memoriam" have been purchased by the foot. Moreover, scientific progress follows a necessary law of continuity, and important advances can not be made until the time is ripe. The most that can be done with the direct endowments for research is, to multiply trustworthy observations, and thus prepare the way for discovery; and more than this can not be expected.

A more efficient means of cultivating science, and one which is certain, in the long run, to yield a far more abundant and richer harvest, is to secure the conditions which are known to be [Pg 278] favorable to scientific discoveries, and to hold in honor such discoveries when made; and I think there will be little difference of opinion among competent scientific authorities that the one essential condition above all others is a certain atmosphere which results from the association of men who are engaged in scientific study.

An association of scholars acts in many ways to favor either literary or scientific production. In the first place, it leads to competition, which, although a low motive, is a very potent one in all forms of human activity. In the second place, the contact of minds engaged in similar studies leads the student to take a broader view of his subject, and to see it from the various points of view which the criticism of his associates may point out. Above all, work done in such associations is not done without observation, and there are present witnesses to attest the results, and publish them with the authority which is required to insure for them general acceptance. A great deal of scientific work is lost to the world because done in a corner, and buried in the transactions of local societies, from which it is not disinterred until the work has been repeated. The advantages of such association are only too evident to the numerous workers in science at the isolated colleges of this country, who are forced to compare their opportunities [Pg 279] with those of their compeers in the great capitals of Europe; and the want of scientific productiveness in the United States which we so greatly lament is due chiefly to the want of the stimulus which combined action so greatly gives. Happily, however, the conditions favorable for scientific investigation are multiplying at home, and already there are several centers at which the productiveness is rapidly increasing, and gives great promise of the future. Moreover, this growth gives us a good indication as to the points at which we can most advantageously apply aid; and I am confident that there is no way in which we can so effectively encourage scientific investigation as by establishing at the institutions of learning, which are at present the chief centers of scientific activity, more professorships and fellowships, in order to give support to those who are ready to devote their lives to scientific study.

The teaching which a professorship implies, instead of being a hindrance, ought to be a great stimulus to scientific investigation. Of course, this influence is greatly impaired if, as in many of our colleges, the available energies of the teacher are exhausted by the daily routine of instruction, or by the outside work required to supplement his meager salary. But, if the teaching is only moderate in amount and in the direction of the professor's own work, there is no stimulus [Pg 280] so great as that which the association with a class of earnest students supplies.

Were it necessary to sustain the opinions here advanced by further illustrations, we need only point to the Royal Institution of Great Britain, which holds foundations like those we have advocated; for the names of Davy, Young, Faraday, Tyndal, and Dewar, are a conspicuous memorial of the very great success of such endowments in advancing physical science.

It is obvious, however, that the endowment of professorships and fellowships will be of no value to the community unless it is understood that the incumbents are set apart for their special work; and the suggestion that such positions could be used to favor private ends, or as the basis of mercantile transactions, is sufficient to show how inconsistent such a practice is with the true conception of scientific culture.

Our patent laws have a very marked and not altogether a beneficial influence on the scientific culture of the country. It is true that they foster mechanical ingenuity and inventive talent in certain directions, but they also set before the people a very low and mercenary standard of scientific attainment, upon which the popular notion of the utilitarian tendency of scientific studies is to a great extent based. No one can question that the discoverer of a new process, or [Pg 281] the inventor of a new machine, has a right to keep his knowledge to himself, and to make the best use he can of his good fortune to increase his wealth. But certainly the motto at the head of this essay points to a more excellent way, and it is at least an open question whether it is for the interest of the community at large to encourage by its laws the more selfish course. The argument by which the patent laws are usually defended by legal writers—that it is for the benefit of the community to encourage and therefore to protect inventive talent—is by no means so unanswerable as it appears *prima-facie*.

In the first place, it may be questioned whether, in the present condition of our patent laws, they do not hinder more than they foster invention. Any one who has attempted to perfect a machine, or improve a chemical process, knows to what extent he is hampered on every side by patent rights, which often have no value to the holders except that which the new improvement may give to them.

Again, the inventions which the patent laws foster are only those having an immediate pecuniary value, and it is often exceedingly simple contrivances—like the needle of a sewing-machine or a gaudy toy—which yield the greatest return; simply because they have been accommodated to present emergencies or to passing popular fancy. Such contrivances usually manifest no [Pg 282] extended knowledge and no special talent, and the inventor owes his good luck to the sole circumstance that he was in a position to recognize the want.

Now, every scientific investigator knows that the ordinary work of a physical or chemical laboratory frequently demands inventive ability of a high order, and that few important scientific results have been reached that have not involved inventions as worthy of admiration as the sewing-machines and power-looms which are so frequently cited as examples of the beneficent influence of our patent laws; and the question arises, is it for the interest of the community to promote one class of inventions more than the other? Certainly, if we consider either the sacrifice involved, or the ultimate good which eventually results to the community, there can not be a moment's question which class is the most valuable or most worthy of commendation. Yet the patent laws not only give their immense prizes solely to inventions of immediate utility, but also tend to raise a false estimate of the intrinsic value of such inventions in the public mind.

Some writers have gone to the extreme of claiming that a man has the same right in his inventions or discoveries that an author has in his books; but this claim will not bear analysis. The first duty of a government is to protect its citizens in the enjoyment of the results of their [Pg 283] lawful labor, and certainly any one who has written a book knows that it is just as much the product of day-labor as any article of merchandise. On the other hand, an invention or discovery may be the result of a fortunate accident, and, although it may be the fruit of superior knowledge and intelligence, it can not be regarded in the same sense as a direct product of labor. It is much more frequently a free gift of Nature.

Moreover, it is seldom if ever the case that a useful invention, meeting a popular want, and therefore having a large commercial value, is in any sense the product of one man. As a general rule, the patentee who enjoys the right to the invention has actually added to the old stock only a single detail. It may be that this detail was the one thing required to make the invention practically useful; but it is certain that the addition could never have been made if the previous knowledge had not existed, and it is at least an open question whether the community ought to grant to the last man an exclusive right to the whole inheritance. Volta discovered—invented, if you please—the mode of generating a current of low-tension electricity, which has been ever since, with certain modifications, in general use; Oersted and Ampére discovered the magnetic effects of this electrical current; Faraday, again, learned how to produce an electric current from [Pg 284] a magnet, and invented the original dynamo-machine; Henry discovered the conditions under which the magnetic effects of an electric current might be produced at great distances from the source of the power. All these men were inventors of the highest order, whose inventions have never been excelled either in the ingenuity displayed, or in the influence exerted on the welfare of mankind. Moreover, these far-reaching inventions were a willing contribution to the world's knowledge, for which no pecuniary compensation was either asked or received. Is it not, then, a question if any man of the present day has a right to the exclusive use of these inventions; for writing messages at a distance, for transmitting sound over wires, or for any purpose whatsoever?

There is of course another side to the question, and I freely admit the difficulty of the problem which our patent laws present; but I feel that in their present condition they do more harm than good, and do injustice more frequently than they protect right. I greatly doubt if it is safe to grant by statute property in any invention or discovery beyond the definite mechanical contrivance in which it is for the time embodied. To grant the sole use of a well-known power of Nature to produce a specific effect, although the effect be a novel one; to give the monopoly of a process of Nature to the man who was the first to claim it; above all, to grant the sole right to make a [Pg 285] specified mixture of materials—is certainly a policy which directly encourages vast monopolies, that tax the public without rendering a corresponding benefit.

In this connection it must be remembered that the discoverer or inventor himself rarely reaps the fruit of his sagacity or skill; but his rights, frequently purchased for a song, are made the basis of great business enterprises in which he has little or no share. On such a slender basis have frequently been built up huge monopolies, in which the patent laws have been made the instruments of oppressive exactions, and have become the nucleus of a most complex system of usages and legal decisions, by which the original intent of the laws has been wholly overlaid, and to a great extent nullified.

Certainly, there ought to be some limit to the inventor's claims on a grateful people. Admit to the utmost the inventor's merit; rank him in the fore front of the long procession of the great benefactors of the human race; rank him before Faraday, before Volta, and before Newton; rank him before Washington and the Fathers of the Republic; rank him before the patriots and martyrs who have died in the defense of human rights, or in attestation of the truth: and yet, in virtue of these transcendent merits, should he or his representatives be authorized to tax his countrymen [Pg 286] millions on millions of dollars a year? Surely, there could not be a greater travesty of our motto, "Noblesse Oblige"; and a system which gives a legal sanction to such abuses will soon force on the public mind that most convincing of all proofs of perversion, the *reductio ad absurdum*.

It is not, however, our intention to discuss the abuses of the patent laws, much less to suggest the required remedies. We clearly see the difficulties of the subject, and we perceive that it involves questions, both of political economy and of jurisprudence, with which we are not competent to deal. Our interest is solely to maintain the dignity of scientific culture, and to demand for it the respect to which it is entitled; but which is seriously compromised by the mercenary and utilitarian spirit that the patent laws encourage and make prominent. We are most anxious that the intelligence of our people should fully recognize the fact that, among the students of science in this practical age, there is such a thing as devotion to the truth for the truth's sake; that throughout the length and breadth of these United States may be found many an earnest student of Nature who, under great disadvantages, and often at great personal sacrifice, is devoting the noblest intellectual power, and the highest inventive skill, to the sole end of advancing knowledge: and we rejoice to believe that the time will come when it will be [Pg 287] plainly seen by all that these silent workers have been laying broad and deep-enduring foundations, on which national greatness can securely rest. [Pg 288]

XIII.

THE SPIRITUAL LIFE.[Q]

We have reached the end of our long journey, and now we are ready to turn back and start for home.

The Reis is at his helm, the great sail is furled and bound closely to the long yard; for, as the wind during the early spring blows here constantly from the north, we must depend on the rapid current of the Nile to bear us back to civilization: a river which, flowing through so many generations of men from the unknown to the unlimited, not unfitly typifies the course of history; and as, in imagination, we drift with this historical stream, we can not fail to learn the lesson which the associations and the scenes are so calculated to teach. That lesson is the grandeur, the glory, and the immortality of the spiritual life of man.

We go back six thousand years, and find the Sphinx, as to-day, looking toward the rising sun, and [Pg 289] pondering the problem of human destiny.

The pyramid-builders come, and erect those neighboring piles to preserve their bodies when dead for that glorious destiny in which they trust.

The long procession of the Pharaohs passes, and each inscribes indelibly on rocky walls his faith in the great God who holds human destiny in his hands.

Moses comes, and leads out of Egypt the chosen people to prepare the way for the expected Messiah.

The Assyrians and the Persians come, and, while seeking to read their destiny in the courses of the stars, pay homage to the same great hope.

The Greeks come, and, even amid gross licentiousness and idolatry, erect magnificent temples, in attestation of a belief in human destiny which, however degraded, still survived.

The Romans come, and in this mystic land lay aside their legal codes, and add their testimony to the same great truth.

The Christian hermits come, and make the storied stones of the Pharaohs re-echo with their triumphant songs.

The Arab comes, and, as morning and evening he gazes into the East, sees visions of the glorious Mecca of his hopes for which the Sphinx has looked so long. [Pg 290]

Last of all, the modern traveler comes, and he journeys in vain if he does not recognize in all this aspiration and all this yearning the attestation of those spiritual truths which to him the risen Christ has revealed.

As in material nature every unemployed organ distinctly points to a previous use or to a future fruition: so, in the spiritual world, every striving is a promise of a possible good; and these yearnings of humanity, which have come down through the ages, are as truly a promise of the Eternal as were the words spoken to Abraham on the plains of Mamre.

Coming home from the East, we can not fail to see, more clearly than before, how artificial are most of the conventionalities of our modern civilization, and how greatly such cares of the world tend to obscure the great distinction between the spiritual and the material which is ever present to Oriental thought; and this is especially true in our own country, where the demands of material nature are so pressing, and where the physical wants, which our highly artificial life entails, so completely engross the attention of us all.

It is well to go away at times, that we may see another aspect of human life, which still survives in the East, and to feel that influence which led even the Christ into the wilderness to prepare for [Pg 291] the struggle with the animal nature of man.

We need something of the experience of the anchorites of Egypt to impress us with the great truth that the distinction between the spiritual and the material remains broad and clear, even if with the scalpel of our modern philosophy we can not completely dissect the two; and this experience will give us courage to cherish our aspirations, keep bright our hopes, and hold fast our Christian faith until the consummation comes.

My young friends, there are many who will tell you that the Sphinx has merely propounded a riddle to the ages; and that the yearnings of your young lives—like those of the early Egyptians, who set up this memorial of their hopes—are merely a delusion and a snare.

Do not believe in any such pessimism.

It is merely the dying gasp of your animal nature! But give your utmost efforts that these aspirations be not smothered by the cares and trials which must come to you as they come to all.

Have faith in the Eternal who implanted those cravings in your nature; and remember that all knowledge rests on the assurance that the Eternal can not be false. Be loyal to the truth of that witness in your hearts, and advancing years will only bring you increased reliance on the [Pg 292] promises he ever whispers to those who trust him; and he will certainly lead you, at last—as he has led the faithful in all ages—into the clear light of the perfect day.

My fellow-students, if these fleeting pictures of scenes which have given me fresh courage, shall aid any of you in the conflict of life, my object in these lectures will be gained, and however incongruous with the associations of physical science such scenes may have appeared, you will bear me witness that the great lesson they teach has constantly been enforced in this place. The spiritual life of man recognizes its exalted intellectual likeness in the life of Nature, and it is this vision of the Omniscient which distinguishes and ennobles mental culture, whether it be in the fields of science, of literature, or of art.

THE END.

[Pg 293]

FOOTNOTES:

[A] As some of the readers of this volume may be interested to compare these values, we reproduce the "Table of Molecular Data" from Professor Clerk Maxwell's lecture on "Molecules," delivered before the British Association at Bradford, and published in "Nature," September 25, 1873.

Molecular Magnitudes at Standard Temperature and Pressure, 0° C. and 76 c. m.

RANK ACCORDING TO ACCURACY OF KNOWLEDGE.	Hydrogen.	Oxygen.	Carbonic Oxide.	Carbonic Dioxide.
RANK I.				
Relative mass	1	16	14	22
Velocity in metres per second	1,859	465	497	396
RANK II.				
Mean path in ten billionths (10^{-10}) of a metre	965	560	482	379
Collisions each second—number of millions	17,750	7,646	9,489	9,720
RANK III.				
Diameter in hundred billionths (10^{-11}) of a metre	58	76	83	93
Mass in ten million million million millionths (10^{-25}) of a gramme	46	736	644	1,012

Number of molecules in one cubic centimetre of every gas is nineteen million million million on 19 (10^{18}).

Two million hydrogen molecules side by side measure a little over one millimetre.

[B] *See* Professor Maxwell's lecture, *loc. cit.*; also, Appletons' "Cyclopædia," article "Molecules."

[C] There is an obvious distinction between the free and the disturbed path of a molecule, and we can not overlook in our calculations the perturbations which the collisions necessarily entail. Such considerations greatly complicate the problem, which is far more difficult than would appear from the superficial view of the subject that can alone be given in a popular lecture.

[D] See notice of these investigations by the author of this article, in "American Journal of Science and Arts," September, 1877 (3), xiv, 231.

[E] The reader will, of course, distinguish between the differential action on the opposite faces of the vanes of the radiometer and the reaction between the vanes and the glass which are the heater and the cooler of the little engine. Nor will it be necessary to remind any student that a popular view of such a complex subject must be necessarily partial. In the present case we not only meet with the usual difficulties in this respect, but, moreover, the principles of molecular mechanics have not been so fully developed as to preclude important differences of opinion between equally competent authorities in regard to the details of the theory. To avoid misapprehension, we may here add that, in order to obtain in the radiometer a reaction between the heater and the cooler, it is not necessary that the space between them should actually be crossed by the moving molecules. It is only necessary that the momentum should be transferred across the space, and tide may take place along lines consisting of many molecules each. The theory, however, shows that such a transfer can only take place in a highly rarefied medium. In an atmosphere of ordinary density, the accession of heat which the vanes of a radiometer might receive from a radiant source would be diffused through the mass of the inclosed air. This amounts to saying that the momentum would be so diffused, and hence, under such circumstances, the molecular motion would not determine any reaction between the vanes and the glass envelope. Indeed, a dense mass of gas presents to the conduction of heat, which represents momentum, a wall far more impenetrable than the surrounding glass, and the diffusion of heat is almost wholly brought about by convection currents which rise from the heated surfaces. It will thus be seen that the great non-conducting power of air comes into play to prevent not only the transfer of momentum from the vanes to the glass, but also, almost entirely, any direct transfer to the surrounding mass of gas. Hence, as stated above, the heated molecules bound back and forth on the vanes without change of condition, and the mass of the air retains its uniform tension in all parts of the bulb, except in so far as this is slowly altered by the convection currents just referred to. As the atmosphere, however, becomes less dense, the diffusion of heat by convection diminishes, and that by molecular motion (conduction) increases until the last greatly predominates. When, now, the exhaustion reaches so great a degree that the heat, or momentum, is rapidly transferred from the heater to the cooler by an exaggeration, or, possibly, a modification, of the mode of action we call conduction, then we have the reaction on which the motion of the radiometer wheel depends.

[F] "Nature," No. 22, March 31, 1870.

[G]

For example, the native crystals of sulphur have	$a : b : c = 1 : 2{\cdot}340 : 1{\cdot}233$.
Crystals of gypsum have	$a : b : c = 1 : 0{\cdot}413 : 0{\cdot}691$.
Crystals of tin-stone have	$a : b : c = 1 : 1 : 0{\cdot}6724$.
And crystals of common salt have	$a : b : c = 1 : 1 : 1$.

[H] The origin of the axes is always taken as the center of the sphere of projection.

[I] "Obituary Notices from the Proceedings of the Royal Society," No. 206, 1880, to which the writer has been indebted for several biographical details.

[J] This notice is reprinted from the Proceedings of the American Academy of Arts and Sciences, vol. xviii, 1882-'83.

[K] Reprinted from the Proceedings of the American Academy of Arts and Sciences, vol. xix, 1883-'84.

[L] A. W. Hofmann, in "Nature," February 6, 1880, to whose admirable and extended biography the writer is indebted for much of the material with which this notice has been prepared.

[M] Hofmann, *loc. cit.*

[N] Remarks made at the dinner of the Harvard Club of Rhode Island, Newport, August 25, 1883.

[O] This article was written and read to the Faculty of Harvard College shortly after Lord Coleridge's visit to the United States, in the autumn of 1883.

[P] An address delivered at the opening of the Summer School of Chemistry at Harvard College, July 7, 1884.

[Q] An Address to College Students at the close of a course of lectures on Egypt and her Monuments. Illustrated by lantern photographs.

Origin of the Planetary System.—On Thought in Medicine.—Academic Freedom in German Universities.

"Professor Helmholtz's second series of 'Popular Lectures on Scientific Subjects' forms a volume of singular interest and value. He who anticipates a dry record of facts or a sequence of immature generalization will find himself happily mistaken. In style and method these discourses are models of excellence, and, since they come from a man whose learning and authority are beyond dispute, they may be accepted as presenting the conclusions of the best thought of the times in scientific fields."—*Boston Traveler.*

Science and Culture, and other Essays. By Professor T. H. Huxley, F. R. S. 12mo. Cloth, $1.50.

"Of the essays that have been collected by Professor Huxley in this volume, the first four deal with some aspect of education. Most of the remainder are expositions of the results of biological research, and, at the same time, illustrations of the history of scientific ideas. Some of these are among the most interesting of Professor Huxley's contributions to the literature of science."—*London Academy.*

"It is refreshing to be brought into converse with one of the most vigorous and acute thinkers of our time, who has the power of putting his thoughts into language so clear and forcible."—*London Spectator.*

Scientific Culture, and other Essays. By Josiah Parsons Cooke, Professor of Chemistry and Mineralogy in Harvard College. 12mo. Cloth, $1.00.

These essays are an outcome of a somewhat large experience in teaching physical science to college students. Cambridge, Massachusetts, early set the example of making the student's own observations in the laboratory or cabinet the basis of all teaching, either in experimental or natural history science; and this example has been generally followed. "But in most centers of education," writes Professor Cooke "the old traditions so far survive that the great end of scientific culture is lost in attempting to conform even laboratory instruction to the old academic methods of recitations and examination. To point out this error, and to claim for science-teaching its appropriate methods, was one object of writing these essays."

WORKS ON ASTRONOMY.

Elements of Astronomy. By Robert Stowell Ball, LL. D., F. R. S., Andrews Professor of Astronomy in the University of Dublin, Royal Astronomer of Ireland. With Illustrations. 16mo. Cloth, $2.25.

Elementary Lessons in Astronomy. By J. Norman Lockyer, F. R. S. Richly illustrated, and embracing the Latest Discoveries. American edition. Adapted to the Schools and Academies of the United States. 12mo. Cloth, $1.50.

Outlines of Astronomy. By Sir J. J. W. Herschel. With Plates and Woodcuts. Eleventh edition. 8vo. Cloth, $4.00.

The Sun. By C. A. Young, Ph. D., LL. D., Professor of Astronomy in the College of New Jersey. With numerous Illustrations. 12mo. Cloth, $2.00.

"Professor Young is an authority on 'The Sun,' and writes from intimate knowledge. He has studied that great luminary all his life, invented and improved instruments for observing it, gone to all quarters of the world in search of the best places and opportunities to watch it, and has contributed important discoveries that have extended our knowledge of it."—*Popular Science Monthly.*

Spectrum Analysis, in its Application to Terrestrial Substances, and the Physical Constitution of the Heavenly Bodies. Familiarly explained by Dr. H. Schellen, Director der Realschule I. O. Cologne. Translated from the second enlarged and revised German edition by Jane and Caroline Lassell. Edited, with Notes, by William Huggins, LL. D. With numerous Woodcuts, Colored Plates, and Portraits; also, Angström's and Kirchhoff's Maps. 8vo. Cloth, $6.00.

"This admirable work does credit to, or should we say is worthy of, the author, the translators, and the editor. The first part treats on the artificial sources of high degrees of heat and light; the second on Spectrum Analysis in its application to the heavenly bodies. We must approve the method followed in the translation and by the editor. In many translations the views of the author are suppressed, in order that the views of the translator or editor may be expounded; but here Dr. Huggins, however leniently such a fault might have been looked upon with him, has permitted the author's views to remain intact, clearly stating his own and wherein lies the difference."—*The Chemical News.*

"Certainly, as regards mere knowledge, the 'Spectrum Analysis' has let us into many secrets of the physical universe which Newton and Laplace would have declared impossible for man's intellect to attain. The science is still in its infancy, but it is prosecuted by some of the ablest, most patient, and most enthusiastic observers, and some of the keenest thinkers, at present existing on our little, insignificant physical globe."—*Boston Globe.*

Studies in Spectrum Analysis. By J. Norman Lockyer, F. R. S., Correspondent of the Institute of France, etc. With Sixty Illustrations. 12mo. Cloth, $2.50.

"The study of spectrum analysis is one fraught with a peculiar fascination, and some of the author's experiments are exceedingly picturesque in their results. They are so lucidly described, too, that the reader keeps on, from page to page, never flagging in interest in the matter before him, nor putting down the book until the last page is reached."—*New York Evening Express.*

Origin of the Stars, and the Causes of their Motions and their Light. By Jacob Ennis. 12mo. Cloth, $2.00.

Astronomy and Geology Compared. By Lord Ormathwaite. 18mo. Tinted paper. Cloth, $1.00.

The Expanse of Heaven. A Series of Essays on the Wonders of the Firmament. By R. A. Proctor. 12mo. Cloth, $2.00.

"'The Expanse of Heaven' can not fail to be of immense use in forwarding the work of education, even when it is read only for amusement, so forcible is the impression it makes on the mind from the importance of the subjects treated of, while the manner of treatment is so good."—*Boston Traveller.*

The Moon: Her Motions, Aspect, Scenery, and Physical Conditions, with Two Lunar Photographs and many Illustrations. By R. A. Proctor. New edition. 12mo. Cloth, $3.50.

Other Worlds than Ours; the Plurality of Worlds, studied under the Light of Recent Scientific Researches. By R. A. Proctor. With Illustrations, some colored. 12mo. Cloth, $2.50.

Our Place among Infinities. A Series of Essays contrasting our Little Abode in Space and Time with the Infinities around us. To which are added Essays on the Jewish Sabbath and Astrology. By R. A. Proctor. 12mo. Cloth, $1.75.

WORKS ON GEOLOGY, Etc.

Principles of Geology; or, The Modern Changes of the Earth and its Inhabitants, considered as illustrative of Geology. By Sir Charles Lyell, Bart. Illustrated with Maps, Plates, and Woodcuts. A new and entirely revised edition. 2 vols. Royal 8vo. Cloth, $8.00.

The "Principles of Geology" may be looked upon with pride, not only as a representative of English science, but as without a rival of its kind anywhere. Growing in fullness and accuracy with the growth of experience and observation in every region of the world, the work has incorporated with itself each established discovery, and has been modified by every hypothesis of value which has been brought to bear upon, or been evolved from, the most recent body of facts.

Text-Book of Geology, for Schools and Colleges. By H. Alleyne Nicholson, M. D. 12mo. Half roan, $1.30.

The Ancient Life-History of the Earth. A Comprehensive Outline of the Principles and Leading Facts of Palæontological Science. By H. Alleyne Nicholson, M. D. With numerous Illustrations. Small 8vo. Cloth, $2.00.

Elements of Geology. A Text-Book for Colleges and for the General Reader. By Joseph Le Conte, LL. D., Professor of Geology and Natural History in the University of California. With upward of 900 Illustrations. Revised and enlarged edition. 12mo. Cloth, $4.00.

Town Geology. By the Rev. Charles Kingsley, F. L. S., F. G. S., Canon of Chester. 12mo. Cloth, $1.50.

TRANSCRIBER'S NOTES

1. Footnotes have been reindexed and moved from the end of the page to the end of the text.

2. The following misprints have been corrected:

"$^{1}/_{0000}$" corrected to "$^{1}/_{1000}$" (page 111)
"strucure" corrected to "structure" (page 139)
"fevric" corrected to "ferric" (page 141)
"d'antorité" corrected to "d'autorité" (page 188)
"resourses" corrected to "resources" (page 206)

3. Other than the corrections listed above, printer's inconsistencies in spelling, punctuation, and ligature usage have been retained.