Engineering and Pure Science

The search for reality, an ultimate goal for men in all ages, has led to a dichotomy of effort in which the empiricism of human experience and the empiricism depending on the properties and structure of matter itself play a dual and occasionally conflicting role.

By W. F. G. Swann

I have often wondered why the cathedrals of mediaeval times didn't fall down. If I enter one of these edifices I feel disturbed by a number of conflicting emotions. I say to myself: "Now, Swann, you are not an architect, and you do not know anything about building churches. However, you do know a little bit about the theory of elasticity and how to calculate the stresses in various structures; you know a little bit about the things which are fundamental in providing that the cathedral shall not fall down, and yet, the fellow who designed that dome did not have any knowledge at all of these matters." I start with the feeling that I ought to be able to design a much better dome than he has,

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and yet, if somebody sentenced me to this task, and even if I should, in my own humble way, muddle through the calculation necessary in my opinion to insure safety, I should never have the courage to erect the dome until I had talked with some practical engineer and asked him whether he thought that my dome really would stand up in practice, or tumble down, to my great disappointment and humiliation.

Now, why didn't the dome built by that ignorant mediaeval architect—who knew nothing about the equations of elasticity, who had no differential or integral calculus, who had no knowledge of mechanics and of all the things which it would seem he should have known—why should his dome stand up, whereas mine would probably fall down? I feel very humiliated about the matter.

Experience versus Science

In the development of modern technical industry, two partners are called upon to cooperate—practical experience and what is called scientific research. Experience is the product of 6000 years of civilization. Science is the product of 300 years, and in its relation to industry as a working partner, it is a product of less than 50 years. It is, therefore, not remarkable that this healthy, white-haired Methuselah who is Experience looks occasionally with suspicion at the energetic young upstart who is Science. Nor is it remarkable that the young upstart, looking back at his partner, regards him occasionally as a stubborn old fogey, hidebound in his ways, and extolling continually the merits of horse sense. However, it has to be admitted that the old fogey seems fairly prosperous, in spite of the ancient cut of his clothes; and moreover, that he has much money in the bank which he has accumulated as the result of his methods and which—humiliating thought—provides in one way or the other much of the daily bread of the young scientist. How shall we appraise the relative merits of these partners? How can we plan for their most successful cooperation? How can we bring the old fellow to realize to the full the value which lies in what sometimes seem to be the high-falutin, impracticable activities of the youngster? Is there anything of value in those methods of horse sense, of cut and try, of long experience, which can be recommended to the youngster as things to be valued? And if so, how and in what form can we persuade the youngster to utilize this value?

I picture on old violinist, highly skilled in his art, but devoid of scientific knowledge. There comes to him a young physicist who says: "My friend, I have been watching you play that instrument and I am going to tell you how to play it better, for I am a student of acoustics and know all about the laws of sound." "Very well," says the old violinist, "here is the violin—play it." "Oh no," says the young physicist, "I would not wish to use that instrument at all. It is, indeed, a very stupid instrument, with no scientific background. It is strung with a cat's inside and played with a horse's tail. It has a form dictated by no scientific principles and the only information I have been able to find with regard to it is to the effect that the form had something to do with the supposed figure of the Virgin Mary. I would like to study a very simple case first." And so our young physicist suspends a simple stretched string between two fixed points in space and he discusses all the various modes of vibration. He discusses how the frequency of vibration determines the pitch, how the overtones determine the quality, and so forth. The old violinist, much impressed but much bewildered, says: "All right, here is the bow. Now play it." On drawing the bow across the string, the old violinist hears nothing, for we all know that a string so mounted would emit practically no sound at all. The old violinist complains that he cannot hear anything, but the young physicist feels that it is very unreasonable of him to insist upon what he deems the relatively minor matter of hearing something and proceeds to argue that it is much better to understand what you do not hear than to hear what you do not understand. But the old violinist is sad about this matter and goes away a little comforted by the fact that although he may not know what he is doing, he knows how to do it.

The Scientific Approach

And so it is characteristic of the ways of the scientific attack to take a simplified problem and, by studying that thoroughly, hope that one may proceed to understand and control the complex problem. In the field where the man of science has had the matter in hand from the beginning, this procedure has been very successful. Thus, he started with pure academic interest to inquire why electricity was emitted from hot wires in a vacuum. These experiments led to others and ultimately to the thermionic vacuum tube and to the whole science of electronics. In this development, the physicist had everything under control from the beginning. There were other matters starting in the realm of pure academic interest which became welded with the matters pertaining to the discharge of electricity from hot wires. All of these infants, born more or less in isolation and with no great individual prospects, were brought together by the man of science, who nurtured their development, watched over their progress, marshalled them from time to time into more efficient groups as regards their potentialities, until finally we had in the world of today radio, television, and a hundred other things whose operations, if viewed for the first time, would seem so complicated, so unrelated, and so miraculous that no brain would have the courage to interpret them. If we could imagine some super-genius of the inventor kind who, by a rule of thumb and horse sense—it would have to be a very special kind of a horse—had arrived where we have arrived today in the science of electronics, but without knowledge of the basic fundamentals pertaining to the subject, and had presented us with the various pieces of equipment, with sales bulletins telling us how to turn on the switches to set it in operation, we would have a marvelous time for a week; and even if the apparatus continued to function for longer, I venture to say that further improvement in its operation would take place very slowly indeed, if at all.

Inventors

As distinct from the procedure of the conventional man of science, one has that of the inventor. Frequently the inventor is very hazy as regards the fundamental principles which control the phenomena with which he deals. In a certain sense, this is an advantage to him in his method of working because he tends to compensate for his lack of power as regards rigidity of prediction by the utilization of knowledge of an enormous number of experimental facts and processes which he combines in all sorts of ways in search of the end he desires. There is apt to be a high mortality in the expected achievement; but valuable end products frequently appear, even when, in the light of a strict appraisal of affairs as represented by the scientific knowledge of the day, it would seem that they never should have appeared.

The inventor walks in a territory which the man of science has mapped out in regions of assured fertility, dubious fertility, and almost certain sterility. The man of science is inclined to conserve his efforts by walking in the rather limited realm of assured fertility, but the inventor walks with courage everywhere. He sees a pasture which he thinks has promise. The physicist would explain to him that his reasons for expecting something from that region are invalid, and in 90 per cent of the cases they are, but the inventor walks nevertheless. He walks persistently, so that every now and again he finds some spot which is rich in content, not perhaps for the reasons that he expected it to be, but for other reasons of which he may be only partially conscious. If we should trace these reasons to their origin, they might constitute a set of heterogeneous associations with no very obvious logical connection, but which, through the scheme of profound regularity inherent in nature, have conspired to give a suggestion which is fruitful in spite of the very dubious foundations upon which the suggestion is made.

It is characteristic of one who concerns himself almost exclusively with the practical needs of a science or art that wide experience should supplement in considerable degree refinement of exact prediction. I have been accustomed to state as my experience that when there is a controversy between an artist—a musician, for example—and a man of science in relation to something which concerns the actual practice of the art, then in 90 per cent of the cases the artist is right and the man of science is wrong. However, the situation does not end here, because unfortunately the artist proceeds to give the reasons for what he says. Then everything that he says is wrong and the man of science has merely to sit back and pull him up at the end of each sentence, leaving him completely bewildered, but unconvinced nevertheless.

There was a celebrated inventor whose employees hung upon the walls of his laboratory a placard which stated as follows: "The poor fool didn't know enough to know that it couldn't be done, so he went ahead and did it." You know, the telephone never should have worked. Think of the impossible situation with which we are presented in this device. Think of the cables which carry the telephone current in the form of electrons. In the absence of the current, the electrons are moving in all directions. As many are moving from left to right as are moving from right to left; and the nothingness which is there is composed of two equal and opposite halves, about a million million amperes per square centimeter in the one direction and a million million amperes per square centimeter in the other direction. The telephone current constitutes an upsetting of the balance to the extent of one-hundredth of a millionth of an ampere per square centimeter, or about one part in a hundred million million million. Then if this one part in a hundred million million million is at fault by one part in a thousand, we ring up the telephone company and complain that the quality of the speech is faulty.

In the realm of pure experience, one has frequently started out with something which is very complicated at the beginning. By trying this and that, one has arrived at a number of procedures which are not unrelated, which in some cases are redundant, and which in others are even inconsistent with one another, and yet, through the process of trial and error and much lapse of time, there has resulted a set of operations and procedures which work in reasonably satisfactory manner. That which we call understanding is now much less fundamental and, indeed, less powerful than the understanding of the scientist, but is in some sense effective. Our old violinist can certainly play his instrument and make it sound well. He tells his student to imbue his soul with the spirit of good tone and good tone will come from the instrument. The student tries to follow this advice. He does a lot of wrong things and the master lambastes him continually with all sorts of other criticisms. He tells him that he slouches too much when he plays—that he is lazy—that unless he holds his bow more firmly the spirit of tone in his soul cannot permeate through to the instrument. And so, as a result of a lot of trials and errors and of doing this and that, sometimes consciously and sometimes unconsciously, the student succeeds in producing the good tone. Possibly, he still retains the feeling that his soul produced the tone, and it does no harm if he should think that, so long as the idea in its implementation is supplemented, consciously or unconsciously, by all that heterogeneous conglomeration of other things which really conspire to produce the ultimate end.

The Nature of Physical Laws

As a physicist I seek a logical framework of knowledge in which all parts of my science are related in unambiguous ways. I am unhappy about two different criteria bearing upon the same subject unless I can understand clearly whether they are independent or related.

And yet, out of this completely formulated system of laws which represents my ideal, I could obviously pick certain isolated elements and put them into forms which would stand by themselves and which would hide their relationship. These isolated elements could well serve as a useful guide to the artisan or general practical man even though the language appropriate to their more complete setting in the fundamental frame might be unintelligible to them. We see this kind of thing happening in almost every branch of physics which finds a utilitarian service.

Of course, the reason for this state of affairs lies in the fact that the fundamental laws frequently express their consequences in forms which are not conveniently adaptable to problems. However, it is possible to dress them up in different kinds of clothes suitable to the various realms in which they have to function, and sometimes the clothes are so different that it is hard to recognize in them the same individual. However, from the practical standpoint, this existence of different forms of raiment is not to be decried, however much it may irritate the master of fundamentals to see his beloved concepts so variously represented. Occasionally the whole success of utilization of the concepts depends upon the raiment. An example is to be found in a problem which, for a considerable time, taxed the genius of the great Newton. This problem concerned the proof of the fact that a spherically symmetrical distribution of matter obeying the law of inverse squares acts, at external points, as though all the matter were concentrated at the center. By the utilization of Gauss' theorem, it is possible to prove this result, which baffled the great Newton for so long, and to write the proof on the area of a postage stamp; yet Gauss' theorem is no more than the law of inverse squares garbed in such a form as to make it particularly at home in the realm of spherical symmetry.

And so, in meditating upon our ancient and mediaeval architects, I have to believe that, though unconscious of the general fundamental laws, they nevertheless sensed many things which were true and were able to mould them into a frame of procedure which was sufficiently concrete and self-consistent to serve as a guide in their operations. *We* should feel very insecure in this frame, fearing that something had been forgotten, unless we could see the elements of that frame as consistent parts of the more complete whole. However, there is another respect in which the rule of thumb procedure has something to be said for it. Many problems which are controlled by fundamentals perfectly well known to us are incapable of solution by known mathematical procedures and we are driven to illustrate the matter by appeal to simplified cases. If I tap a table with my finger, I say that I understand in a general way how the vibrations which ensue come about. I think of those interactions of elasticity and inertia which are fundamental to the solution of the problem. I can even write down the differential equations which control the solutions, and yet no mathematician on earth is clever enough to work out the solution for this particular case.

Now, frequently, the rule of thumb procedure, while deficient in the obviousness of its relation to fundamentals, is apt to take care of complications in circumstances which might be almost infinitely difficult for any mathematician to take care of by trying to solve for the consequences of the fundamentals. Thus, if an authority on acoustics should endeavor to construct a violin without collaboration with an exponent of that craft, I doubt that he would produce as good a violin as Stradivari. Moreover, I rather surmise that if Antonius Stradivari and Nicholas Amati came to life today and held a discussion with the great violin makers of our epoch, the discussion would be much more harmonious than would one between engineers of these periods.

When the physicist is presented with a complex situation, where the complexity has not grown under his own guiding hand, he may feel temporarily at a loss to know where to begin the attack upon his problem. His standard method of procedure is to take the simple, understand it thoroughly, and build up from it the complex. When he cannot start with the simple, his natural desire would be to peer through the complex in the hope of finding the simple as the origin of it all in the background, as one might suppose a person, suddenly coming upon a television apparatus, seeking to peer through the complexity of operation down to those fundamentals which constituted the experiment of 40 years ago. Having found the fundamentals in this way, he would like to watch the offspring of these fundamentals develop through themselves, their children, and their grandchildren, to the television set which is before him. In this way, he would feel that he could understand the operation of the set and be in a position to keep it in order and possibly improve it.

However, when the complex is presented to the physicist, he is faced with several difficulties. In the first place, the complex is apt to be made up of a heterogeneous mixture of methods and principles, some of dubious relevance and some even inconsistent. Or even, if irrelevancy and inconsistence are absent, the complexity of the situation may be such that it is very difficult, if not humanly impossible, to trace matters back to their fundamentals. One then has to deal with empirically discovered laws which one must believe to have their origin in more fundamental laws, although he may not be able to trace that origin. Such empirical laws are represented in perhaps their nearest approach to their fundamentals by the ordinary laws of stress and strain applicable in the theory of elasticity. In a vein farther removed from the fundamentals one has such empirical regularities as have dictated the general shape and method of construction of a violin.

The fact is that the solution of a problem involves two parts, the fundamental laws which control all problems of the class studied, and the features (boundary conditions) which determine the particular case in which we are interested. Sometimes the contribution of the latter to the features which interest us is simple and the problem is one for exact solution by the theoretical physicist. Sometimes the said contribution is complicated, but important, and the solution becomes more the problem of him who applies approximate, or even rule of thumb, methods.

The Development of Methods of Thought

It is of interest to inquire whether the fundamentals of thinking are necessarily very different today from what they were in past ages. In this connection, it is perhaps not without interest to transport oneself in imagination to the time of Galileo and inquire as to the nature of the thinking of those days. Galileo wrote a book called *Two New Sciences*, in which he presents his ideas in the form of a supposed discussion between three interlocutors, Salviati, who represents himself, Sagredo, and Simplicio.

Again and again in these discourses we see the mind of Galileo doing the same kind of thinking that a good experimental physicist or, for that matter, a good mathematical physicist does in the laboratory today, and we cannot question the fact that if Galileo, with all that he had and no more than he had 300 years ago, were planted in one of our laboratories today, he would be an outstanding physicist in the problems which are of interest to us today.

In this general epoch, we see the birth of Hooke's law on the proportionality between stress and strain, and we see the accumulation of those fundamentals going back even to far earlier days, which constitute the basic principles upon which the present engineering science is based. However, I think it safe to say that, by and large, we must regard the pre-Newtonian era as one in which the laws available, such as they were, were of an empirical kind, and even in the later epochs, extending almost to the present time, the fundamental laws were empirical. The growth of the power of mathematical physics, brought about by the invention of the calculus and by the developments of Newton, Lagrange, and others, enabled mankind to extract in richer form the more complete consequences of the empirical laws of hydrostatics, elasticity, dynamics, and so forth, and, indeed, until the advent of the electrical age scientific attention was devoted largely to the unravelling of the consequences of such laws. It is true that in the field of optics there were primitive attempts at theories devised to give a richer content to such empirical laws as existed in that field. Such attempts, however, were guided largely by the ideas of elasticity and inertia characteristic of the mechanical domain.

The Search for Reality

The advent of the electrical era, initiated primarily by Faraday, Henry, Ampère, Oersted, etc., a little more than 100 years ago, found its formal development in the work of Clark Maxwell. The man of science of the day was mechanically minded and sought to understand all things in terms of the thoughts appropriate to elastic waves in solids and fluids. Maxwell's theory was an almost insurmountable stumbling block, inviting, as it did, concepts which were ultra-abstract in terms of the thinking of the day. The matter is illustrated by a comment in Sir Arthur Schuster's *Theory of Optics*, written as late as 1904, and it must be remembered that Schuster was one of the world's high priests of natural philosophy in that epoch. He writes: "The study of physics must be based on a knowledge of mechanics, and the problem of light will only be solved when we have discovered the mechanical properties of the ether." Writing in another place on Maxwell's equations, he remarks: "The fact that this evasive school of philosophy has received some countenance from the writings of Heinrich Hertz renders it all the more necessary that it should be treated seriously and resisted strenuously."

The search for reality in which to frame the new thoughts born of electrodynamics so persistent at that time has changed considerably in its aims as the years have rolled by. In my student and early teaching days it was the custom, following the lead of Maxwell and his school, to seek an explanation of electrodynamic phenomena on purely dynamical bases. If we wanted to make somebody understand a circuit with self-induction, capacity and resistance, we would refer to a ball vibrating in a viscous fluid at the end of a spring. We would say: "Now the self-induction in this circuit is like that mass on the end of the spring. This capacity itself is like that spring. The electrical resistance of the wire is analogous to the viscosity of the liquid, and so forth." By thinking of the spring and ball, which we of the older generation felt we understood more or less, we endeavored to accommodate our thinking so as to understand the electrical problem. Today all of this appears to be changed. At an early age youngsters start to play with radios and to acquire quite a little knowledge concerned with the essentials of their operation. This fact has reversed the whole situation as regards reality in the mind of youth, and the youngster of today and the older youngsters who are doing research in our laboratories seek to understand dynamics by showing that it is like electrodynamics. And if the youngster wishes to understand how a ball bobs up and down on the end of a spring when immersed in oil, he is apt to say: "Now this weight is just like that inductance. The spring is like the capacity, the viscosity of the fluid is like the resistance of the wire. Now you know that the electrical circuit will oscillate; and in a similar kind of way, the ball and spring oscillate. You know that if the electrical circuit is stimulated by an external force of frequency equal to its own, it will resonate and build up a big amplitude; and for exactly similar reasons, the ball on the end of the spring builds up an amplitude when subjected to an external force which harmonizes with the system in frequency." Thus, since you understand all about the nature of the electrical oscillations of the circuit, you ought to be able to stimulate your brains to the point of understanding why and how a ball bobs up and down on the end of a spring in oil.

No longer does the engineer seek to understand his electrical problems through mechanical ones, but when he gets a mechanical problem, the first thing he does is to seek the electrical analogue and think in terms of that—he seeks the equivalent electrical circuit. And so this concept, reality, is indeed like a chameleon, changing its color to harmonize with the setting of its time. Ah! reality, what an elusive thing it is and how its search has tormented mankind from time immemorial. Reality, that will-o'-the-wisp of philosophy! You may think you have it in your hand but to find that you have merely the shadow of something else. You will pursue that something else; you will clutch it, and again it will feel real until you find that your consciousness of its touch is no more than the tingle of your own blood as your hands clasp upon it. Reality is the most alluring of all courtesans, for she makes herself what you would have her at the moment; but she is no rock on which to anchor your soul, for her substance is of the stuff of shadows; she has no existence outside your own dreams and is oft no more than the reflection of your own thoughts shining upon the face of nature.

The concepts which one is willing to accept into his category of thinking and to regard as natural without further inquiry as to their origin change with the epoch, and today the average mathematical physicist at any rate encounters no obstacle in classical electrodynamics. Indeed, he would be very content and feel that he had a very understandable picture of nature if all atomic phenomena could be brought into a picture in which classical electrodynamics was the only controller of that picture. Today, however, he finds himself driven to new realms of abstraction in understanding the atom. If he had been forced into these realms 100 years ago, he probably would have given up and have felt that if he were to have no further security in the matter of what I might call common sense understandableness, he might as well go back another couple of hundred years and join with the forces of the astrologers or the alchemists. However, realizing what has happened to his mental accommodation in the past, first through Newtonian dynamics—which was by no means a concretely understandable matter in its day—through electrodynamics, he is now more or less content to adapt himself to any new philosophy which fits the facts and he is willing to forego too much desire for understandability in terms of horse sense.

The Origin of Periods of Stagnation

Perhaps I may here make a slight digression in relation to the general significance of scientific theories. The matter has a bearing upon that cycle of depression in science in which, every now and again, we seem to come to the conclusion that everything worth while has been done and nothing remains but to cull over the old material. What is the reason for this condition of affairs? I think the reason is not far to seek. When a new set of phenomena reveal themselves, the man of science seeks to correlate these phenomena in the form of a theory. Sometimes in the formulation of the postulates of the theory there are details which are artificial to him, there are starting points which seem unreal, so the theory is at first abstract and few understand it. To the layman, in fact, some of the postulates of the theory may seem to be nonsense. However, the working purpose of the theory is not primarily to give pictorial satisfaction to the lay mind, but rather to correlate the phenomena which it concerns. The theory is a means by which, through the process of saying few things, we may deduce many as a consequence. Having moulded the theory so as to comprehend all of the newly discovered phenomena, the theory of itself starts to predict other phenomena; and it is well worth while to look for these phenomena. And so there comes a period in which science devotes itself to verifying the predictions of the theory and tracing its consequences to their limit. In the olden days, this took a long time. In modern times it has taken increasingly shorter and shorter periods, as the would-be PhD's and their mentors stalk around like roaring lions seeking something to measure. In any case, before very long everything that the theory suggests as an object of measurement has been measured and every phenomenon which it has predicted has been found, if it is a good theory. By this time, the theory has acquired a good deal of prestige. It has been responsible for suggesting many new discoveries. Those postulates and premises in the theory which were a little repugnant to us in the beginning have become more natural and reasonable in our eyes. They sit well in the realm peopled by the interesting phenomena they have brought into it. They, the nonsense of yesterday, have become the common sense of today. And now, the theory, having grown old in a useful life, becomes rather like a conventional old gentleman who, radical in his youth, has become conservative with age, who now hates to see anything other than what he has been accustomed to, and who is able to exert great influence in virtue of the respect in which he is held through his good deeds of the past. Radical in his youth, he has become extremely conservative in his own radicalness. The old theory, having in its active youth exhausted all of its potentialities in saying: "Do this, and thou shalt find that," now starts to adopt a negative attitude in saying: "It is not worth while to do such and such, because it is guaranteed beforehand that you will find nothing if you do." "To find anything," says the old theory, "would constitute nonsense in my creed, and would be very humiliating to me. It would be contrary to common sense, the new common sense of my era." And so the old theory now becomes as declamatic in saying that certain things are impossible, as before it was declamatic in holding that other things must occur. It is for this reason that in the autumn of the life of some far-reaching theory of physical phenomena, science seems to have come to an end. The phenomena divide themselves into two categories: first, those which are known or are such obvious consequences of the known facts, or of the theory correlating them, that it does not seem worth while to investigate them further; and secondly, those which look as though they are probably embraced by the theory but in a form beset with such complications of calculation as would render the dissection of their whole story beyond the power of man. As a result of this, there seems nothing more to do; research seems to have come to an end and science to be dead. Then some irrepressible individual discovers a phenomenon which goes violently contrary to the theory. After due castigation by the old gentlemen, in the form of the devotees of the theory, the results of the young upstart are confirmed by others and have to be accepted. The theory must then be remoulded or possibly completely rebuilt so as to include the new facts. In this rebuilt theory, much that before seemed impossible is now rendered likely. Suggestions which would have been dismissed as impossible with the briefest thought in the light of the old theory, have a reasonable place in the realm of possibilities of the new theory. And again common sense grumbles at having to readjust itself to a new form. In his proper domain, common sense is a counselor of priceless value; and it is because he justly inspires such confidence in that domain that he becomes the most dangerous of deceivers of those who seek his guidance outside of it. For "common sense" seeks to pin all thoughts of the new to the fabric of the old, and so, ofttimes, it distorts the meaning of the new by destroying that form which was inherent in its own right, and for no purpose other than to fit it to a pattern in which it has no place. The result is a bizarre and shapeless thing out of harmony with the form into which it has been forced, and out of harmony with the form which was its own. Common sense in natural philosophy repatterns itself from age to age. At each stage of its development it seeks to generalize the ideas born of the experience of the immediate past and to weld them into bonds which sometimes restrain the future. Thus, the breeders of error in the epoch to come are sometimes the truths of the days which have gone. So beware how you extol too much the virtues of good old horse sense, for I fear that, in the last analysis, horse sense is the kind of sense that a horse has.

I think with some regret of many experiments which in my youth occurred to me as worthy of being tried, but which on further meditation I failed to perform because in terms of common sense, as exemplified by the theories of the day, they seemed destined to give trivial results. Sometimes I wish that I had not thought so much and had done the experiments in any case, for in later years many of these experiments have been done and have given results of value, results which are harmonious in the frame of thought of today, however strange they would have appeared in the light of our concepts of forty years ago. If a proposed experiment lies far within the boundaries of established facts and theories and would, according to their diagnosis, give a perfectly clear-cut result, I do not deem it worth while to do the experiment. If someone comes with a scheme for perpetual motion involving the utilization of ordinary machinery and the like, I give him but little attention. If he claims that, since the experiment has never been done, one cannot predict with surety what result it would give, I have to agree with him, as I would also agree with him if he claimed that the sun might not rise tomorrow morning. I then answer to the effect that while no one can predict the result of an untried experiment, the *chance* of his perpetual motion experiment giving a valuable result is, in my judgment, so small that we should not be justified in discontinuing the other experiments which we are doing in its favor. If, however, I am confronted with an experiment which lies near the horizon between the known and the unknown, I prefer to give it the benefit of the doubt; for it is such boundary dwellers as these who establish connection with the knowledge of today and that of tomorrow.

Empiricism

And now perhaps it will be well if I get back to what is supposed to be the main theme of this discourse, the relation of engineering to physics.

In speaking of the empiricism I have perhaps implied that today we have something better than empiricism. In the last analysis, this is not true. All our laws of nature are empirical. However, the desire of the theoretical physicist is to limit empiricism in the sense that from the fewest number of empirical starting points he can deduce the richest law content. His aim is to take what was formerly half a dozen apparently unrelated empirical statements and represent them all as a consequence of perhaps two empirical statements.

It is perhaps well, in this connection, to recognize two degrees of empiricism. There is the empiricism characteristic of the situation up to and including atomic processes, and there is the empiricism of the correlation of the atomic processes themselves, which second form of empiricism most physicists would not be willing to count as empiricism at all, but as a getting down to the last elements of understanding.

Taking the first realm of empiricism, however, the complete story of the content of a law is, as I have remarked, contained in mathematical form, which it is not easy to simplify to a form applicable to all cases. However, the practical need of getting matters down to a degree which enables a large number of people to use the principle results in seeking some kind of simplification which is sufficient to cover a fairly wide realm of practical experience. Here the laboratory man or the practical engineer takes hold, and after a time his intuitions become sharpened so that he adopts a kind of thinking which simulates a more exact frame of thinking but is, as it were, a self-contained set of laws of its own. One has an example of this in matters pertaining to electrical circuits where, provided that the wavelength of any oscillations concerned in the circuits is long compared with the dimensions of the circuit, we can think in terms of a certain type of simplification. There grow the concepts of capacity, inductance, impedance, to which the practical engineer, stimulated perhaps by rivalry with the medical profession, feels the urge to add another number of Godforsaken words, such as admittance, transconductance, etc. In this connection, I have thought of a new term "abuttance". Although this may seem like the doctor's discovery of a "cure" for which there is no disease, I present it to the radio engineers in the hope that they will find a meaning for it.

In terms of the simplified laws, the practical man proceeds to manipulate these various quantities and to become very clever at predicting what will happen in this case and in that. Occasionally, however, situations arise in which the simplified laws no longer are adequate. The practical man does something about this by making some kind of correction as far as possible in the language of his old formulation. As knowledge advances, however, more and more of such cases arise and the patches on the patched up framework become more obvious than the framework itself.

And now, superposed upon all that I have spoken of so far, which has concerned itself for the most part with what we may call the classical physics of matter in bulk, we have, in the last few years, encountered a realm in which the fundamentals of physics are no longer diluted so as to show their effects only as averaged quantities—as temperatures—as pressures—as elasticity, etc. The advent of electronic physics has brought us down to the properties of the atomic particles themselves. In the photoelectric cell, in the photomultiplier, in the radio vacuum tube, and a dozen similar devices, the matters which determine successful operation are things which can only be understood in terms of the fundamental processes of nature or, at any rate, I think it would be safe to say that it is not much more difficult to understand them in these terms than to understand them in terms of some artificial scheme of simplification devised because one has learned to expect simplification in the past and to hope for it in the future.

And then, as the realms of empiricism in the ordinary properties of matter have become exhausted, the new realms of enlightenment following our modern picture of the structure of solids have tempted us to hope that, even here, the barrier of knowledge need not be fixed by the laws of empiricism or, if we like, by an extrapolation of the past, but rather by the possibility of prediction in relation to what we know from the atomic structure of matter itself.

It is a matter of great importance to understand what governs the strength of materials, what governs the dependence of this strength upon temperature, particularly in the light of modern requirements in high temperature operation such as is encountered in turbines. The atomic picture is very illuminating in this field and can, in many cases, point the way to success, whereas to achieve that success by what we may call the Edisonian method of multitudinous trial would involve untold expenditure of time and effort. We have not reached the stage at which we can design substances of any desired characteristics, but we have reached the stage at which our knowledge of atomic physics provides us with very good hunches as to courses of procedure which have a good chance of being successful. Of course, one of the most spectacular of all such predictions is that involved in the act of man in creating an entirely new element, plutonium, in connection with his work on atomic energy.

Now, in order to manipulate atomic properties successfully, it is necessary to think in terms of atomic laws, and such laws are rather artificial to the thinking of the conventional metallurgist. However, in the last analysis, they are really no more artificial than the laws with which he has become familiar. It is for the future to season the younger generation with a broader sensitivity to the forms of nature's laws, so that he may not, forever, stay with his feet bound in the mud of classical antiquity of which he has already exhausted most of the good essence. It is necessary to bring him to a stage where he is not limited to looking at the new fields from afar but is enabled to walk in them with confidence, and pluck such good fruit as comes his way.