a guess as to WHAT IS SCIENCE

By Dan McLachlan, Jr.

A MEMORANDUM on the above topic (addressed to "The Record") has been received from Prof. McLachlan of Stanford Research Institute, Menlo Park, Calif. The original document, dated January 24, 1961, was prefaced by the following explanatory remarks:

"Although this subject has been of interest to us for a long time, the first clue as to how to pursue it came to the present author through a midnight argument in a barroom during the 1959 meeting of the Geological Society of America in Pittsburgh. The participants were Professor Garrels of the Geology Department of Harvard, Dr. Charles Christ of the Geological Survey, Washington, Professor Zwolinski of Carnegie Tech, and McLachlan of SRI. It all started when Professor Garrels said 'I wish there was some way to make a science out of geology.' The accompanying memorandum represents what I got when I tried to patch together the pieces of the fight which Garrels put up when the chemists and physicists present attempted to help him glue geology into a single package by means of quanta and a bunch of laws of diffusion, crystallization, thermodynamics, and kinetics. It turned out to be more complicated than I had planned."

I. Introduction

THAT the meaning of science is somewhat weakly defined is exemplified by the following popular concepts. "Cavendish discovered hydrogen, De Soto discovered the Mississippi River, and Ziegfield discovered Gypsy Rose Lee." Only one of these discoveries is considered scientific. By scientific evaluation, the discovery of Pikes Peak has a different rating than the discovery of the Van Allen Belts. When James Corbett beat John Sullivan in 1892, he established a reputation that still holds today, of being the most scientific boxer of all time; and when farmer Jones ran a wire from his house to the barn to attach an incandescent lamp on it in the Ozark Mountains in 1922, he was hailed by the neighbors for being a modern, scientific farmer. Scientific research can be carried on in the laboratory, out in the field, or in the library. Some people will tell you that psychology is not a science while physics is, that mathematics is the only one hundred percent exact science, that genealogy ceases to be a science when the investigator looks up his own family tree, and so on.

The *Encyclopædia Britannica* says that "science" is synonymous with learning and knowledge; Webster's dictionary has several closely related definitions of the word; and years ago we were taught that science is the accumulation, classification, and systematization of facts. In general, people don't usually worry about the definition of science since they are content to know that it developed hybrid corn, put dinosaurs in the museums, and gave us television sets, the atomic bomb, and medical institutions. But now that science is being scrutinized, we need to know whether or not we are in it, and also, in this age of newly developing scientific fields, it would be good to know the stages through which a new science grows.

II. Stages in the Growth of a Science

EACH branch of science that has reached a position of recognition has gone through similar stages of development in about the same sequence. For example, we can cite two rather dissimilar sciences, botany and classical crystallography, which, from one viewpoint, have identical histories. In the first stage we identified the fields by noting (hundreds of years ago) that there are plants and there are minerals. The second stage was the stage of collecting and identifying, wherein the crystallographer climbed the mountains, visited mines, and roamed the deserts in search of all possible examples of crystalline forms while the botanist searched the woods, meadows, and swamps of the world for new species. Then came the naming of the detailed parts of each example, then classification, measurement, and finally the functional interrelationships were tackled and studied. Thanks to the successes in this last stage, we have the aristocrat of botany, plant *ecology*, and crystallographers are studying the laws of crystal growth, ore genesis, etc. After examining several sciences, we have made the following list of stages, in chronological order, which we think is applicable to all branches of science, and with which we hope to clarify the meaning of the word "science".

1. Recognition of field
2. Qualitative description and definitions
3. Collecting samples
4. Classification
5. Quantitative measurements
6. The choice of orthogonal measurables
7. The search for fundamental functional relationships
8. The deduction (for convenience) of other functional relations

The definitions of some of the more ambiguous terms in the above are to be woven into the text.

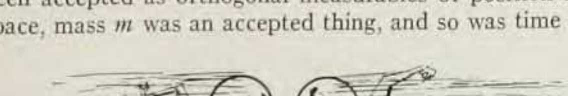
Perhaps the best way to convey the full and clear meaning of these steps is to present some illustrations of already accepted sciences.

III. Examples of Established Sciences

EXAMPLES of pure, complete, and isolated sciences are to be chosen with caution. Many branches of science can be incomplete; in fact, most of the living branches are not complete. Also some sciences are composites of other sciences, some *use* other sciences, while occasionally a science will *swallow up* other sciences. In regard to the latter possibility, it is the ambition of philosophers to find *the* science which swallows up everything. We shall discuss these matters later. For the moment we give just four more or less pure, complete, and isolated sciences: physics of colliding spheres, plane geometry, thermodynamics, and the theory of probability.

A. *The Physics of Colliding Spheres*

The history of this subject probably goes back to the beginning of man. The concept of collision is likely as old as fighting, while that of spheres is as old as ball games. The collision of spheres could certainly be observed upon the introduction of games like billiards and certain kinds of lawn bowling. Recognition of the field of the science was probably early, but the time of the event went unmarked because no historical fact is associated with it. The variables x, y, and z had already been accepted as orthogonal measurables of position in space, mass m was an accepted thing, and so was time t, before the 16th century. Now we wish to state what we mean by *orthogonal* measurables. First let us say that a science that has nothing to measure is hardly a science at all. When a science is young, usually there are too many things to measure and the task of studying the field seems hopeless. We loosely define the orthogonal variables (or measurables) as those measurables which are independent of one another and cannot substitute for one another. Since no two of these five measurables x, y, z, t, and m could be substituted for another in describing a system of spheres, then the orthogonal variables were known in the 15th century. The search for functional relationships got under way to a great extent because of the contributions of Newton, who established some laws such as: (1) neglecting resistance and interference, a body moving in a straight line will continue in a straight line; (2) action and reaction are equal and opposite; (3) momentum is conserved; and so on. These fundamentals were extended to the cases where the bodies attract or repel one another. The concept of potential energy on a par with kinetic energy was introduced, and the conservation of total energy was demonstrated. The fundamental principles of this science were extended to great and massive bodies in astronomy and also to the minute atoms in near-perfect gases.



B. *Plane Geometry (in a restricted sense)*

In some respects plane geometry is a poor example to put so near the first in the list of subjects, but it was chosen because of its few measurables and because so many readers are familiar with the subject. Before telling what makes the subject inappropriate as a beginning example, let us skip to item six of the list in section II and say that the orthogonal measurables in the most restricted forms of geometry are just two, (1) the distance between the two points along a given line at which two other lines cross it, and (2) the angle made by the intersection of two lines. The measurables of geometry are orthogonal because the magnitude of an angle is independent of the length of the lines which intersect to form it, and likewise the distance between the points of intersection of one line with two others is independent of the angles at the two intersections. The nonsubstitutive character of angles for lines is shown by the fact that no matter how many angles are measured on a geometrical figure the size or internal proportions of the figure are still unknown. That the restricted geometry as we define it is complete with just these two variables is shown by the fact that when the angles and lengths are measured, the figure is completely described.

Now the first thing that makes geometry (in our restricted sense) a poor example is that no available current book on the subject is restricted to only two orthogonal measurables, although the ancient literature provides examples.[1] The nearest one of recent printing that I could find permitted circles and arcs of circles,

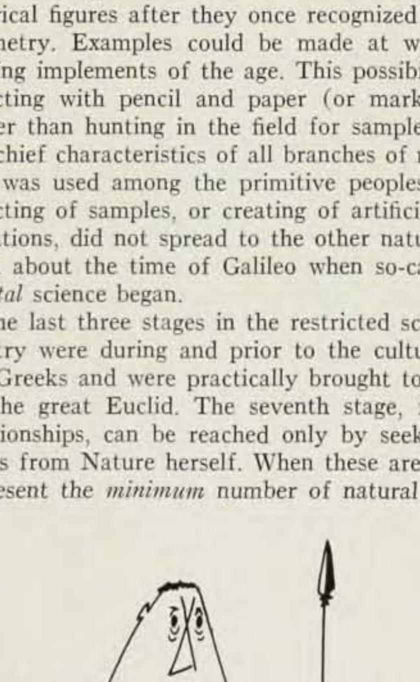
[1] J. R. Newman, *The World of Mathematics* (Simon and Schuster, Inc., New York, 1960), Vol. 1, pp. 10–14, 79–80, 170.

thus introducing a third orthogonal measurable, radius of curvature. Referring again to the *Encyclopædia Britannica* we note that there geometry covers "the properties of space" and includes such subjects as analytical geometry, differential geometry, projective geometry, and topology. We shall show later that, according to our definition of a closed and complete science, these subjects are really combinations of more elementary sciences.

The next objection to geometry as an illustration is that the first stage listed in section II, recognition of the field, is lost in antiquity. However, one can imagine that the field could have been recognized from observations of natural lines such as those produced by the crisscrossing of animal paths in the forest or the crossing of chariot tracks in dusty fields, patterns of cracks on drying clay, the direction and streaks of flying arrows, or the positions of timbers in simple abodes, etc. Likewise the second stage, qualitative description, is prehistory.

The most objectionable aspect of geometry as an example pertains to the third stage, collecting samples. The early students of geometry did not need to roam the forests, visit the grounds after chariot races, or watch the flight of arrows to collect examples of geometrical figures after they once recognized the field of geometry. Examples could be made at will with the writing implements of the age. This possibility of constructing with pencil and paper (or marks on clay), rather than hunting in the field for samples, is one of the chief characteristics of all branches of mathematics and was used among the primitive peoples. This constructing of samples, or creating of artificial and ideal situations, did not spread to the other natural sciences until about the time of Galileo when so-called *experimental* science began.

The last three stages in the restricted science of geometry were during and prior to the cultural apex of the Greeks and were practically brought to completion by the great Euclid. The seventh stage, fundamental relationships, can be reached only by seeking the answers from Nature herself. When these are found they represent the *minimum* number of natural laws which are necessary to make deductions. Using geometry again as an example, we do not need to measure every distance and all the angles in sight to describe a diagram completely if some of the laws are known. After the fundamental natural laws are known, man's mind is capable of making deductions and combinations for convenience, thus deriving corollaries, axioms, etc., and we are in stage eight of the development of a science. The role of theory in science will be discussed later.



C. *Thermodynamics (again restricted)*

No attempt will be made here even to hint at the history of thermodynamics except to say that its history is a hectic story of confusion associated with steam power, among other things; and the field was finally reduced to manageable limits by stipulating equilibrium conditions under study. The four orthogonal variables in our restricted view of thermodynamics are pressure p, volume v, temperature T, and heat Q. Going to the laboratory with instruments that are capable of measuring just these four variables, wonderful things can be discovered. These wonderful things are the fundamental functional relationships (see section II-7), among which are three that are universal for all substances: namely, the first, second, and third laws of thermodynamics. For special substances, less general laws are obtained. For example, since certain gases act almost ideally, i.e., they almost obey the law that the product of pressure and volume equals a constant times the temperature ($pv = RT$), we have the perfect gas law.

In the process of developing the science, new terms such as energy, enthalpy, entropy, work, heat capacity, coefficient of expansion, etc., were introduced as concepts in the useful deductions derived from the field (see II-8).

As relationships between thermodynamics and other fields were established, measuring devices other than pressure gauges, thermometers, and volumetric containers were introduced. These new devices include potentiometers, densitometers, interferometers, etc.

D. *Theory of Probability (restricted)*

This field, in its simplest form, covers the placing of a given number of indistinguishable objects in numbered compartments. The measurables are the number of boxes, N; the number of objects, m_i, in each box; and the number, w, of ways of placing the objects in the compartments with and without various conditions of restraint such as the requirement: "no more than M objects in any one box". The number of ways of placing the objects is greatest without the restraints, and the probability of any given event happening is assumed to be the ratio of the number of ways that the requirement can be fulfilled to the number of ways of placing the objects without restraint. The word "object" is given a broad meaning and might pertain to marbles, packets of energy, or faces on a card, while the word "compartment" might pertain to a throw of a penny, a planting of corn, a box, quantum state, or any distinguishable state. For example, of the six ways

that a die might fall, there are two ways that can give a face number less than three; therefore, the probability of throwing a die and getting a number less than three is 2/6. This is analogous to the chances of casting one object into either of two specified compartments as compared to the chances of casting one object into any one of six compartments.

The history of probability dates back to the successful attempts of Gauss to assist royalty in gambling, and, since this beginning, the science has been applied to a great number of problems ranging from plant breeding to quality control in factories. The reason for introducing the subject is that it has been combined with many other basic sciences to form new sciences.

IV. How Sciences Influence Each Other

IN looking at the following list of the ways sciences influence each other one gets the impression that the sciences are similar to animals or people:

1. Sciences use one another.
2. Sciences "swallow" one another.
3. Sciences alter one another.
4. Sciences combine to produce new sciences.
5. Sciences spawn subsciences.
6. Parent sciences tend to disinherit daughter sciences.
7. Sciences have trouble getting under way.

It is these "goings on" among the sciences which make the problem of finding a pure, isolated science so difficult. Examples of some of these effects of the sciences upon each other will now be given, using the four previously discussed sciences (section III) as much as possible as a basis.

A. *Sciences That Have Used Others*

History shows that a new science was started to be made in ancient Arabia and Greece by taking a piece out of geometry: the science of triangles containing a 90° angle (i.e., right triangles). The science of right triangles, called trigonometry, was urgently needed for surveying and astronomy, but by the time those of us living today came to study the subject every other subject needed in surveying, astronomy, and navigation had been thrown into the book including some algebra, study of complex numbers, logarithms, and the relationships between exponentials and hyperbolic functions.

A prime example of a science that has used almost every other needed science (to the extent of nearly forgetting to unify itself) is geology. Agriculture is an example of a composite of physical, biological, and economic sciences with the practical objectives so strongly emphasized that many practitioners have little regard to the question of whether or not it is a science. Less extreme examples are represented by some of the classical physical sciences such as optics and acoustics which use any known science to investigate themselves. Before discussing the manner of originating a new science, we should distinguish between the words "use" and "swallow" as we apply them.

B. *The "Swallowing" Process*

At the turn of the century, two of the sciences mentioned above, probability theory and the physics of colliding spheres, were combined into one which became known as statistical mechanics. This was introduced to the United States by such men as Tolman of Caltech. The measurables or variables in this new science included the variables of both of its parent sciences (see A and D, section III), namely x, y, z, T, m, N, m_i, and w. This science is not a finished science yet, as viewed by the theorists who wish to use it for all problems involving gases, liquids, and the phases of solids, but early in its development it showed marked power in deducing thermodynamic principles. Thus, thermodynamics finds itself inside another science; it was "swallowed". Of course this would have been impossible if the thermodynamics variable v could not be deduced from measurements in the x, y, and z directions; the variable p shown to be force divided by area and ultimately deduced from directional measurements of area and mass-distance-time measurements of force; and the variable T connected with energy. (The latter task is still incomplete.)

When one science swallows another in this manner, the general attitude among scientists is that the new science has built a firm foundation under the old science. The physicists and chemists would like to do this for geology, and many scientists would like to explain the basis of life itself. We will express the thought, later in this report, that this would be a good general direction in which to continue striving because of the unifying effect it has on knowledge, but, from a practical standpoint, some of the other life sciences and social sciences need not wait for this any more than thermodynamics did. The swallowing can be done later.

C. *Some Sciences That Altered Others*

A very good example of a new science which had a broad alteration effect on other fields was quantum theory which reached a useful stage of development about 1927. Statistical mechanics had to be re-examined and the new principles woven into it. The theories of radiation, spectroscopy, and atomic structure were altered by the new idea of the quantum.

The effect of anthropology on psychology is another example. Also the effect of psychological facts and findings on the beliefs regarding justice and jurisprudence was great because it became recognized that a person could be *mentally* sick. The impact of biochemistry on medicine is well known, and now we are seeing the mutual influences of the fields of electronics, computer theory, and the theories of the working of the brain.

D. *Sciences That Combine to Produce New Sciences*

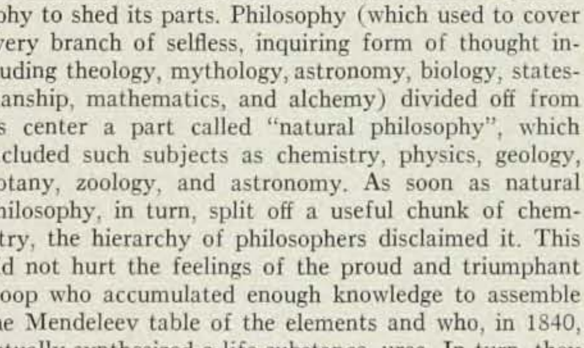
Chemistry combines with biology to produce biochemistry, the scientists in microwaves team up with the astronomers to produce radio-astronomy, etc. Such combinations of two sciences are usually initiated by some man who is on the borderline between the two sciences and has an acquaintance with both. One of the oldest twinned sciences is analytical geometry, which is a combination of geometry and algebra.

E. *Sciences That Spawn Subsciences*

This subject can be combined with the next paragraph concerning the disinheritance of sciences because almost all subsciences spawned from parent sciences eventually get disinherited.

F. *Sciences That Have Disinherited Daughters*

Starting out with Confucius, the consultant of kings, and following through Plato, Aristotle, and Archimedes, and coming to the age of great philosophers in Europe such as Newton, Kant, Nietzsche, and later Whitehead and Russell, we see a trend for the grand field of philosophy to shed its parts. Philosophy (which used to cover every branch of selfless, inquiring form of thought including theology, mythology, astronomy, biology, statesmanship, mathematics, and alchemy) divided off from its center a part called "natural philosophy", which included such subjects as chemistry, physics, geology, botany, zoology, and astronomy. As soon as natural philosophy, in turn, split off a useful chunk of chemistry, the hierarchy of philosophers disclaimed it. This did not hurt the feelings of the proud and triumphant troop who accumulated enough knowledge to assemble the Mendeleev table of the elements and who, in 1840, actually synthesized a life substance, urea. In turn, they eventually proceeded to disinherit, or at least cast from their central academic ranks, some too practical and not sufficiently inquiring groups such as the petroleum engineer and the rubber chemist. Physics, too, after having been forgotten by the central group of philosophers, spawned and disinherited, in one coordinated act, all civil engineers, mechanical engineers, and many other groups who have today turned back to hire physicists.



G. *Sciences That Have Trouble Getting Under Way*

While some branches of human endeavor have been slow to acquire the stature of an accepted science, the participants have not been troubled about the matter. Culinary art promises to stay an art for some time. Although people have a feeling that there is quite a bit of chemistry going on in the pans in the kitchen, it is not disrespectful to say that almost any question in the theory of relativity has a simpler answer than the question, "What happens when the little lady throws a fresh fish into the skillet?" The practitioners in medicine were once content to have their lore in dispensing herbs and potions called "medical arts". Now, with biochemistry, electronic equipment, knowledge of bacteriology, anatomy, and histology, the word "art" is not fully appropriate. Glass technology, or ceramics, started about 1300 years before Christ with Chinese glazed pottery and did not get on its feet scientifically until some time between World Wars I and II. In contrast, radio engineering was a science the day the initial success was illustrated by Marconi. X-ray diffraction has a similar history, because the records show that von Laue and his team spent months trying to demonstrate the phenomenon long after the measurables had been selected and the fundamental functional relationships (see section II-7) had been established.

However, there are some groups of investigators who are seriously and conscientiously concerned that they cannot get beyond certain stages of growth in their fields. Some of these groups are the psychologists, meteorologists, statesmen, and sociologists. Frequently the difficulty arises from (a) mapping out too big a field, (b) having no measurables, (c) having too many measurables, which often means that the orthogonal measurables have not been identified, or because (d) the fundamental functional relationships are difficult to find since the extraneous variables cannot be kept under control either in the field or in the laboratory, or (f) the time is not ripe for the reduction of the particular chosen field to a science.

V. Launching a New, Isolated Science

FOLLOWING the steps outlined in section II, let us illustrate how one might launch a new, isolated science. In step one, let us assume that we have recognized the field as the care of a human being and call it the Science of Human Needs. Suppose steps two and three have been fulfilled since we have good descriptions of human needs and no further samples are necessary. We have seen that man consumes beef, carrots, olives, fish, avocados, flattery, encouragement, fresh air, adventurous thrills, dry Gibsons, musical sounds, information, exercise, etc. If one kept on naming without classifying (step 4) one could go on endlessly only to discover that limburger is considered a delicacy in some quarters or that people can eat crow if they have to. If one embarks on step 5 in section II and starts classification, he might decide (as James and others have done in different ways) that it is possible to divide the needs into seven or more classes such as food, shelter, entertainment, limited freedom from fear, etc. When one goes to measuring these things, he might find that he can measure food by the pound and shelter by insulative properties such as thermal conduction, but in measuring entertainment he might have to resort to measuring it in hours of diversion per day and assume that the subject will choose it himself. Admittedly this is cowardly, but if the anthropologists and psychologists are not ready to come to one's aid, this portion of the new science must wait.

In the choice of orthogonal measurables (section II-6) one might agree, for example, that food and shelter are orthogonal because beans and adobe bricks are not substitutes for one another. However, one finds on closer inspection that there is a suborthogonality in food because proteins, carbohydrates, and vitamins are all needed; and further orthogonality is found in proteins because more than one kind of an amino group is required.

Going to the search for fundamental functional relationships (II-7) one might enclose the subject in an imaginary (or real) box bristling with ingoing and exit pipes and measure the quantities of each of the orthogonal ingredients necessary to keep him alive. By varying the rates of inflow and outflow of the ingredients * the functional relationships are then forthcoming as a gift of Nature. When the relationships are examined and reduced to the minimum number, then they are the *fundamental* ones and the remainder can be deduced by reason from these few.

VI. Procedures For Making Discoveries

THE history of science and the biographies of the discoverers disclose many modes of bringing new truths to light. Below is an incomplete list of some of the procedures.

1. *Extrapolation.* A man who knows the frontier of his field can see likely directions for pursuit of further data and decide to proceed. For example, the electrical conductivity of lead was measured at temperatures as low as minus 200° C. In the University of Leyden the decision was made to continue the investigation to as near minus 273° C as possible. At about minus 271° they discovered superconducting lead. Other examples carry us to higher pressures, shorter wavelengths of radiation, faster particles, etc.

2. *Interpolation.* Napier studied the integral powers of numbers and upon investigating fractional powers discovered logarithms. In calculus one encounters the first, second, and third derivatives of functions. If he asks about the in-between derivatives such as the one and one-sixth derivative, he is in for some fun. A geologist notices that in between the great areas that have been explored and mapped there are some areas of Nevada that are untouched and he decides to fill the gap.

3. *Pattern lifting.* This is one of the most common procedures followed by a scientist who migrates from one field into another. A pattern of thought applicable in the old field is recognized to be appropriate in the new field. For example, the theory of evolution of biological species was found by Darwin's grandson to apply to the trends in ocean waves where waves having wavelengths most suitable to the conditions "eat up" those having unsuitable wavelengths. Biological evolution with emphasis on selection closely fits the pattern of the learning process in education or training. The exponential law once called the law of organic growth, first recognized in the growth of yeast, was carried to population studies in humans, reaction rates in chemistry, the computation of nuclear abundances, and many otherwise unrelated fields. The theory of nucleation, when learned as a basic principle, applies in crystallization of chemicals from solution; bubble formation in beer, glass, and lava; droplet formation in the clouds; minimum sizes for planting a colony; minimum populations for founding a steel age; minimum manpower for fighting a fire; etc., etc.

The following procedures are only mentioned here but not discussed.

4. *Idea-fitting with an objective.* (Invention.)
5. *Finding the unexpected on the path.* (Stumbling upon it.)
6. *Routine application of new tools.* (Like the electron microscope in bacteriology.)
7. *Unification of two or more fields.*
8. *Trying everything to see what might happen.*

In order to understand the role of theory in science, one must study the philosophy of models [2] and their meaning. We have not space nor time for this at present.

* In carrying out this science as it is defined, it is unfair to take the man's temperature, or look at his tongue. The measurables are the quantities going through the tubes and therefore H_2O, CO_2, and other exit gases and liquids are the only diagnostic tools. (With our present knowledge, this is impractical but the above illustration falls flat as an isolated science if we borrow from other fields.)

[2] This was discussed by the author in a memorandum to the record dated September 25, 1957, and in a paper "Description Mechanics", *Information and Control* **1**, 240–266 (1958).