SCIENCE

Vol. 88 FRIDAY, AUGUST 12, 1938 No. 2276

SCIENCE: A Weekly Journal devoted to the Advancement of Science, edited by J. MCKEEN CATTELL and published every Friday by

THE SCIENCE PRESS

New York City: Grand Central Terminal
Lancaster, Pa. Garrison, N. Y.

Annual Subscription, $6.00 Single Copies, 15 Cts.

SCIENCE is the official organ of the American Association for the Advancement of Science. Information regarding membership in the Association may be secured from the office of the permanent secretary in the Smithsonian Institution Building, Washington, D. C.

CHEMISTRY AND THE FUTURE

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IN discussing any subject which deals with an extrapolation from the past to the future, one can not make any certain or dogmatic statements. In the physical sciences extrapolations are very likely to be incorrect even when they involve only a small percentage of the region covered by reliable data unless a very fundamental theory of the phenomena based upon broad scientific evidence exists. Such conditions do not obtain with regard to my subject, and I can not risk more than the most general predictions in regard to the future. Moreover, these general predictions must be predicated upon several alternatives which are definitely beyond the control of chemists or scientists, and which are vital to their future.

It is necessary, in the first place, to consider the objectives of two groups of people. The first of these is the scientific group, and the second is the group consisting of the community as a whole. In neither case are the objectives exactly formulated, though it seems to me that those of the scientific group are more definite than those of the community in which we work. Of course, the objectives for all chemists or all scientists are not the same, but there is a very considerable agreement between these individuals. The people of the community, on the other hand, are swayed by so many emotions that these appear to be the most unpredictable quantity in the entire problem.

Scientific men are those who are posing particular questions to nature and its laws as they operate about us. In doing so they arrange most carefully devised experiments to test whether the ideas which they have in regard to the operation of natural law are in fact in accordance with these laws. If their postulates are not correct, the answer which they receive is an emphatic negative, and nature resists all efforts to impose erroneous ideas upon her. But if their postulates are in accordance with what we call natural law, nature unlocks her secrets with an amazing ease. When this occurs there is a communion between scientists and the eternal laws governing the behavior of this universe that is very intimate indeed. This communion represents the highest reward which a scientist receives for his services, and it is this that furnishes the major driving force for all his activities.[1]

A secondary objective of his activities is also important. Experience has shown that this understanding of nature's laws makes it possible for man to improve his physical well-being by adapting them to his own purposes. No matter where we work in our university or industrial laboratories, whether upon purely intellectual pursuits in connection with scientific things or upon the immediate use of these laws of nature, we all have in mind this second objective. We desire that the things that we do shall at some time and somewhere be of use to our fellow men in their physical and intellectual pursuits.

On the other hand, the divergence of the objectives of the people of the community, as shown by current activities, is truly amazing. There are extensive organizations of men whose activities if successful would make man supremely wealthy, would bring him dire poverty, would make him well informed even if not more intelligent, reduce him to the ignorance of dumb beasts, would destroy not only his home and useful material things, but would waste and destroy the sources of this wealth. As one watches to-day and attempts to see what chemistry or its sister sciences will do in the future, one can only feel that his own and all other prophecies are mere guesses without even an estimate of the probable errors. I can not say what it is that man really desires. In fact, it is not the desires of any localized group, but very largely the desires of men in the entire world that are important in this connection, for those in any one part of it may be forced to do things which they do not desire, because of the activities of others. I can only contribute to this discussion by pointing out some things which can be aided by chemistry if certain objectives are desired.

In the first place, chemistry can and perhaps will destroy our European civilization. In the efficient destructive machines which are in use to-day the most important agent is a chemical substance, an explosive, an incendiary mixture or a poison gas. All the other scientific contributions to these machines are to make this distinctly chemical contribution effective. The last great war demonstrated that these destructive methods can destroy the wealth of countries to such an extent that many years are required to even partially recuperate, and as a secondary result they can damage governmental régimes beyond repair and can make a world less safe for democracy or anything else. It appears to-day that even greater effects will result from another such war, and I do not believe that it is too much to say that a complete destruction of our civilization may result from such a war. The most crucial requirements for such conflict are chemical in nature. The secondary materials required for the support of armies and their movements are also to an important extent chemical in nature and greatly dependent on chemical industries. Liquid fuel is vital to the transportation of armies at the present time, and in addition chemistry contributes to nearly all the materials used in a modern war, as well as in peace. If the people of the world desire to make war chemistry will aid them. It will destroy people, their material possessions, and will dissipate and destroy the resources of the earth.

A very different future of chemistry can be painted if people so desire. If chemistry is permitted to devote its energies to peaceful pursuits, an abundance of goods valuable to man can be produced, and in addition it can contribute, together with its sister sciences, to man's knowledge of the universe and his place in it. It will help to free him from superstition and error, and will bring him intellectual pleasure.

In the past many of our sister sciences have contributed notably to the broadening of man's intellectual horizon. Astronomy gave him a proper perspective of his own importance and his own position in this universe. His earth is not the center of the solar system, nor is his solar system the center of this galaxy. At the same time that he was robbed of his central position in the physical universe what a grandeur has been spread before him as our knowledge of astronomy grows! Biology has robbed him of his miraculous creation by one or another anthropomorphic god, and has placed him in the lowly position of one of the animals, that one, in fact, who in this particular geological age dominates the earth, but at the same time the grandeur of an organic evolution with time has been spread before him. Geology has shown him the long length of time that man and his lowly ancestors have existed on this planet, and in fact that life on this planet has been nearly coexistent with the planet. Chemistry up to the present time can claim no such important contributions to man's understanding about himself. People have had no previous conceptions of the structure of matter either erroneous or otherwise, and thus the atomic theory has not driven clouds of superstition

[1] R. S. Mulliken (SCIENCE, 86: 65–68, 1937), has given an excellent discussion on the methods and objectives of scientists.

away. No traditions or prejudices have prevented us from manufacturing soap and sulfuric acid, or even synthetizing such things as sex hormones, and thus chemistry has operated during the past years with great freedom and with little opposition from our fellow men. Chemistry is, however, perhaps contributing to the present situation which has stimulated conferences of this sort. During the last century, and particularly the years of the twentieth century, chemistry and the other sciences have greatly increased our productive capacity. This productive capacity has been increased beyond anything which the world has previously seen, and promises to greatly increase it in the future. At the present time this development is probably causing the enormous social change which we who are here can not see in the proper perspective because we are a part of the phenomena. It seems to me that there is little doubt but what much of the unrest of the civilized world for the past twenty-five years, resulting in revolutions, new systems of governments and world-wide depression, is all rather closely related to this productive capacity largely brought about by science. This has been recognized by others and the suggestion has been made that the proper cure of these things is to artificially decrease our ability to produce. This is a cowardly point of view. In spite of all the many perturbing events which have arisen, it seems to me, as a result of this important change, we should look forward to the future with the greatest hope. If we act with courage our descendants will live in an abundance of necessities and luxuries the like of which we can not imagine. If we are not courageous, they may live with less than we have at present.

Chemistry is a study of the substances which we find about us. From the materialistic side chemistry can supply materials in abundance and in great variety. Most of the materials used in all construction to-day, with the exception of wood, are the product of chemistry, and wood as it is used is improved and preserved in many cases by the use of chemicals. Metallurgy is essentially a branch of chemistry, dealing with the preparation and the utilization of metals. Just how much of such materials are supplied in the future is not a matter of chemistry, but one of social organization. We have laboratories and men to produce all that can be accepted by industry at the present time, and we can train the necessary men and build and equip all laboratories needed in the future. The cost of chemical research, and, in fact, of all research, is but a very small fraction of the production costs, and the result pays most handsome dividends in new materials and new processes.

Without in any way wishing to place blame, we may note that since the world war no country has arranged its internal affairs in such a way that anything approaching the maximum production of material goods for peaceful purposes has been accomplished. Among the large countries Russia only has stated that her objective was the production of goods for use. Due to a mistake in political philosophy, inadequate numbers of properly trained men and the necessity of defending two borders some six thousand miles apart against threats of invasion, her achievements have not been satisfactory. England, with a correct political philosophy, with a remarkable mineral wealth and being the home country of a friendly commonwealth of nations, has not succeeded in this respect, as any one can see who travels in England and who observes the amount spent on the dole, and has sufficient imagination to think of living on its stipend. Germany, with another political philosophy, has definitely decided in favor of guns rather than butter, and in addition has a definite lack of natural resources and apparently lacks the bargaining ability to secure them. The United States and Canada have succeeded better than any other country, due undoubtedly to a correct political philosophy, adequate resources, adequately trained men and freedom from threats of invasion. We desire peace, and we have a desire for the good things which science and technology can bring. There was, however, some fatal defect which caused an increasing unemployment which led to the break in 1929, and our inability since then to get this production machinery going again. The average for the years since the world war for all the people of these two countries has not been satisfactory. Other countries could be reviewed, but the story is so similar as to be monotonous. Perhaps the Scandinavian countries have done as well as or better than any in this respect, but they are not easily compared with the larger units which I have just mentioned. Perhaps the correctness or incorrectness of the political philosophy is important, but I think that it is impossible to see clearly that such is the case from the examples that we have considered so far.

Our people wish those things which chemistry can bring to them, but for some reason our chemical plants are partly idle, our chemists unemployed, and our workmen are on some form of direct or indirect relief. This is the problem of the future of chemistry which does not yield to chemical methods of solution, and without its solution it is only possible to express hopes for the future.

Since the beginning of scientific chemistry some 150 or 200 years ago there has been an accelerated rate with which our scientific discovery and invention has taken place. At the beginning of the nineteenth century Dalton proposed the atomic theory, which has dominated all chemical theory and experiments since then. During the century, 34 chemical elements were discovered, bringing the total known elements to 81. The chemical properties, methods of preparation and analysis of the elements and their compounds were extensively studied. The system of classification of the chemical elements known as the periodic system was discovered. The extensive chemistry of the compounds of carbon and the syntheses of compounds occurring in natural products were begun and greatly advanced during the century. The fundamental laws of thermodynamics were proposed and the beginning made of their application to chemical problems. The foundations of statistical mechanics which have been used recently in the understanding of chemical problems were laid in that century. In addition to the old chemical processes, such as the limited manufacture of soda and mineral acids, this century saw the beginning of the extensive manufacture of coal-tar dyes and the use of petroleum. The growth of chemistry during the century was so great that in 1900 one might wonder what was yet to be done, and yet growth since 1900 has been so great that one naturally feels that very little was known at that time.

I wish to illustrate the growth of this science since 1900 by giving a partial list of the important discoveries made since then. I am including in this table some things which perhaps belong rather in the field of physics because they have contributed in such an outstanding way to the science of chemistry.

1899	Discovery of the quantum theory by Planck
1901	Synthesis of polypeptides—E. Fischer
1902	Hydrogenation of fats—Normann
1905–1913	Development of the Haber process
1906	Third law of thermodynamics—Nernst
1872–1908	Bakelite—first of important plastics
1911	Nuclear atom—Rutherford
1911	Discovery of isotopes—Fajans and Soddy
1912	Diffraction of x-rays and crystal structure—v. Laue and Bragg
1912	Preparation of pure anthocyanines—Willstätter
1913	Quantum theory of the atom—Bohr
1916–1938	Structure of monomolecular films—Langmuir
1919	First transmutation—Rutherford
1920–1930	Rapid development of rayon manufacture
1920–1938	Chemistry of sterols, bile acids and sex hormones—Windaus, Ruzicka, Karrer and others
1921	Discovery of insulin—Banting
1923	Debye-Hückel theory of electrolytes
1923	Ultracentrifuge and molecular weights of biochemical substances—Svedberg
1926	Attainment of very low temperatures by magnetic methods—Giauque and Debye
1926	The exact quantum theory—de Broglie, Heisenberg, Schrödinger, Dirac
1926	Constitution and synthesis of thyroxin—Harrington
1926	Isolation of vitamin B_1 in crystalline form—Jensen and Donath
1926	Preparation of vitamin D by irradiation of ergosterol—Windaus and Pohl, Rosenheim and Hess
1927–1938	Theory of valence—Heitler, London, Slater, Pauling, Mulliken
1927	Isolation of vitamin C—Szent-Györgyi
1927	Application of quantum theory to kinetics of reactions—Polanyi, Eyring
1929	Synthesis of porphyrins—Hans Fischer
1930–1938	Crystallization of enzymes—Sumner, Northrup
1931	Deuterium—Urey
1931	Synthetic rubber
1931	Constitution of carotinoids and vitamin A—Karrer
1932	Discovery of Flavin enzymes—Warburg
1933	The constitution of coferments
1934	Artificial radioactivity—F. and I. Joliot-Curie
1935	Isolation of the tobacco leaf mosaic virus protein—Stanley

There are three main developments which are worthy of discussion in regard to the development of the last thirty-eight years. These are:

(1) The development of our understanding of the structure of atoms and molecules, and the application of this knowledge to an understanding of chemical reactions.

(2) The development of the field of biochemistry, which has concerned itself with the isolation and synthesis of compounds occurring in living organisms and with their physiological effects and applications to medicine and hygiene, and

(3) The development of one of the largest modern industries, namely the chemical industry with its many ramifications.

Other important developments represented in this list not included in the three items that I have just mentioned are the Debye-Hückel theory of electrolytes, the discovery of monolayers by Langmuir and others, and the discovery of artificial radioactivity and its important effect upon chemical research.

In the very closing years of the nineteenth century Planck announced his first postulates of the quantum theory, and this theory has dominated the developments of physical science during this century in much the same way that Dalton's atomic theory dominated the chemistry of the nineteenth century. Parallel with this development and within a few years of its first proposal, radioactivity was discovered, which led to an understanding of the structure of the atom. Rutherford recognized the essential character of the structure of atoms as the result of the use of the projectiles spontaneously emitted from radioactive substances.

The study of radioactive substances led to the discovery of isotopes. X-rays, discovered within a year or so of the discovery of radioactivity, have unlocked the structure of crystals and have given us the means of measuring the distances between atoms in solids and in liquids. Bohr's theory of the atom combined Rutherford's work on the nuclear atom with Planck's quantum theory and gave us our first explanation of the thousands of wave-lengths of light emitted by atoms, and finally led to the exact statement of the quantum theory by de Broglie, Heisenberg, Schrödinger and Dirac, and from this follows an understanding of the valence forces between atoms and compounds and the velocity of chemical reactions.

Much of the biochemical work has been concerned with an understanding of protein substances, the understanding of chlorophyl and haemoglobin, the isolation of enzymes, hormones and vitamins and their syntheses. This information is particularly useful, not quite from the standpoint of medicine exactly, but more from the standpoint of avoiding in many cases the necessity for medicine, for, after all, medicines are in many ways foreign substances to living organisms. By understanding the hormones secreted by the internal glands of animals and the vitamins which we secure from foods, man in the future can be kept well rather than cured of disease. The work which I have included in this list at this time has been done principally with the object of understanding the fundamentals of biochemistry, that is, the chemistry of living things. Their use in this way is a by-product of this activity.

I have also included in the list some of the industrial processes. The hydrogenation of fats makes it possible to secure large amounts of solid fats from such cheap substances as cotton seed oil. The Haber process for the manufacture of ammonia enabled Germany to hold out against great odds in the world war. I think there can be little doubt but what Haber was the most important single individual in Germany so far as the prosecution of her war was concerned. It is interesting indeed that he was exiled by his own country in 1933 and was welcomed by his enemy, England.

Bakelite was the first of the important synthetic plastics which is now used for so much of our electrical insulation. The success of this plastic also led to the development of many others since then. The development of the modern lacquer industry is closely related to this. So many objects to-day are protected by a thin film of what is essentially cellulose, together with pigments of all brilliant colors. The manufacture of rayon greatly increased during the decade from 1920–1930, though the essentials of the process were discovered during the nineteenth century. Its successful commercial exploitation has only been possible in recent years.

In 1931 synthetic rubber was produced. This can not be produced in competition with natural rubber, but the synthetic variety has desirable properties not possessed by natural rubber. There are so many chemical processes which have been developed during this century that it is difficult to select even a few for special mention. One might mention the recovery of bromine from sea water as carried out by the Dow Chemical Company. This bromine is mostly used in the manufacture of ethylene bromide and together with lead tetraethyl is added to our gasoline. Of course, one is immediately reminded at this point that the development of gasoline is an enormous business in itself. We must immediately think of cracking processes, hydrogenation processes, processes for the recovery of natural gas, the manufacture of lubricating oils, the hydrogenation of coal, etc. It is only necessary to mention stainless steel for one to realize the great revolution in metals that has taken place in this century, for stainless steel is only one of many varieties of alloys which have found their place in modern industry. How important the whole field of detergents is! One should not forget to mention dyes, which in dollars and cents are in a way quite unimportant but which beautify our clothes, our homes and practically all articles that we use. The cost of these brilliant colors has been reduced until the poorest of the population are arrayed in colors that only the most wealthy could have afforded even so short a time ago as one century. So many of these processes of industrial chemistry are so commonplace that we fail to recall that they have not always existed. Many of them have existed only a matter of years, and a large percentage of them only a matter of decades.

The list of the important contributions which I have presented can not be extrapolated to the future. If I could make a reasonable estimate of what the next great development would be, that would be a very important step in making the next discovery. One can not predict the discovery of the Haber process or insulin or artificial radioactivity before they occur, for the reason that these are such new and outstanding things that before their discovery no one had the slightest idea that they existed. I can only point the trend. During the last twenty years the organic chemistry of products produced by living organisms has shown a remarkable growth. Vitamins, hormones, enzymes, have been discovered and isolated. Proteins have been crystalized, and, in fact, one, the tobacco leaf mosaic, appears to be a dead protein which can cause a disease and multiply itself, thus in a way bridging the living and the inanimate. This field will certainly develop markedly in the next years. In the second place, there is a marked trend toward the understanding of the fundamentals of chemical behavior. Nernst stated the third law of thermodynamics in 1906, but to-day,

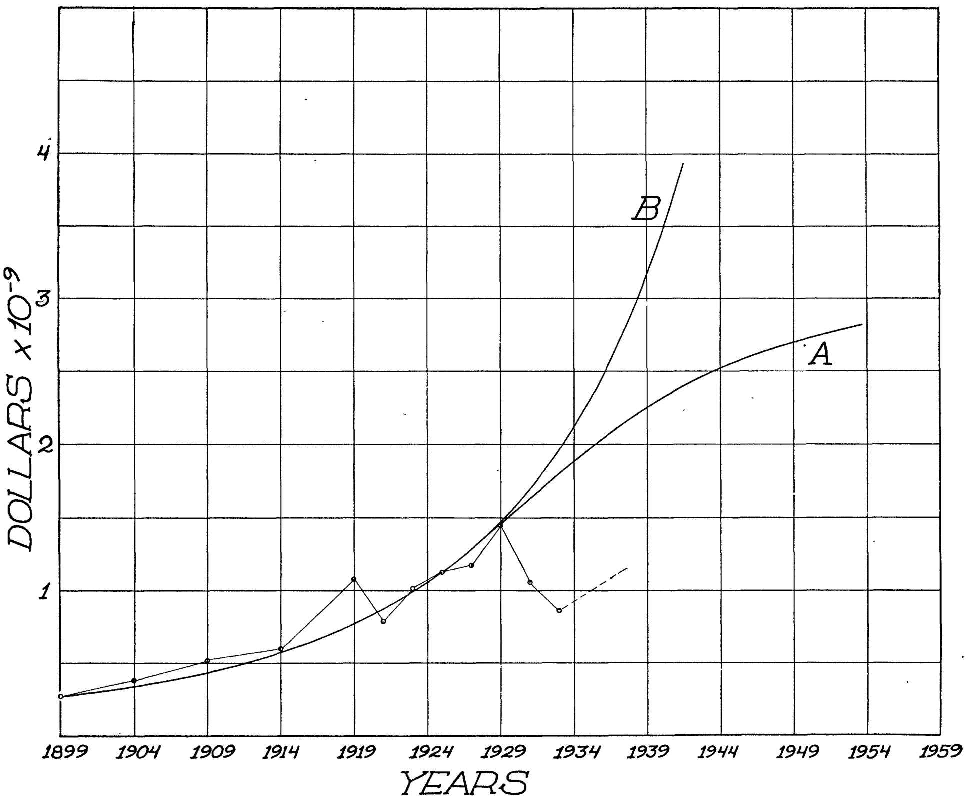

FIG. 1. Value added by chemical and allied industries to raw materials in the United States. Compiled from the Biennial Census of Manufactures, U. S. Dept. of Commerce.

together with the quantum theory, we have far more exact understanding of that law than ever before. It is being applied to chemical reactions of considerable complexity with confidence and enables us to understand far better the fundamentals of our chemistry. The new artificial radioactivity and the great activity in physics in this connection are important developments for chemical research. In the industrial field straight through the depression the number of useful products has been increased in many ways.

To show the possible future industrial development I can best use a plot showing the value of chemical products produced as a function of time in the past. The plot shown in Fig. 1 is constructed from data for the United States. This is probably one of the best countries to select for our present purposes because its industry was disturbed less by the war than most others and because there has been no change in political institutions since 1900, and, finally because it is such a large industrial country that most processes and products will be adequately represented. This shows a plot of the value of chemical products in current dollars against years. No attempt has been made to correct the dollars for the gradual depreciation of the dollar which has occurred over that time. The solid curve shows the approximate course from 1900 to 1929, and an extrapolated curve, A, beyond that time, which one might have expected the industry to follow had the 1929 catastrophe not occurred. The curve is of the usual kind characteristic of industries, grows rapidly for a while and then gradually flattens out. Further growth can not be expected unless some very marked rejuvenation occurs. The figure makes evident the fact that from 1929 to the present the production did not increase as would be expected from this curve. I leave the question of the 1929 catastrophe to economists, except for the suggestion that chemical industry and its masters, together with other industries and their masters, may not have realized the inflection point in the curve and may have stubbornly tried to make production follow the curve, B, as shown in the figure. This break in the curve in 1929 shows again how dependent the future of chemistry is on factors beyond the control of chemists. Perhaps my analysis of this problem as shown by this curve is not correct, but I do believe that the method of approach is valuable. People working with the social sciences are apt to make the postulate that there are no laws of nature underlying these economic problems and that the only important factor is man's wishes and desires. I believe that man's will in regard to these things is one factor in the problem, but that it is not by any means all of it. We can solve our economic problems of this kind when we approach them with the same point of view as that with which physical and biological science approach their problems. There are underlying natural laws behind the phenomena; with these laws we get the maximum good out of our efforts. If we attempt to superimpose false points of view on these natural phenomena, nature resists and our efforts bring us only the greatly decreased returns which the experimental data of this curve illustrate.

Because of the difficulties evident in this curve, as well as those that I have emphasized before in regard to the unpredictable desires of man, I can only express some hopes for the future for the industrial application of my science. I hope that in the near future the chemical production will fall on the curve, A, of Fig. 1, and that this will represent products designed for peace and not for war. It would appear that the future is able to bring better clothes for people from better cotton, silk, wool or linen or fibers better than these. These will be far more beautifully dyed than they are at the present time, and they will probably be produced with less effort than they have been in the past. The food of man will be produced in greater variety than at present. Fertilizers will make the arable areas of the earth produce a great abundance for the present populations of the earth and for even much greatly increased populations than now exist. The study of vitamins will mean that the foods will be better, more wholesome than they are at present. The dwellings of man in the future will be made of materials as yet unknown. They will be more durable, more beautiful and more easily constructed.

In addition to necessities, many luxuries will be supplied. Even if petroleum is exhausted liquid fuels will be made from materials grown on our farms. The automobile will continue with us and plane travel will still be possible so far as its fuel and lubrication is concerned. In addition to the preventive medicine which I have mentioned, in which we see to it that the proper vitamins, hormones and other necessary substances are supplied, internal medicines have been developed in the last few years which are very effective against many diseases. This development will certainly continue in the future. Since the beginning of the century many diseases have almost disappeared from civilized countries. Typhoid, for example, has largely been eliminated by adding small amounts of chlorine to drinking water. Chemistry will produce the anesthetics for surgery in the future, and disinfectants, as it has produced them in the past.

Finally, the greatly increased productive capacity which results from the use of chemistry and the other sciences must be expected to profoundly modify our social and economic institutions. This should be regarded as one of the great contributions which these things will bring to man.

My remarks at this point are not particularly original with me, nor can I prove them with the exact marshalling of data characteristic of my science. I think they are worth presenting, nevertheless. Sometimes it happens that the details of a complex set of phenomena can not be followed, but that general statements can be made about them without a knowledge of the details. The weather is a much-discussed subject, just as economics is. While we can not say precisely why the weather was hot and sultry last week, and it is cool and clear this week, we know that the general temperature is determined by the distance of the earth from the sun. Though spring may be early or late without any evident reason, we know that the changing seasons are caused by the inclinations of the earth's axis to the plane of the earth's orbit.

During the past century or so a science has developed which never existed before. Its application to industry by the various branches of engineering has proved most effective for the production of goods. These methods of production have the characteristic that they may be used to make goods cheaply in abundance but also to make them cheaply only if they are made in great quantities. The invention of limited liability corporations has proved to be the type of business organization necessary to carry out this production with the use of scientific methods. These things, together with an inadequate method for distributing the goods produced, are to my mind the underlying cause of most of the serious difficulties of this century. Probably the business rivalries which led to the world war, communism in Russia, the invasion of Manchuria and China and of Ethiopia and world-wide depression have all resulted from the great production of goods by scientific methods, together with archaic methods of distribution. If goods are to be produced in large quantities, they must be consumed in large quantities. Whatever that distributive system will be, it must distribute an abundance to many people and not to the privileged few only. If this is not done, we must abandon these mass production methods. I am optimistic enough to believe that we will accomplish this and that chemistry and her sister sciences will bring an abundant physical and intellectual wealth to our posterity; it will decrease labor and bring leisure, beauty and health. We solicit the help of the community to the end that we shall not always have the poor with us.