SCIENCE

FRIDAY, NOVEMBER 30, 1917

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THE PRODUCTION OF SCIENTIFIC KNOWLEDGE[1]

THE great value of scientific research both to the industries and to the nations at large is now generally recognized throughout the world and the last few years have seen a remarkable increase in the efforts made to stimulate the production of scientific knowledge. In 1914 the American Association for the Advancement of Science appointed a Committee of One Hundred to inquire into the steps which should be taken for the increase of scientific research in the United States and the work of this committee has been continued and expanded by the National Research Council. Among the European nations there is a great awakening to the national value of scientific research. The British government has appointed a Department of the Privy Council to deal with the subject, while it is announced that in France a new national laboratory on a very large scale has been projected. In Australia the government has appointed a special department to consider what steps should be taken for the organization and development of research work in the Commonwealth, and in Canada the matter has been the subject of government inquiry and solicitude.

The increase of scientific knowledge can be divided into three steps: first, the production of new knowledge by means of laboratory research; second, the publication of this knowledge in the form of papers and abstracts of papers; third, the digestion of the new knowledge and its absorp-

[1] Being a paper read before the Rochester Section of the Optical Society of America, October 23, 1917.

tion into the general mass of information by critical comparison with other experiments on the same or similar subjects. The whole process, in fact, may be likened to the process of thought. We have first the perception by means of the senses. The percept is then stored in the memory and in the mind is compared with other previously stored percepts, and finally forms with them a conception.

I desire in this paper to consider the methods by which these three sections of the production of knowledge may be carried on, to suggest an arrangement of laboratories to produce experimental results dealing with any branch of science, then to consider how the knowledge so obtained may best be stored and classified and finally the methods to be employed to make the results of scientific research available for application.

1. RESEARCH WORK

The agencies engaged in scientific research are of several kinds. The traditional home of research work is in the university, and the bulk of the scientific production of the world comes from institutions connected with teaching. The industries are more and more supporting research laboratories, a large number of which contribute to the general fund of scientific knowledge by publishing the results which they obtain, and some of which are engaged upon purely scientific work of no mean order. Consulting and technical laboratories engaged in industrial work make frequent contributions to science, and there are some very important laboratories engaged in pure research work which are supported by philanthropic foundations.

The classification of research laboratories is not altogether an easy task. They may obviously be classified according to the source of the funds which support them; that is, we may classify them as university laboratories, industrial laboratories, government laboratories, institution laboratories, and so on, but if we look at them simply in the light of the research undertaken, this does not seem to be altogether a logical classification since there is little distinction between the work done in some university laboratories and some industrial laboratories, and the work of the government and institution laboratories again overlaps that of the two former classes.

The University of Pittsburgh, for instance, has an industrial laboratory where definitely technical problems are dealt with. The research work on photometry done at Nela Park and at Cornell University would seem to be similar in kind, and work on physical chemistry or on the structure of chemical compounds is of the same type, requires the same class of workers, and produces the same results, whether it be done in a university, in a laboratory of the Carnegie Institution or in such an industrial laboratory as that of the General Electric Company. It is equally difficult to classify laboratories according to the purpose for which researches are avowedly carried on. Most university laboratories are willing to undertake work of industrial value, and, indeed, some specialize in such problems; while many industrial laboratories are quite willing to carry out a research of purely academic and theoretical interest provided the problems involved bear a relation to the general work of the laboratory.

A useful classification of laboratories can, however, be obtained if we consider whether the problems investigated in a laboratory are all connected with one common subject or whether the problems are of many kinds, having no connecting bond of interest. I would suggest that the first type of laboratory might be called "convergent" laboratories and the second "divergent."'

In the "divergent" group of laboratories are included all those institutions where research is carried on which are interested in science in general or in science as applied to industry and which will attack any problem which may seem to promise progress in knowledge or, in the case of an industrial laboratory, financial return. Most university laboratories are of this type. When they devote themselves to special problems it is usually because of the predilection of some professor, and as a general rule a student or instructor may choose any problem in the whole field of the science in which he is working and may carry out an investigation on that problem if he be interested in it without regard to the relation of his work to the other work which is carried on in the same laboratory.

Correspondingly, in most industrial laboratories the problems investigated are those which present themselves as a result of factory experience or of suggestions from the men working in the laboratory and which promise financial return, and the different problems carried on in the same laboratory are not necessarily related in any way whatever.

The greater number of university and industrial laboratories are necessarily of this type. It would be a disadvantage for a university laboratory, whose primary business is training students, to be too narrowly specialized. Specialized university laboratories are only desirable in the case of post-graduate students, and it would be very inadvisable to allow the laboratories responsible for the general training of scientific men to specialize in one branch of science, since as a result the students would acquire a proper acquaintance with only a limited portion of their subject.

Industrial laboratories, on the other hand, must necessarily be prepared to deal with any problems presented by the works, and as these will be of all kinds, covering generally the whole field of physics, chemistry and engineering, it is impossible for the usual works laboratory to specialize except in so far as it deals with the works processes themselves.

In the "convergent" laboratories, however, although the actual investigations may cover as great a range of science as those undertaken in a "divergent" laboratory, yet all those investigations are directed toward a common end; that is, towards the elucidation of associated problems related to one subject. Thus, the staff of the Geophysical Laboratory, which includes physicists, geologists, crystallographers, mineralogists and chemists, works on the structure of the rocks, and although the field of the actual investigations ranges from high temperature photometry to the physical chemistry of the phase rule, yet the results of all the work carried out are converged on the problem of the structure and the origin of the earth's crust.

The Nela Park Laboratory, in the same way, is studying the production, distribution and measurement of illumination, and all its work, which may involve physiology, physics and chemistry, is related to that one subject. Such convergent laboratories sometimes develop in universities owing to the intense interest of a professor in a single subject and to the enthusiasm which inspires students and assistants to collaborate with him and to concentrate all their energies on the same group of problems. There are many examples of such laboratories, such as the laboratories dealing with radio-activity, and those which are concerned chiefly with spectroscopy. Among others may be mentioned the Cavendish Laboratory at Cambridge and several of the larger university laboratories which deal with the physical chemistry of solutions.

But these university laboratories are rarely able to concentrate on to the group of problems which they are studying specialists from such different branches of science as are available for similar laboratories outside the universities owing to the fact that it is very difficult to obtain interdepartmental cooperation in research in a university. In a specialized laboratory, on the other hand, workers in all branches of science may well collaborate in the investigation of problems representing different points of view of one general subject.

In addition to the examples of industrial and institutional laboratories mentioned above I should like to illustrate the structure of a convergent laboratory, if I may be forgiven for doing so, by referring to the organization of the research laboratory with which I am connected—that of the Eastman Kodak Company.

The purpose of this laboratory is the investigation of the scientific foundations of photography and its applications, everything relating to photography in all its branches and applications being of interest. The branches of science which are of chief importance in photographic problems are those of optics in physics and of the colloidal, physical and organic branches of chemistry, and the relations of these sciences to photographic problems are shown in graphic form in Fig. 1.

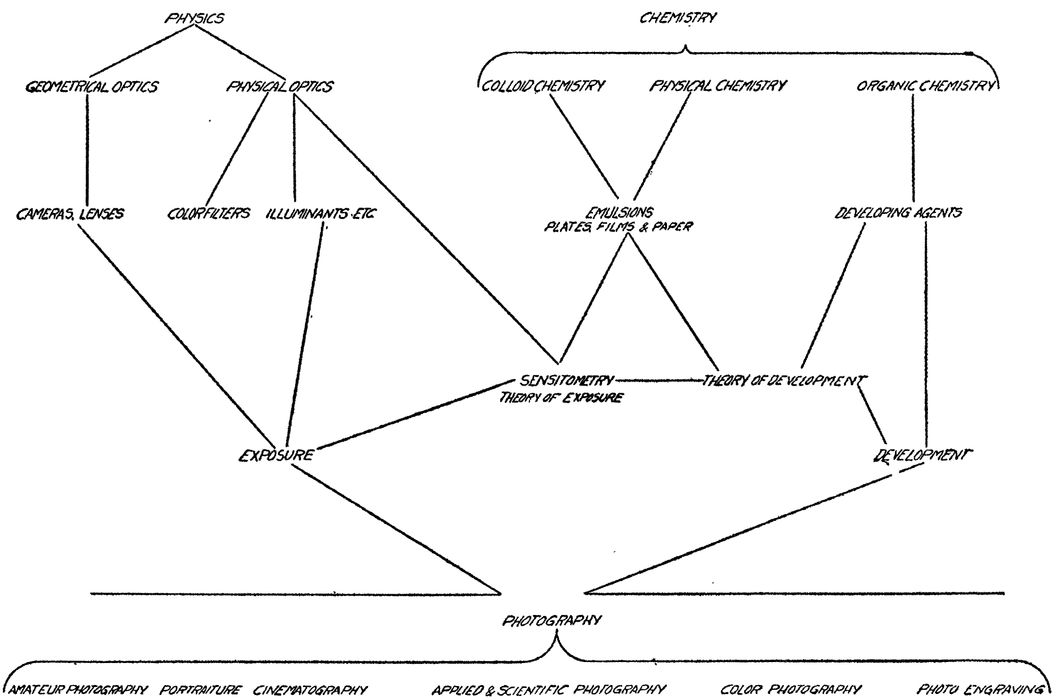

Fig. 1.

Optics deals on its geometrical side with the materials used in photography—cameras, lenses, shutters, etc.—and on its physical side with such materials as color filters and illuminants, but especially with the study of the relation of the photographic image to the light by means of which it was produced—a study which is known by the name of sensitometry. The manufacture of the sensitive material itself, which in the case of modern photographic plates, films and paper is called the emulsion, is a province of colloid and physical chemistry, colloid chemistry dealing with the precipitation and nature of the sensitive silver salts formed in their gelatine layer, while physical chemistry informs us as to the nature fore deals with sensitometry and the theory of exposure, the chemist must deal at the same time with the theory of development and with the conditions relating to the development of photographic images.

A laboratory, therefore, for the study of photographic problems must be arranged with a number of sections such as are

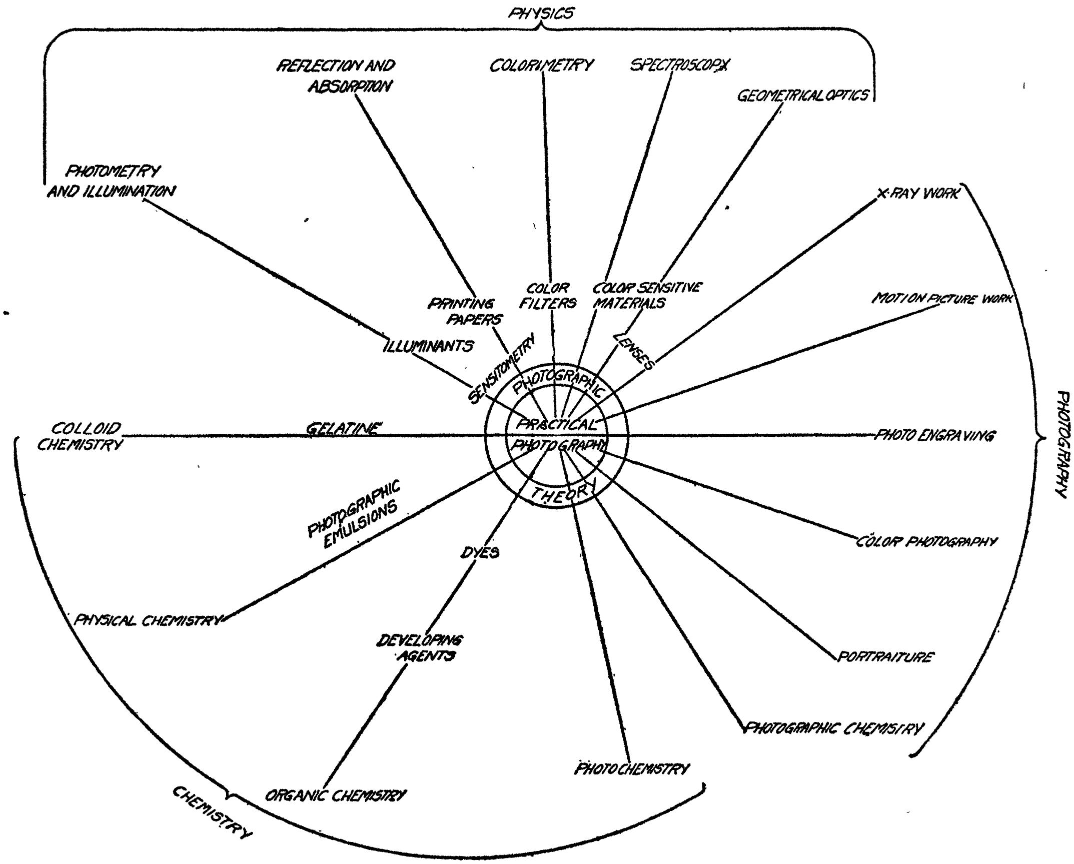

FIG. 2.

of the reactions which go on, both in the formation of the sensitive substance and in its subsequent development after exposure.

The organic chemist prepares the reducing agents required for development and the dyes by which color sensitiveness is given to the photographic materials and by which the art of color photography can be carried on, and while the physicist there- shown in Fig. 2. In physics we require departments dealing with sensitometry and with illumination, reflection and absorption, colorimetry, spectroscopy and geometrical optics. We need a department of colloid chemistry, one of physical chemistry, one of organic chemistry, one of photo-chemistry to deal with the action of light upon the plate, and finally a number of photographic departments, dealing with photographic chemistry, with portraiture, color photography, photo-engraving, motion picture work and X-ray work, and all these departments are converged together first upon the theory, and then upon the practise, of photography.

Each research specialist in the laboratory is given work corresponding to a limited field of science, so that while his special attention is devoted to that one department his field of activity just overlaps that of the departments on each side of him, while his general knowledge of the subject should, of course, cover a much wider range. It is important that each man should have his own special field of work and that overlapping should not be complete since such complete overlapping will inevitably produce friction destructive of cooperation and harmony. The way in which such a subdivision is arranged may perhaps be best illustrated by Fig. 3, which shows the range of the specific investigations of those who in our laboratory cover the range of research work between sensitometry and pure physical chemistry. There are five workers in this range; the first, *A*, being a pure physicist; *B*, a physicist with a considerable experience of chemistry; *C*, a physical chemist who has specialized in photography; *D*, a physical chemist who has specialized in photographic theory; and *E*, a pure physical chemist. The interest of each of these workers overlaps the field of the other workers but nevertheless each of them has his own specific problem, his own equipment and apparatus. Thus, *A* and *B* use sensitometric apparatus chiefly; *C*, both sensitometric apparatus and the thermostatic and electrical equipment of physical chemistry; *D*, microscopic apparatus and chemical apparatus dealing with the precipitation of silver salts; and *E*, the analytical and solubility apparatus of chemistry.

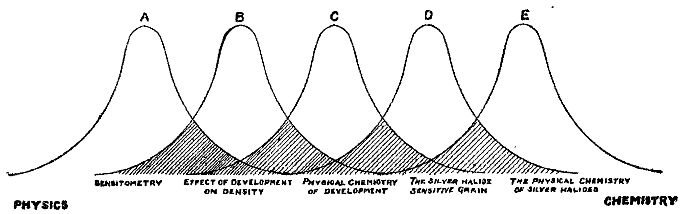

FIG. 3.

The whole of this range is also connected with colloid chemistry and especially the overlap of the different sections involves colloid problems, so that we can consider colloid chemistry as dealing with the interrelations of the different sections of photographic chemistry and can represent its province in the diagram by shading the overlapping areas. The colloid division of the laboratory will therefore be interested in the work of each of the specific investigators and will be of assistance to all of them.

These charts, prepared for a photographic laboratory, are equally applicable in form for almost any other convergent laboratory, so that if we have to work out the organization of a research-laboratory which is to study any inter-related group of problems, we can do it by the construction of charts similar to these. Thus, considering Fig. 1, we place first at the bottom of the chart the general subject considered and its various branches and then above these the scientific problems involved, separating out on opposite sides of the chart those problems which would involve different branches of pure science. Thus, we can place on one side biological problems, then physical problems, then chemical problems and so on, so reconstructing a chart similar to Chart 1 from the bottom up until at the top we have the various branches of pure science involved, subdividing these branches until each subdivision represents the work capable of being handled by one man in the laboratory.

It will now be possible to draw Fig. 2, showing on the circumference the different sections of the laboratory for which accommodation, apparatus and men must be provided and showing the relation of these sections to the problem as a whole, and having worked this out it is easy to find the amount of space and the number of men which will be required or which the funds available will allow for each part of the work.

Specialized laboratories may originate in various ways, but it seems clear that with an increasing total amount of research and with an increasing realization of the importance of research more laboratories will be developed and no doubt laboratories which originally were of the divergent type will with their growth tend to split into a linked group of convergent laboratories. Consider, for instance, a very large industrial research laboratory covering a wide field of research and dealing with many different types of problems. There are two types of organization possible to such a laboratory. It might be divided according to the branches of science in which the workers were proficient. It might have, for instance, chemical divisions, physical divisions, and so on, but if the groups of problems dealt with were reasonably permanent in their character it would more probably develop into a group of convergent laboratories in which men from different branches of science—chemists, physicists and so on—worked together (and probably even had their working places in proximity) because they were working on the same general problem. Any national laboratory which is developed for industrial research, for instance, should almost certainly be organized as a group of convergent laboratories rather than as a group of separate physical, chemical, engineering, etc., laboratories.

We may expect then that the general organization of scientific research will tend towards the production of numbers of specialized laboratories, each of which will be working on an inter-related group of problems and attacking it from various standpoints.

Some of the questions relating to the internal organization suitable for these convergent laboratories have already been discussed in a former paper[2] and I need only add here that the "conference" system described there as a method of actually carrying on the scientific work of the research laboratory has continued to prove quite satisfactory.

2. THE CLASSIFICATION OF SCIENTIFIC KNOWLEDGE

The work of the research laboratories is published by various methods in the form of scientific papers, and with the increasing amount of research done the number of technical journals is increasing steadily, so that the workers in most branches of science find it difficult to keep up adequately with the current literature and especially those who become interested in the light thrown upon their own problem by other branches of science find it a task of great magnitude to acquaint themselves adequately with the literature. In order to meet this difficulty the various scientific societies publish journals giving abstracts in a conveniently indexed form of all the important papers published, and these abstract journals are of great value in searching for information on special subjects.

[2] "The Organization of Industrial Scientific Research," SCIENCE, 1916, p. 763.

In spite of these abstract journals the task of obtaining all the references to the literature on a given subject is still a formidable one and might be very much simplified by the adoption of some radical changes in the organization of the abstraction and classification of scientific knowledge.

In the first place, there seems to be no reason why abstracts of scientific papers should be prepared by the national societies. At present, for instance, there are at least four complete sets of abstracts of chemical papers prepared in different countries, together with a number of less complete sets, and this represents a great overlapping and duplication of effort. On the other hand, sciences which have not so many or so wealthy workers as chemistry can not afford to produce any complete abstract journals, so that in these sciences reference to the literature is much more difficult. There seems to be no reason why an interchange of abstracts between different countries could not be arranged and, indeed, it might be the best method of obtaining abstracts to have the author of a paper supply an abstract suitable in form and length for the abstract journal at the same time that he sends his paper in to the journal which publishes it. The editor of that journal could suggest modifications in the abstract which in his opinion were desirable and forward both the corrected and uncorrected abstract to the editor of the abstract office, where it would be re-edited for insertion in the international abstract journals and these journals would, of course, be supported by subscriptions either through the societies or individuals in the same way as the abstract journals which are at present published.

Whether such an ambitious scheme of international scientific abstracts is capable of realization or not, reference to the abstract journals would be made much simpler if some method of numerical classification could be adopted.

In this connection, an experiment has been made in the last two years at the laboratory of the Eastman Kodak Company which has proved successful and which seems to be worth trying on a larger scale. The laboratory publishes each month for the use of the employees of the company an abstract bulletin of the photographic journals, including also abstracts from other scientific journals which have any relation to photographic problems or manufacture, the abstracts being made by the laboratory staff, and attached to each abstract is a reference number. These numbers refer to a numerical classification of photography based somewhat on a decimal system but adapted to the special needs of the subject. Each month as the bulletin is issued the abstracts are clipped out, pasted on cards and filed under the number printed on them in numerical order so that each recipient of the bulletin can prepare for himself a file either of all photographic literature or of any portion of it in which he may be specially interested. For example, in the classification photographic apparatus commences with the number "2," and if any particular worker is not interested in anything but apparatus, if he has no interest in materials or in photographic processes or in applications of photography, then he need only file the cards starting with "2," while, if his interests are even more limited, if, for instance, he is interested only in photographic shutters, he can file the cards starting with "262" thus obtaining only a very limited file which is, however, complete for the subject in which his interest lies.

If the abstract journals would print such a numerical classification attached to each abstract, adopting as their basis either the numerical classifications of the international catalogue of scientific literature, which have proved themselves satisfactory after trial, or some different classification adopted after due consideration, then each recipient of the abstract journals could prepare for himself card index files of the scientific literature in which he was interested.

To prepare a card index of all science or even a complete index of one large branch of science in this way would be too formidable an undertaking either for an individual or even for a small library, but it should certainly be possible for large libraries such as those of the scientific societies or of large cities to keep such numerically indexed files to which reference could be made by correspondence from any research worker. Thus, adopting the classification of the international catalogue, a worker who became interested in questions, *e. g.*, of catalysis, could apply for a copy of the reference cards on this subject, which would include all those indexed under 7065 and could be supplied with a complete file or with a partial file covering any period of time; the copies could easily be made by photographing the cards with such a camera as the "Photostat."

3. THE UTILIZATION OF SCIENTIFIC KNOWLEDGE

The actual application of science to industry is so vast a subject that it can not be considered here, but it is not satisfactory to leave the results of research at the point where they are published in papers and filed in the abstract journals. In order to make them available as a part of scientific knowledge the new information as it is obtained must be incorporated in books.

There are three classes of books dealing with scientific work which require separate consideration. The first class comprises the dictionaries, in which almost all the progress in some branches of science can conveniently be summarized. Beilstein's "Handbook of Organic Chemistry" is a good example of the way in which almost all the facts of a science can be absorbed in a classified form and made available for ready reference. These dictionaries, in fact, represent the critical and discriminating summary of the scientific publications on the subjects with which they deal and the preparation of such dictionaries should be ensured by international cooperation of the national societies.

Other sciences, however, do not by their nature lend themselves to the convenient preparation of dictionaries and what is wanted in this case are critical and well arranged handbooks covering the whole science and resuming impartially but critically the various additions which are made from time to time in the different branches of the subject. These handbooks as well as the dictionaries would, of course, require the addition of supplementary volumes from time to time and occasional complete revision.

The preparation of both dictionaries and handbooks would, of course, be greatly facilitated by the existence of a numerically classified card index to the literature concerned, and the preparation and revision of such books might well be undertaken in connection with the large libraries having in their possession the complete classified card indexes.

On the other hand, for the assistance of advanced students of science, what is required is a steady supply of monographs correlating critically and comprehensively all the literature in a special field, and these must be brought up-to-date from time to time. Such monographs are especially required in connection with rapidly developing new branches of science; it is difficult to overestimate the importance and value for progress in research of such a book as Bragg's "X-Rays and Crystal Structure" for instance, and while nothing should be done to hinder individual initiative in publishing such books, it would seem that when it was apparent that some branch of science required such a monograph a national society might very well approach well-known workers in the field and request them to write such a book, offering its assistance in the matter of bibliography and also offering to arrange for the publication of the manuscript. The initiative in indicating the need for such a book might come in the form of suggestions from members of the society or other scientific men. It is quite true that at the present time the scientific publishers are extremely active in searching for suitable books to publish, but necessarily they must consider the probable demand rather than the actual need for a book, and this leads to an over-production of books dealing with those fields of science which have a large following and an insufficient supply of books in those fields where the workers are few, though for progress the more sparsely worked fields would seem to require almost as much representation in literature as those which are of wider interest.

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October 26, 1917

THE DEPARTMENT OF AGRICULTURE AND THE FOOD SITUATION[1]

According to the calendar it is almost a year to the day since my last meeting with you. Judged by the experiences through which we have passed, it seems more like a generation. Then this country was at peace, though its patience was being sorely tried. Now it is at war for reasons which I need not discuss before this body. It had no alternative. It either had to fight or to admit that it had no honor, was not a free nation, and would henceforth be subjected to a medieval power that in the last analysis knows no law but might. The nation was living on a peace basis and was not fully prepared for war in any respect; but it was fortunately circumstanced in the character of its agricultural organization and the number and efficiency of its expert agencies.

The nation may well pride itself on the fact that it had had the foresight generations ago to lay deep its agricultural foundations. I congratulate the representatives of the land grant colleges on the fine opportunity for service presented to them and on the splendid way in which they have seized it. The Department of Agriculture has had great comfort in the thought that these institutions, ably planned and wisely directed, existed in every part of the nation and stood ready not only to place themselves at the service of the national government but also to take the initiative in a vast number of directions.

When a state of war was declared on April 6, the food situation was unsatisfactory. The need of action was urgent and the appeal for direction was insistent. The nation looked for guidance primarily to the federal department and to the state agencies which it had so liberally supported for many generations. It was not disappointed. In a two-days' session at St. Louis, the trained agricultural officers of the country conceived and devised a program of legislation, organization and practise the essential features of which have not been successfully questioned and the substantial part of which has been enacted into law and set in operation. This great democracy revealed its inherent strength.

To the normal forces of the government leading with agriculture and rural problems there has been added an emergency agency with great and unusual powers, with enormous possibilities for good, and with a remark-

[1] From an address given by Secretary of Agriculture Houston, addressing the Thirty-first Annual Convention of the Association of American Agricultural Colleges and Experimental Stations in Washington on November 14.