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A PHOTOGRAPHIC RESEARCH LABORATORY[1]

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THE research laboratory of the Eastman Kodak Company was established in 1912 to study the problems involved in the production and use of photographic materials.

Photographic research occupies a somewhat unique position in the field of applied science both because photography is so much used in other scientific work that interest in it is very widespread and because the methods of photographic research are so different from those of all other branches of scientific work that it is rare for the professional scientific man to understand them.

Very little work on the theory of photography has been done in the universities and there are perhaps three reasons for this: In the first place, information with regard to the theory of photography is not easy to obtain; there are few books on the subject and these deal generally with only a limited part of the field, and the original papers to which recourse must be had for information are scattered through a wide range of photographic and other journals. In the second place, work on the theory of photography necessarily involves work with photographic materials, and these materials are now made entirely by manufacturing companies, the methods of manufacture not being disclosed, so that the actual nature of the photographic materials themselves is but little understood by the user of them. In the third place, the apparatus required for photographic research is very specialized and somewhat expensive.

Our knowledge of photographic theory we owe chiefly to enthusiastic amateur photographers, supplemented in recent

[1] Being a paper read before the American Physical Society at the Rochester meeting.

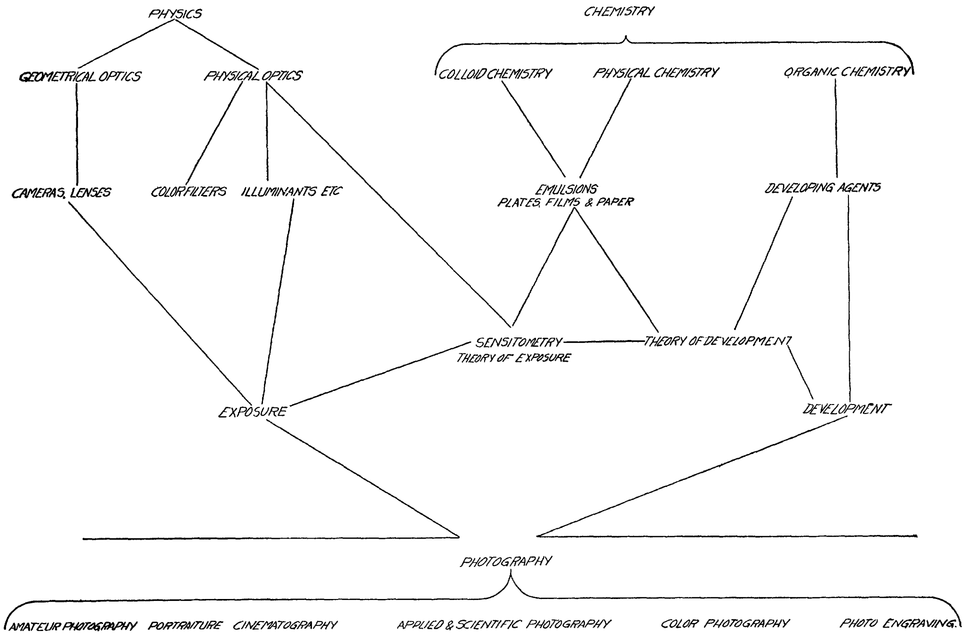

FIG. 1.

years by the research done by the photographic manufacturing firms, and it was in order to produce a considerable increase in the amount of this specialized photographic research work that the Eastman Kodak Company established its research laboratory.

The work of the laboratory deals, of course, not only with the theory of photography but with many points of practical importance both in the manufacture of photographic materials and apparatus and in their use, and the laboratory is divided into different sections corresponding to the general divisions of science, notably physics, chemistry and practical photography, the workers in these divisions collaborating in investigation of the problems with which the laboratory is concerned.

The branches of science which are of chief importance in photographic problems are those of optics in physics and of the colloid, physical and organic divisions of chemistry, and Fig. 1 represents an attempt to show the relations of these branches of science to photography.

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 of 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 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 therefore 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 shown in Fig. 2. There will be physical departments, dealing

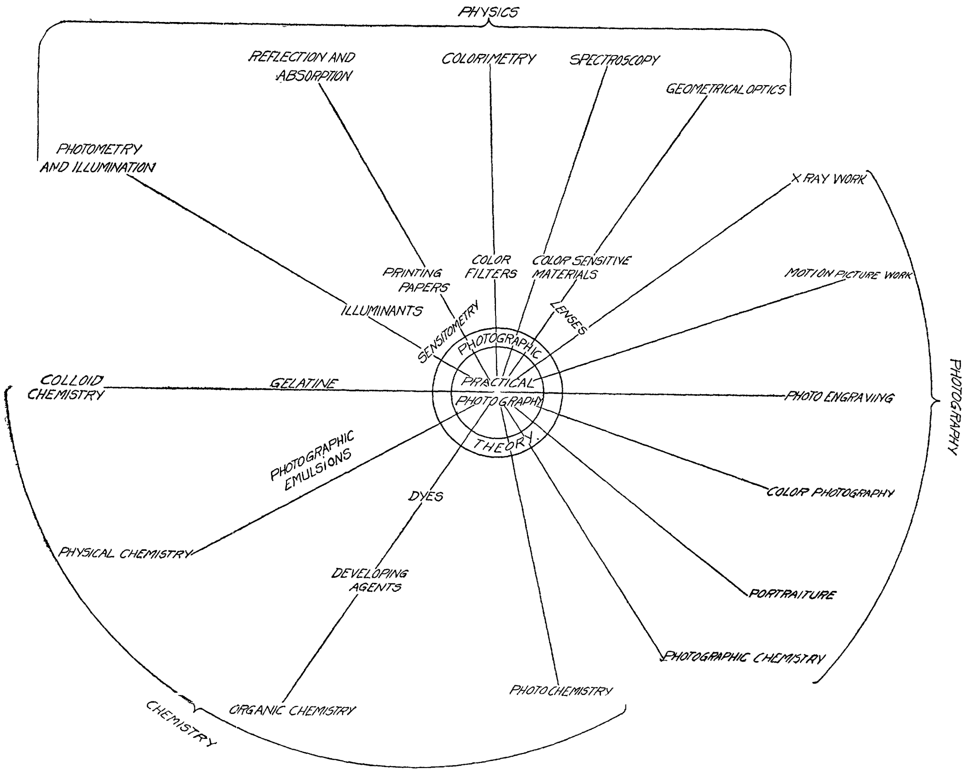

FIG. 2.

with sensitometry and illumination, reflection and absorption, colorimetry, spectroscopy and geometrical optics. There will be 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 a 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 the results obtained in all these departments will be applied first to the theory and then to the practise of photography.

In order to concentrate the different departments of the laboratory upon the photographic problems that arise and to ensure that on each problem the full knowledge and experience of the different specialists is made available, the main lines of work under investigation are discussed at a morning conference at the beginning of the day's work, one day of the week being assigned to each special subject, so that on Monday, for instance, those doing work in relation to one subject meet; on Tuesday the same men or other workers discuss a second aspect of the work of the laboratory, and so on. The laboratory organization, then, resolves itself into these several groups,

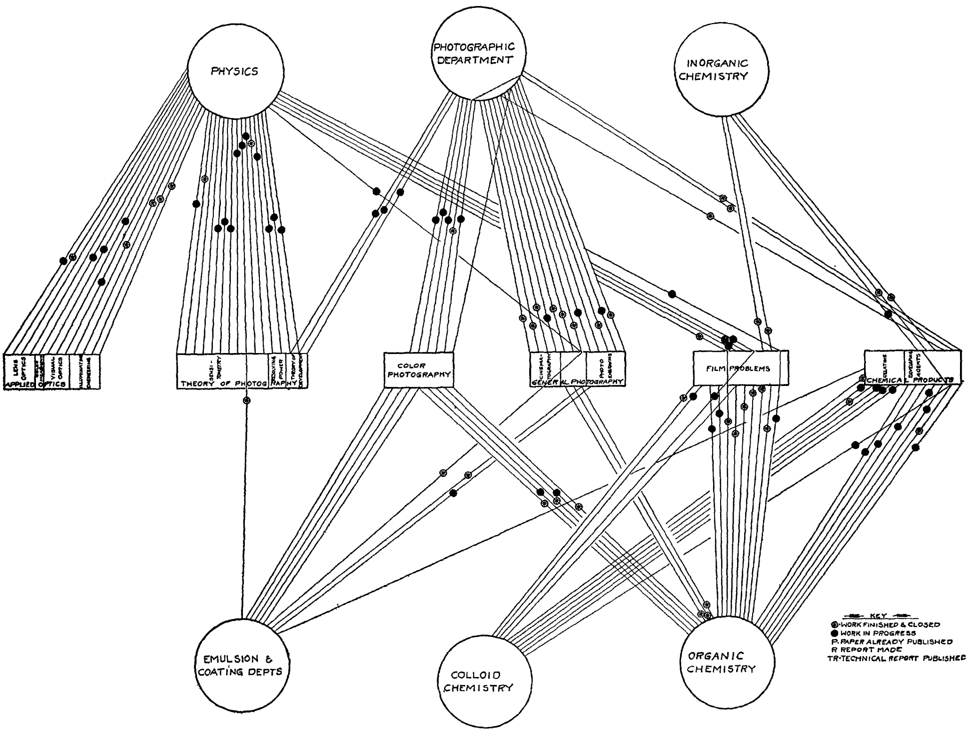

FIG. 3.

interlocked by their common members, who are dealing with a number of different lines of work.

The total work of the laboratory during the year may be represented by Fig. 3.

The departments of the laboratory are represented as circles on the outside of the chart, the main divisions in which problems group themselves being represented by the rectangles, subdivided in some instances, occupying the middle of the chart. Each of these rectangles corresponds to a morning conference; thus on Thursday mornings a conference is held on general photography, at which there are present members of the photographic department, the physics department, and the emulsion and coating or manufacturing departments. There is present at the conference, in fact, every scientific worker of the laboratory, whatever his rank, who is directly engaged on the subjects which are included under the head of general photography, and in some cases, or on special occasions, members of the staff of the company external to the laboratory are invited to these conferences, although it is not possible for many of them to be regularly present. All the main lines of investigation are laid down at these conferences and the progress from week to week carefully discussed. By the use of this system full cooperation and concentration of the different sections of the laboratory upon the problems to study which it has been founded is ensured.

Since the establishment of the laboratory, which was completed in 1913, a good deal of work has been finished and the foundations laid for much further research which can now be considered to be planned and arranged.

The work of the laboratory is published in the form of scientific papers, these being printed in the usual technical journals to which the special subject of the paper may be appropriate, and then at intervals, as sufficient papers accumulate, full abstracts of all the papers are collected and published in a volume under the title of "Abridged Scientific Publications." At the time of writing, October, 1917, about 65 papers have been completed.

The scientific work of the laboratory can be classified under the headings of the physics of photography, the chemistry of photography, the reproduction of tone values by photography, and work on special photographic processes, including those required for photography in natural colors. In addition to this a considerable amount of research has been done in pure chemistry and in the various branches of applied optics which are closely allied to photography.

THE PHYSICS OF PHOTOGRAPHY

Photographic sensitive surfaces do not consist of continuous coherent films of homogeneous material but have a definite granular structure, the sensitive material itself consisting of grains embedded in an insensitive matrix, so that in considering the properties of a sensitive photographic material we are considering really the properties of a collection of sensitive grains, which may differ considerably from each other in their individual properties. The properties of such a collection will be the statistical average of the individuals composing it and in order to understand the properties of a sensitive material we must therefore consider the properties of the individual grains and their relation to the aggregate material of which they are units.

The question at once arises: Do these grains consist of crystals of pure silver halide or of a gelatine silver complex? Microscopical study shows it to be probable that the grain is a pure silver halide crystal, for when these crystals are exposed to the action of water no swelling at all is observable even under the highest power of the microscope. The grains of silver bromide prove to be regular semi-transparent crystals belonging to the isometric system, occurring chiefly in triangular and hexagonal tablets and in needles of various thick-

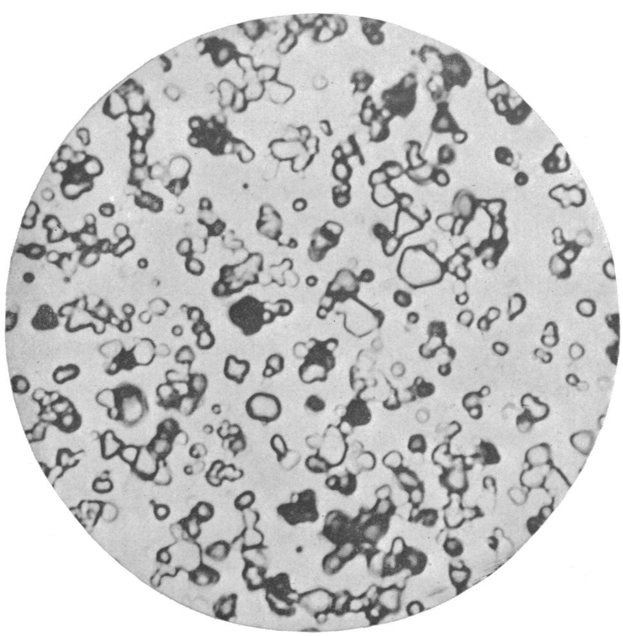

FIG. 4. PHOTOMICROGRAPH SHOWING SILVER BROMIDE CRYSTALS IN PHOTOGRAPHIC EMULSION.

nesses, these needles being formed in the same way as the tablets (see Fig. 4). As they occur in a gelatine emulsion, these grains are doubly refracting, though this would not have been expected from their crystalline form (see Fig. 5). Silver

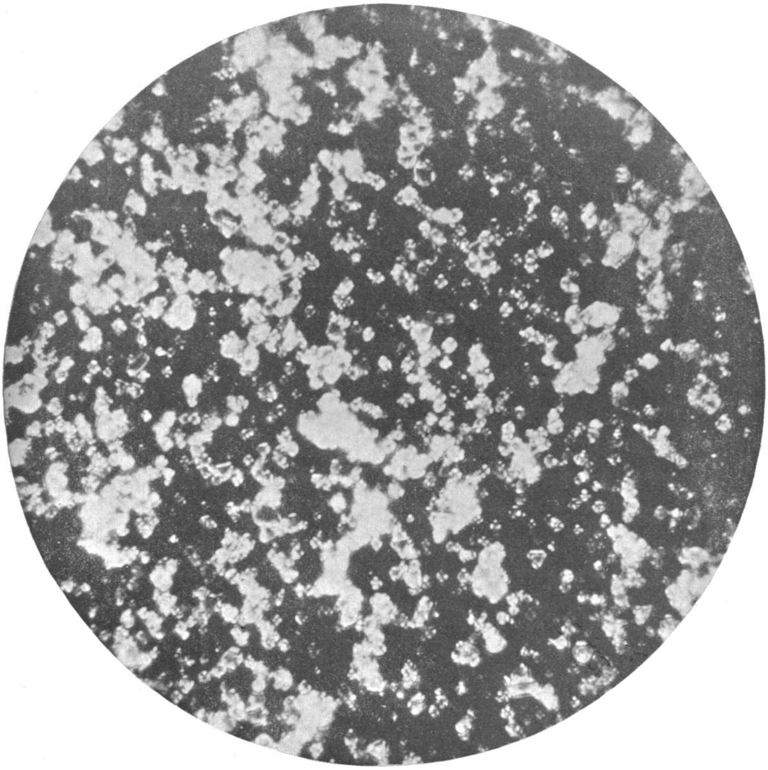

FIG. 5. PHOTOMICROGRAPH OF CRYSTALS OF SILVER BROMIDE BY POLARIZED LIGHT SHOWING DOUBLE REFRACTION

bromide can be crystallized out from its solution in ammonia to show all the forms in which it occurs in emulsions, and the physical chemistry of the preparation of these crystalline grains is under investigation in the laboratory at the present time.

When the silver halide grains are developed, the crystalline form is lost, the silver being deposited in a sponge-form in soot-like particles, the form of the deposit being generally considerably distorted from the original shape of the silver bromide crystal grain, though in some cases the original shape is fairly well reproduced in the deposit of metallic silver.

In viewing a negative by transmitted light we can not, of course, see these isolated grains with the naked eye but we see a conglomeration caused by the penetration of light through the interstices between the grains distributed throughout the emulsion layer, and thus we obtain regular large patches or chains of grain, the pattern and regularity depending upon the particular type of emulsion used. This granularity, the formation of which can be studied by the examination of a vertical section through the film, is what is meant by the "graininess" of photographic negatives in general and is the grain met with in enlarging, in projection, and in portraiture.

The granular structure of a photographic emulsion involves a limit to the resolving power of the emulsion; that is, it requires a certain finite distance between two points of light falling upon the film in order that they may record themselves as separate deposits of silver grains. The study of the resolving power of a photographic emulsion can be accomplished by the examination of the spread of the edge of an image. Suppose, for instance, that we lay upon a photographic film a knife edge and then illuminate this knife edge vertically from above; some of the light passing the knife edge will be scattered into the shadow by reflection from the grains of silver bromide and will produce developable grains within the shadow so that upon development we shall obtain a distinct extension of the image beyond the edge into the shadow. If we determine the relation between the number of grains rendered developable and the distance from the edge, we shall have a relation which will depend upon the scattering of the light by the silver bromide grains and upon the absorption of that light by the grains. These two factors we might term the "turbidity" and "opacity" of the emulsion.

An emulsion having high turbidity and low opacity will have a very low resolving power. On the other hand, even if the emulsion has high turbidity, if its opacity is also high, the resolving power may be good. A typical example of this is the wet collodion plate, in which the turbidity is considerable but the opacity of the silver iodide for blue-violet light is so great that the resolving power is high. In the grainless Lippmann emulsion the resolving power is high if the emulsion is very clear, because the turbidity is very small, but the opacity is also small so that the slightest increase in turbidity may make the resolving power very low.

A convenient way of measuring resolving power is to photograph a converging grating, observing the point in the photograph at which resolution first occurs, from which a numerical measurement of the resolving power can be obtained.

The importance of photographic resolving power in relation to many branches of scientific work and especially spectroscopy and astronomy is obvious, and much work is being done in the laboratory upon these applications.

Of course, the fundamental problem in the physics of photography is the effect of the light on the film itself; that is to say, the change which occurs in a grain of silver bromide when it is exposed to light that makes it developable. It is extremely difficult to attack this directly, and the only possibility of evidence which we have been able to get is a statistical calculation by Dr. Nutting as to the amount of light which will produce a developable grain of silver bromide. Consider the exposure to light which is sufficient after full development to produce a deposit of unit density, that is, one which will transmit one tenth of the incident light.

A deposit which has this density contains 10 milligrams of metallic silver per square decimeter, or one tenth milligram per square centimeter, which represents roughly 10^{19} molecules of silver, or 10^{7} grains $3\,\mu$ in diameter. Now, the energy of the amount of violet light required to give an exposure necessary to make en emulsion film developable to this density is of the order of 10^{-7} ergs per square centimeter. Therefore, each grain (which contains on the average 10^{12} molecules) receives 10^{-14} ergs to make it developable. We know that in order to detach one electron from a molecule, 5×10^{-12} ergs are required in a gas; but this is a maximum amount and it is possible that in the exposure of a photographic plate 10^{-14} ergs are sufficient to detach one electron. Clearly, then, the energy incident on a grain during exposure may be sufficient to affect only one molecule in that grain, and the latent image may be composed of grains in each of which, on the average, only one molecule has lost an electron by the action of light.

The Chemistry of Photography

While the grain structure of the emulsion and its reaction to light must be considered a branch of physics, the development of the emulsion is certainly closely related to physical chemistry. One of the most interesting pieces of work in the laboratory has been the study of the photographic developers in relation to their behavior in the development of the latent image, and the relation of the constitution of the many compounds possible to their properties is being attacked in the laboratory by the collaboration of the department of organic chemistry, which prepares the compounds in question, and of a special laboratory which deals with the physical chemistry of developers. In this laboratory the developers are examined both by their action upon the photographic emulsion and also by the recognized methods of physical chemistry. The most fundamental property of a developing agent is its reduction potential, and this should apparently be measurable electrically by comparing the electromotive force produced on a platinized cathode immersed in the developing agent with the potential of an electrode charged with gaseous hydrogen.

The rate of development is dependent on two factors: first, on the rate of the chemical reaction itself; that is, on the solution of silver bromide, its conversion into metallic silver, and the precipitation of the metallic silver in a solid form; and, secondly, on the rate of diffusion of the developer to the silver bromide grain and of the products of development away from the grain. The second of these factors has by far the greater influence in settling the rate of development, though the time of first appearance of the image appears to be dependent chiefly upon the rate at which the developer attacks the silver bromide grain. It is in the rate of attack on the silver bromide grain that the reduction potential plays so great a part, but this rate of attack under ordinary conditions is limited by the rate of solution of the silver bromide, and a developer does not attack the silver bromide grain proportionally faster by reason of an increased reduction potential.

The reduction potential of a developer, in fact, may be compared to the horse power of an automobile, which for other reasons than the power of its engine is limited in speed. If we have two automobiles and they are confined to a maximum speed of twenty miles an hour, then on flat roads the one with the more powerful engine may be no faster than the weaker, but in a high wind or on a more hilly road the more powerful engine will allow the automobile to keep its speed, while with a weaker engine the speed would fall off; we can, indeed, measure the horse power of an automobile by the maximum grade which it can climb at a uniform speed. In development the analogy to the hill is the addition of bromide to the developer, since the addition of bromide, by the lowering of the solubility of the silver bromide, greatly delays the chemical reaction in development, and the higher the reduction potential of a developer, the more bromide is required to produce a given lowering of the density, so that we can measure the reduction potential by the amount of bromide required to produce a given effect. If we measure the common developers in this way, we shall find that glycin has the lowest reduction potential, then hydrochinon, then pyro and paraminophenol, and finally elon and diamidophenol have the highest.

THE REPRODUCTION OF TONE VALUES

The aim of photography is to reproduce in the print the scale of light intensities which occurs in the original subject, and the study of the way in which a scale of brightnesses is reproduced in the photographic process from the original subject through the negative to the print is necessarily the main study of a photographic research laboratory.

There are four separate sections involved in this investigation: first, the study of the range of brightnesses occurring in natural objects such as one is required to photograph; second, the study of the way in which the photographic emulsion translates a scale of light intensities into deposits of metallic silver in the negative; third, the study of the properties of photographic printing papers and the relation of the reflecting power of the deposits obtained in them to the scale of light intensities to which they were exposed; and, fourth, the study of the accuracy with which the tone values of the original are rendered through the negative on to the printing paper.

Until recently the scale of rendering of the negative material itself was all that had been fully investigated. This was done by Hurter and Driffield in their famous photo-chemical investigation published in 1890, in which they measured the relation between the exposure of the sensitive material to light and the optical density produced. This density they defined as being the logarithm of the reciprocal of the transparency, and

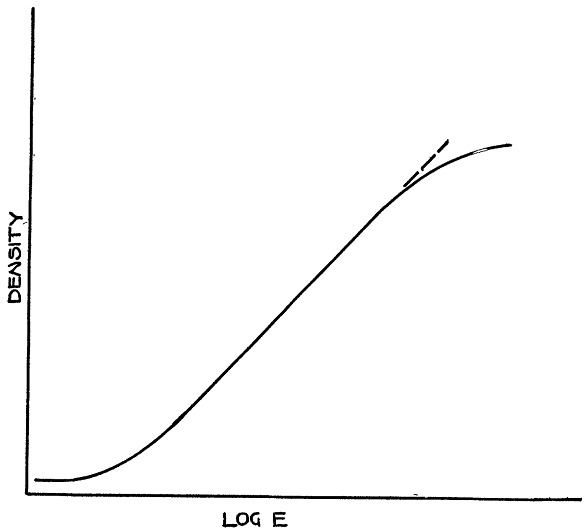

FIG. 6. CHARACTERISTIC CURVE OF PHOTOGRAPHIC PLATE SHOWING DENSITY EXPOSURE RELATIONS.

they found that it was proportional to the mass of silver per unit area. In their curves they plotted the density against the logarithm of the exposure, thus obtaining a curve which for the greater portion of its length is a straight line, though at the beginning and the end it departs from the straight line law (Fig. 6). It is only where the curve is a straight line that correct translation of the light intensities of the original into the density of the negative occurs. The study of these relations is what is known as "sensitometry" and forms a large part of photographic investigation in itself.

Much work has been done in the laboratory on the effect of development on the rendering of tone values in the negative and especially of development in those solutions which produce a somewhat colored image. If a negative be developed with pyrogallic acid the image produced is of a yellowish color, and it has a very different contrast when printed on the usual violet-sensitive photographic materials to that which is obtained when it is measured optically by means of the eye. The study of the relation of the photographic to the visual density of such images has in itself involved a very considerable amount of investigation.

In order to render possible the study of the reproduction occurring in photography an investigation of the sensitometry of papers was necessary.

In the first place, an instrument was designed by means of which the light reflected from small areas of the exposed print could be measured. Papers were then exposed for known periods of time, developed, the reflecting power of the developed image measured and curves plotted of the logarithm of the reciprocal of the reflecting power against the logarithm of the exposure. Several constants were found to express the behavior of photographic papers; thus, any paper had a maximum density, that is a minimum reflecting power representing the deepest black which could be obtained upon it. It showed also a typical scale or total range of exposures through which any difference could be obtained with an alteration of exposure. Again, the straight line portion of the curve showed a definite steepness or "gamma," as we call it, and finally the length of the straight line portion is of great importance, since it is only throughout this straight line portion that exact reproduction can be obtained (Fig. 7).

As a result of the work which has been done we are now able to give a complete solution for the translation of the scale of tone values of an original subject through the negative on to the printing paper, showing how far the light reflected from the deposits in the print will correspond to the brightness existing in the original subject, and finding the effect of alterations in either the negative-making material or in the printing medium on the accuracy of the reproduction, as well as the effect of differences of development and exposure. A series of papers dealing with the whole subject of tone reproduction is in preparation at the present time.

Other branches of sensitometry are under investigation in the laboratory: thus, we have made a very careful study of the effect upon the sensitiveness of the photographic material of the variation of the wave length of the light to which it is ex-

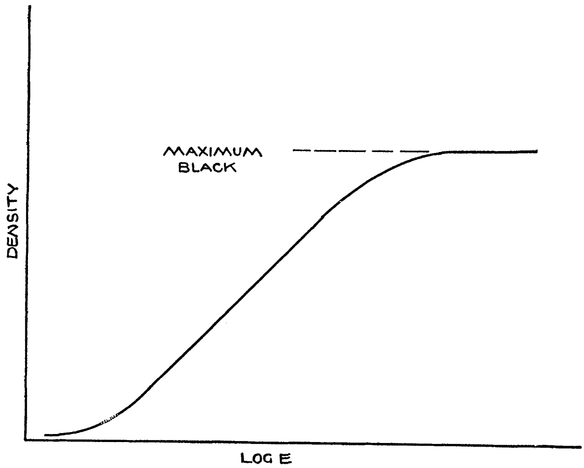

FIG. 7. CHARACTERISTIC CURVE OF PHOTOGRAPHIC PAPER SHOWING DENSITY-EXPOSURE RELATIONS.

posed, and for this purpose have constructed a special wavelength sensitometer with which a number of different materials have been investigated throughout their entire range of sensitiveness.

The study of the sensitiveness of photographic materials towards the X-rays is of considerable importance and for this purpose we have built special sensitometers for radiographic work. In the older types of sensitometers the exposure was graduated by means of a rotating disk from which sectors of varying angle were cut out, but it is known that the intermittent exposures given by such an arrangement do not integrate correctly, the density produced by a number of small exposures being less than that produced by the corresponding exposures impressed continuously. In X-ray work, moreover, there is a danger of stroboscopic effects produced by the rotating sector getting in phase with the X-ray generator, which delivers a pulsating current, and there has therefore been designed in the laboratory a new type of non-intermittent sensitometer in which the exposures are given automatically and continuously, and this has proved very useful for many kinds of work and especially for radiographic sensitometry.

Practical Photography

Naturally, a great portion of the work of the laboratory is concerned with photographic processes and work on all kinds of photographic processes is continually in progress. It is difficult to summarize this work in any brief form, but the work which is being done on color photography is perhaps especially worthy of note.

There are two main divisions of the practical processes of color photography: the processes which are known as "additive," in which the colors are produced by the superposition upon a projection screen or in the eye of beams of the primary colors, and the "subtractive" processes in which negatives taken through the primary filters are printed in colors complementary to those filters and these prints are then superposed.

Most of the work of the laboratory has dealt with the subtractive processes, though a good deal of research work has been done upon the filters required for the additive processes and upon such subjects as the color of mixtures of two nearly complementary colors, work which is of considerable interest in connection with the two color additive processes.

In work on the subtractive process of color photography some interesting results have been achieved in the photomicrography of stained sections, a two-color process having been developed which gives very good results for this purpose. The two-color subtractive process of color photography has also been applied to motion picture work, the pictures being made by using film coated on both sides with a sensitive emulsion, so that negatives taken through the red and green filters can be impressed in register on opposite sides of this double-coated film and then the double images after development can be transformed into dye images complementary in color to the filters through which the negatives were taken. In this way each picture on the film consists of two pictures of complementary colors which give the effect of a two-color subtractive picture. This process, of course, has the great advantage that film so made is suitable for projection in any ordinary motion-picture machine.

Applied Optics

Owing to the great importance of applied optics in all photographic work the physics department of the laboratory has done a good deal of research in relation to this subject.

One branch of applied optics which has not previously received the attention which it seems to deserve is the study of the sensitiveness of the eye to light, and since the sensitometry of the eye is comparable in many respects to that of photographic materials a special series of investigations have been made on this subject in the laboratory as a result of which we have obtained new data with regard to the change of sensitiveness of the eye with different levels of brightness and to the rate of adaptation of the eye when the illumination is changed. A very recent piece of work deals with the change in size of the pupil with the brightness.

In pure applied optics a number of studies have dealt with the reflection and transmission of light by diffusing media and with photometry and brightness measurements, the laboratory being especially well equipped to study absorption photometry both with and without a consideration of color. The study of color in all its branches has occupied a large part of the activities of the physics department. Thus, measurements have been made on the sensibility of the eye to color and to change of hue, and a number of investigations have been made on the use of the monochromatic colorimeter in the quantitative expression of color.

Light filters are of great importance in photography, and the manufacture of light filters for all purposes was commenced with the establishment of the laboratory and has been continued as one of the manufacturing activities of the laboratory since. Over one hundred differently colored light filters are made, including filters applicable to all branches of scientific work. Special filters are made for microscopy, spectroscopy, photometry, etc. The measurement on the spectro-photometer of the absorption curves, both of these filters, and of the organic dyestuffs from which they are prepared, has been a subject of a considerable amount of study, and many interesting results have been obtained both in the visible spectrum and in the ultra-violet.

The work done in the laboratory up to the present time is really, of course, initial work, since the laboratory has only been in active operation for four years, but it is possible already to see the tendency of the work of the laboratory to converge more and more closely upon the purely photographic problems which present an ample field for the entire energy of the laboratory and it is probable that the output of work on photographic questions will steadily increase as more experience is accumulated in the handling of the problems involved.

In addition to the scientific work of the laboratory on the theory of photography, which is referred to in this paper, a great number of industrial questions and works' problems are, of course, referred to the research laboratory, and it has been found that an organization arrànged for the study of the fundamental problems of the theory of photography is well suited to taking care of these works problems and practical questions as they arise, each problem being assigned to the specialist who appears best fitted to deal with it, and it is understood by all the men in the laboratory that a certain part of their time will necessarily be devoted to the study of problems originating in the commercial and manufacturing departments of the company.