PHOTOGRAPHIC REPRODUCTION OF TONE

BY

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The ideal pictorial representation of any object or group of objects is one that produces when viewed by the observer exactly the same visual sensations as are produced when the objects themselves act as the source of visual excitation. The problem of finding how closely this ideal may be approached in practice has engaged the attention of workers in the field of photography for many years, and is commonly referred to as the problem of "tone reproduction." There are many phases of the subject to be considered, and a complete treatment requires a careful analysis of the factors upon which depends the operation of our visual perception of space and spatial relations. A complete analysis, therefore, leads not only into the realm of physical science, but also into those of psychology and philosophy. A careful consideration of these factors leads to the conclusion that brightness and brightness difference, that is, contrast, are by far the most important of those which are reproducible by the photographic process.

It is found in nature that different degrees of brightness or tones, as they are frequently called, are produced either by variation in the reflecting power of surfaces subject to the same illumination or by variation in the illumination incident upon various parts of the surface having uniform reflecting power. Visibility, normally, is due to differences either in the color or brightness of the various objects occupying the field of vision. Since, however, a photographic process does not in general reproduce color, it may be said that photographic visibility is due entirely to brightness differences. The proper reproduction of these differences, therefore, is of pre-eminent importance and it is with this brightness factor and the possibility of its correct reproduction by the photographic process that this paper deals.

The problem of tone reproduction has frequently been regarded as requiring only the correct reproduction of the actual physical

brightness and brightness difference. When it is considered, however, that a given brightness or contrast may produce an entirely different subjective impression, depending upon the state of adaptation of the observer's eye, it is obvious that such a treatment of the subject cannot afford a complete solution of the problem. The problem may, in fact, be divided into two general parts, the one which we term the objective phase dealing with the reproduction of the actual physical brightnesses and contrasts, capable of being completely solved by purely physical methods. The other, which may be termed the subjective phase, includes a consideration of those factors which determine the nature of the subjective impressions produced by the action of given physical stimuli under various conditions and requiring the use of psychophysical methods and data for its adequate treatment.

Hurter and Driffeld,¹ who may be considered as the founders of the science of photographic sensitometry, treated this subject to some extent, but confined themselves to a consideration of the objective phase. Lord Rayleigh² also has treated, although rather briefly, the objective phase of the subject. F. F. Renwick has made valuable contributions to the solution of this problem at various times, dealing in particular with the brightness reproduction possible when using the region of underexposure,³ and later presenting a more complete treatment of the entire subject both from the objective and subjective viewpoints.⁴

Recently A. W. Porter and R. E. Slade⁵ have published a paper on the subject in which they take exception to some of the conclusions reached by Hurter and Driffeld and outline the relations which they consider essential for the solution of the problem. They also deal only with the objective phase, the reproduction of the actual physical factors. Following this, two short papers of a somewhat controversial nature dealing with special cases of the tone reproduction problems have appeared, one by

¹ Jour. Soc. Chem. Ind., May, 1890, and Feb. 1891, and B. J. 1894, p. 417.

² Phil. Mag. Vol. 22 (1911) p. 734.

³ Phot. Jour. Vol. 36 (1913), p. 127.

⁴ Phot. Jour. Vol. 40 (1916), p. 222.

⁵ Phil. Mag. Vol. 38 (1919), p. 187.

F. F. Renwick⁶ and the other by Messrs. Porter and Slade.⁷ Finally Mr. Renwick⁸ has published a paper in which he gives in detail the method by which he obtained the results previously published (*loc. cit.*) relative to the objective phase of the subject. His conclusions are in substantial agreement with those arrived at in the following treatment of the subject although a quite different graphic construction was used.

During the past five years a large amount of work has been done in this laboratory on the theory of tone reproduction, and a satisfactory solution for the objective phase was obtained some two or three years ago. Simultaneously with the work on tone reproduction, research in the field of visual sensitometry has been in progress, which has resulted in data applicable to the solution of the subjective phase of the more general tone reproduction problem.

While some particular details of the subjective data are still lacking, it is felt that sufficient information is now available to establish the general nature of the function necessary for the conversion of objective reproduction into its subjective equivalent. In the meantime further work is being carried out in order to make possible a more precise quantitative evaluation of this function.

SIMPLIFYING ASSUMPTION

In order to simplify the subject and bring it within the limits of a single paper, it will be necessary to make certain simplifying assumptions. Since the sensitivity of the photographic plate to radiation of different wave-lengths is in general radically different from that of the eye, objects in which color is present have not in general the same brightness when considered from the visual standpoint as when the evaluation is in terms of the photographic plate.

Let us, therefore, assume that all areas of the object considered are both visually and photographically non-selective (i.e., colorless), and further that the optical system forming the image

⁶ Phil. Mag. 38: 637, 1919.

⁷ Phil. Mag. 38: 637, 1919.

⁸ Phil. Mag. 38: 151, 1920.

of the object on the negative material is likewise non-selective. Under such conditions values of visual brightness are directly proportional to those of photographic brightness. Thus this treatment will deal with brightness relations uncomplicated by any consideration of selectivity. Let us further assume that all photographic deposits considered are also non-selective in order that visual and photographic density values may also be considered as identical.

THE CYCLE OF TONE REPRODUCTION

In Figure 1 is given a graphic diagram, which although it may be somewhat fanciful will convey a more concrete idea of the problem than a mere verbal statement of the case.

FIG. 1

Graphic Diagram of the Cycle of Tone Reproduction

For the purpose of discussion it is found convenient to divide the cycle into ten distinct steps and these are designated by the Roman numerals enclosed in the small circles.

The first phase, indicated by I, is the subjective object which is defined as the subjective impression existing in the brain of the observer and resulting from the action of the retinal image of the object (II) considered. This subjective impression may be

considered as the fundamental starting point in all tone reproduction problems, and is the thing which is to be reproduced.

The second phase is the object itself represented by the black cross, (II). While it may be convenient in some cases to interpolate one or more distinct steps between this actual physical object and the subjective impression due to this observation, such intermediate steps are unnecessary in the present discussion.

The third phase (III) is the image of the object formed on the negative sensitive material by some type of image forming system. This image when allowed to act through some finite period of time, t_x , produces upon the negative sensitive materials an exposure (IV) indicated in the diagram by the shaded cross. The exposed material is then subjected to various chemical operations such as development, fixing, washing, etc., the result being the fifth step in our cycle, the negative (V). The image (VI) of this negative is then formed either by contact or projection upon the positive sensitive material and forms the sixth step in the series. This image acting during a period of time, t_y , results in an exposure (VII) on the positive material which after development, fixing, or similar chemical processes is converted into a positive (VIII) the eighth step in the cycle. When the positive thus produced is illuminated it becomes the material reproduction (IX), and a comparison of the characteristics of this material reproduction with those of the object constitutes a complete solution of the tone reproduction problem from the objective standpoint. An image of this object is formed on the retina of the observer and creates in his mind an impression which we shall designate as the subjective reproduction (X) the last step in the cycle of tone reproduction. The evaluation of this subjective reproduction in terms of the subjective object constitutes a complete solution on the tone reproduction problem from both the objective and subjective viewpoints. In practice it may be more convenient to consider the object (II) as the starting point of the cycle and to express finally the characteristics of the subjective reproduction evaluated in terms of the subjective object as a function of the characteristics of the object itself. This follows largely from the fact that it is possible to measure directly by ordinary

physical means the essential characteristics of the object while the characteristics of the subjective object must be deduced in an indirect manner from the knowledge of the characteristics of the object itself and of the condition of the observer's eye at the time considered.

In Fig. 2 is given a schematic diagram somewhat analogous in structure to the graphic diagram in Fig. 1, but expanded so as to include not only a statement of the nature of each phase of the problem but also the particular data necessary for the specifica-

FIG. 2

Schematic Diagram of the Cycle of Tone Reproduction

tion of each phase and the factors required for the transformation of the data relative to one phase into that relating to each of the contiguous phases.

In the small circles designated by the Roman numerals from I to X are the designations of the ten steps in the process corresponding to the graphic diagram of Fig. 1. The radial line extend-

ing outward from each of these circles connects with the enclosure in which is a statement of the essential characteristic or attribute which from the standpoint of this problem completely specifies the particular phase considered. For instance, in the case of the object (II) the essential data relative to this phase are the values of the brightness, B_o , of the various areas, while in the case of the negative, complete specification of its characteristics is given by values of density, D_n or transmission, T_n . In the approximately rectangular enclosures marked, A, B, C, etc., are given the transformation factors required for converting the data relative to one phase into that of the next. For instance, if the brightness values, B_o , of the various areas of the object be known and it is desired to compute the illumination of the image formed on the negative sensitive material, such computation can be carried out if the value of K_x the constant of the image forming system is known. Likewise illumination may be converted into exposure by the transformation factor t_x , the exposure time. A careful study of Fig. 2 will convey an excellent idea as to the various factors which must be considered in the treatment of this problem. The final comparison between I and X as indicated

TABLE 1

Part I. "Things"

	Symbol
1 Subjective Object	S O
2 Object	O
3 Negative Sensitive Material	X
4 Negative	N
5 Positive Sensitive Material	Y
6 Positive	P
7 Material Reproduction	M R
8 Subjective Reproduction	S R

Part II. "Characteristics"

1 Radiant Flux	F
2 Illumination	I
3 Brightness	B
4 Reflection Coefficient	R
5 Transmission Coefficient	T
6 Exposure	E
7 Time	t
8 Density (Optical)	D
9 Adaptation Level	A

at the top of the diagram gives the desired information relative to the quality of tone reproduction obtained in any specific case.

TERMINOLOGY AND SYMBOLS

Since the problem to be treated involves so many operations, materials and inter-relations, it is very necessary to adopt at the outset a logical system of terminology and symbols. The essential factors belonging to what we may term the *thing* category are as shown in Part I, Table 1, the symbols adopted being as indicated in the symbol column. The essential *characteristics* or *attributes* descriptive of or applying to these things are given in Part II to Table 1 with the symbols adopted. When any characteristic applies to some particular factor in the thing category this is indicated by attaching the symbol of that thing as a subscript letter to the symbol of the characteristic in question. For instance, B_{mr} indicates the brightness of the material reproduction, while E_x should be read as the exposure on the negative sensitive material. This system of nomenclature, it will be noted, is applied in Fig. 2.

FIG. 3

Characteristic Curve of Negative Material

FIG. 4

Characteristic Curve of Positive Material

CHARACTERISTIC DATA

Some of the data necessary for the solution of this problem are contained in the characteristic curves of the photographic materials and of the retina. As illustrative of these important groups

of data, the characteristic curve of a typical negative material is given in Fig. 3. This contains the necessary information for the transformation of exposure into the resulting negative density. In Fig. 4 is given a typical example of the characteristic curve of the positive material, while in Fig. 9, which will be described in detail later, are given the curves of retinal sensitivity which enables an evaluation of the sensation resulting from the action of the physical stimulus to be made.

GRAPHIC SOLUTION

Having considered thus briefly the problem as a whole, the data necessary for the solution, and the separate steps in which

FIG. 5

Graphic Solution for the Objective Phase of Tone Reproduction

it can be conveniently divided, we will proceed to a consideration of how all the various factors may be combined in order to obtain the desired solution. In Fig. 5 is given a graphic solution of the objective phase of the problem.

This consists of a four quadrant diagram in which are plotted the characteristic curves of negative and positive materials and the curve resulting from a combination of these two which represents the quality of reproduction obtainable by the use of these materials and which we shall refer to as the reproduction curve. Along the line OX of the second quadrant is laid out a logarithmic scale on which may be plotted the brightness values of the various areas of the object considered. Below this scale is plotted the characteristic curve of the negative material, the ordinates being values of density and the abscissae values of log exposure. ($\log E_x$). This curve must be determined by sensitometric methods such that it is a true representation of the characteristics of the negative material when used under the conditions existing in the making of the negative. These conditions include those factors operative in transforming the latent into a real image, as well as the necessary physical conditions relative to quality and intensity of exposing radiation.

The curve A must be so placed in the horizontal direction as to include properly the various points on the $\log E_o$ scale which represent the brightness values of the various object areas. For instance, if the point a_o represent the brightness of the deepest shadow in the object considered, and it is desired to render this brightness by a just perceptible density in the negative, or by any particular density value the curve A is plotted in such position that a perpendicular dropped from the point a_o will cut the characteristic curve at the desired value of density (D_n). Now the characteristic curve B, of the positive material is plotted in quadrant III. The positions of the necessary co-ordinate scales are as indicated in the figure, that is, the scale of exposure, $\log E_y$, is established along the line X', X'Y, while the density scale is established on the line X'Y', Y'. This is equivalent to the characteristic curve as usually plotted but rotated through 90°. The absolute values on the $\log E_y$ scale must be so chosen that

when the characteristic curve is plotted it will occupy the proper position relative to the curve A in the first quadrant.

This position of curve B is determined by deciding what value of positive density is desired for the rendering of some chosen value of negative density. For instance, let it be required to render the highest brightness of the object by a just perceptible density on the positive. Curve B must then be so placed that a horizontal line through the point c_n (which we assume to be the negative density representing the highest light of the object) will cut the curve B at a just perceptible value of positive density (D'_p). Now if we take for example three points, a_o , b_o , c_o representing various brightnesses of the object and project them around as indicated by the dotted lines passing through these points on the $\log B_o$ scale, three corresponding points will be located on the line O, X' designated as a'_p , b'_p , c'_p . Now if on the line OX' a suitable logarithmic scale, $\log R_p$, be established

FIG. 6

Curve of Brightness Deviations

the values read at the points mentioned will give the relative reflecting power values of the areas in the positive by which the originally assumed object areas are rendered. Values read from the $\log R_p$ scale therefore determine the characteristics of the positive. Now this positive becomes a reproduction of the object only when illuminated. Along the line OX' (quadrant IV) is now

established another logarithmic scale ($\log B_{mr}$) related to the scale of R_p by a constant the value of which depends upon the illumination incident upon the positive. This scale having been properly located and the points projected across as indicated, the values of brightness in the reproduction may be directly determined. The relation between the values of brightness in the reproduction to those of brightness in the object determines the quality of objective reproduction obtained. In order to obtain a graphic representation of such reproduction quality it is only necessary to transfer the points located along the line OX' to the line OY . This is most conveniently accomplished by use of a dummy curve, C , in quadrant IV, which is a line passing through the origin at an angle of 45° to the X axis. The points on the line OX' are projected onto this dummy curve as indicated and thence onto the line OY falling at a_{mr} , b_{mr} , c_{mr} .

Now, the points a_x , b_x , c_x in quadrant I are located at the intersections of the dotted lines through the points a , b , and c , as indicated, and the curve drawn through these points constitutes the reproduction curve. The curve of exact reproduction of both brightness and contrast is a straight line, E , at 45° to the axis and passing through the point O' . The position of O' is again dependent upon the relation between the absolute values of the brightness of corresponding points of the object and material reproduction.

The distance between corresponding points, such as, for instance, a_o and a_x , on the curves E and D is a measure of the magnitude of the departure from exact reproduction of brightness of the object area considered, in this case, a_o . If, therefore, these values be determined for the various object areas such as a_o , b_o , and c_o and plotted as ordinates at the proper point on the $\log B_o$ scale a curve will be obtained which is a graphic representation of the departure from exact reproduction of brightness throughout the range of object brightnesses considered. Such a curve is shown in Fig. 6.

A comparison of the slopes or gradients of curves D and E at corresponding points gives an indication of the departure from exact reproduction of contrast. This departure is most con-

veniently expressed quantitatively by taking the ratio of the gradient, G_{mr} , of curve D to G_e the gradient of curve E, but G_e is unity by construction, hence the values of G_{mr} are quantitative expressions of the departure from exact reproduction of contrast. Since the gradient of any curve is expressed by the first derivative of the function a graphic expression of the departure from exact contrast reproduction will be obtained by plotting the first derivative of curve D. This is shown in Fig. 7.

FIG. 7

Now referring again to Fig. 5 let B_o be taken as the value of object brightness at some point on the $\log B_o$ scale and E_x as the value of exposure at the corresponding point on the $\log E_x$ scale. Let K_x , the constant of the image forming system, be defined by the equation,

$$B_o \cdot K_x = I_x$$

where I_x is the illumination at some point on the image formed on the negative material and B_o is the value of object brightness at the corresponding point on the object.

If t_x denotes the required exposure time the following relations are found

$$t_x = \frac{E_x}{B_o \cdot K_x}$$

$$\log t_x = \log E_x - (\log B_o + \log K_x)$$

The required value of t_x can therefore be computed.

Now if the negative is to be printed by contact and I_n is the illumination on the negative during printing, the necessary exposure time can be determined by the relation,

$$\log t_y = \log E_y - \log I_n + D_n.$$

where $\log E_y$ and D_n are the values read at corresponding points on the $\log E_y$ and D_n scales respectively.

If I_p be the value of the illumination under which the positive is observed, the brightness of any given area can be computed from the relation,

$$\log B_{mr} = \log R_p + \log I_p,$$

and the magnitude of I_p will determine the relation between the numerical values of corresponding points on the $\log B_{mr}$ on $\log R_p$ scales thus establishing the scale of $\log B_{mr}$.

The scale established on line OY is identical with that on OX'. The point O' fixed at the point on the line OY where $\log B_{mr}$ is equal numerically to the value of $\log B_o$ read at the point O on the line OX.

Many interesting relations between the various factors involved can be derived from an analytical treatment of the diagram in Fig. 5, and while space does not permit of an extensive treatment of this phase one or two interesting results will be mentioned. Let the first derivative or gradient of the various curves be designated by the general symbol G, and in particular:

G_n = Gradient of negative characteristic (Curve A)

G_p = Gradient of positive characteristic (Curve B)

B_{mr} = Gradient of material reproduction (Curve D)

It can be shown that

$$G_n \cdot G_p = G_{mr}$$

Since for exact reproduction of contrast it is necessary that $G_{mr} = 1.0$ it follows that the equation expressing this condition becomes

$$G_n \cdot G_p = 1.0$$

This is a general statement of gradient relations and assumes nothing as to the shape of the characteristic curves of the material used. In the special case involving the use of the straight line portions only values of gradient become equivalent to the well-known constant of sensitometry γ (gamma), and may be written $\gamma_n \cdot \gamma_p = 1.0$. It should be pointed out, however, in the use of positive materials such as developing-out papers that but a relatively small portion of the curve is straight. Since the entire

FIG. 8

range of density must in general be utilized for rendition of the density scale of the negative the special case $\gamma_n \cdot \gamma_p = 1.0$ is of little value in the evaluation of the quality of contrast reproduction obtainable.

It is evident from inspection of Fig. 5 that if any two of the curves A, B, and D be known or assumed, the third can be

graphically constructed by methods analogous to those used in construction D from known values of A and B.

The applications of the methods outlined to practical problems are too numerous to mention in detail at this time. However, a specific example, Fig. 8, is shown. This illustrates the reproduction resulting from the use of obtainable negative and positive materials, the characteristic curves of which have been carefully determined by sensitometric measurements in this laboratory.

The object is assumed to have a contrast of 40 with $B_o \text{ max} = 1000$ (apparent meter candles). The negative material is assumed to have a latitude greater than 40 (in exposure units), T_∞ greater than 1.00, and log inertia equal to 2.5. The negative characteristic may therefore for the purpose of this discussion be represented as straight lines.

In order to show the effect upon reproduction of the extent to which the negative is developed, three times of development are assumed and the construction carried through for each.

The positive material used is specified by the curves B_1 , B_2 , and B_3 and has a standard exposure of 100,000 (m.c.s.)

This construction is so adjusted that in each case the highest light in the object is reproduced by a just perceptible deposit in the positive.

Values for various factors are assumed as follows:

$$\begin{aligned}K_x &= .01 \\I_n &= 1000 \text{ (m.c.)} \\I_p &= 851 \text{ (m.c.)}\end{aligned}$$

By use of the relations previously derived the value of t_x , and t_y were computed and found to be

$$\begin{aligned}t_x &= .0126 \text{ sec.} \\t_y \text{ (case 1)} &= 70.8 \text{ sec.} \\t_y \text{ (case 2)} &= 135.6 \text{ sec.} \\t_y \text{ (case 3)} &= 250.0 \text{ sec.}\end{aligned}$$

and from the relation

$$\begin{aligned}\gamma_m \cdot \gamma_p &= \gamma_{mr} \\ \gamma_{mr} \text{ (curve } D_1) &= 1.01 \\ \gamma_{mr} \text{ (curve } D_2) &= 1.17 \\ \gamma_{mr} \text{ (curve } D_3) &= 1.34\end{aligned}$$

The reproduction curves obtained by the graphic construction are as indicated at D_1 , D_2 , D_3 .

From a consideration of Fig. 8 a conclusion of considerable importance in practical work may be drawn. This relates to the problem of choosing the printing paper best adapted to a given negative or the inverse problem of making a negative of the proper quality for printing on a given printing paper. Considering Curve B, it will be seen that the useful portion is limited by the points m and n . On portions of the curve lying outside of these limits the gradient $\frac{d D'_p}{d \log E_y}$ is so small as to be practically useless in the reproduction of difference in E_y . Now in practice it is, in the great majority of cases, desirable to render the deepest shadow (lowest brightness) by the maximum useful density of the printing material, and at the same time to render all of brightness differences of the object as density differences in the finished print. If the density in the negative by which the highest light of the object is rendered be designated by the symbol D_{nmax} , and that negative density which renders the deepest shadow be designated by D_{nmin} , it is evident in order to fulfill the condition stated in the previous sentence that $D_{nmax} - D_{nmin} = ES_y$. The quantity $(D_{nmax} - D_{nmin}) = DS_n$ is termed the "density scale of the negative" and applies to a particular negative. This term (DS_n) should not be confused with the similar term DS_x which applies to the negative material itself with a meaning exactly parallel to that of DS_y as applied to the positive material.

From a consideration of Fig. 8, it will be seen if the negative and printing paper be such that $DS_n = ES_y$, that all of the density differences in the negative will be rendered as density differences in the print and further that the maximum negative density will be rendered as the minimum useful density of the printing material, while the minimum negative density will result in the maximum useful density in the print. Such procedure of course results in a diminished contrast in the extreme shadows and highlights due to the shape of the characteristic curve of the printing paper, even though (as is usually possible) all of the object brightnesses are rendered on the straight line portion of the negative curve. Of two printing papers having identical

values of ES_y (and equal to the value of DS_n for the negatives considered) the better result will in general be obtained by use of the one of which the characteristic curve most closely approximates to a straight line between the points m and n . While in some special cases better results may be obtained by some other procedure, it is undoubtedly true that in general the most favorable relation between negative and printing paper is that the "density scale" DS_n of the former shall be as nearly as possible equal to the "exposure scale" DS_y of the latter.

Since it is not the primary object of this paper to deal with particular cases but rather to outline the general theory of the subject, the discussion of the objective phase will be closed at this point leaving the application to practical problems for treatment in subsequent papers. Moreover, a final evaluation of the quality of a reproduction cannot be made without a consideration of the subjective phase of the problem and this will now be treated.

FIG. 9

Retinal Sensitivity Curves of the Retina

THE SUBJECTIVE PHASE

Turning now to a consideration of the subjective phase, it will be well to discuss more in detail the significance of the curves showing Fig. 9. These contain the data relative to the visual

sensitivities necessary for the evaluation of the subjective relative-contrast function. Curve A gives the relation of the sensation to the stimulating brightness. Equal increments on the Y axis correspond to equal increments in the sensation, and the brightness intervals which give rise to these sensation steps can be determined from this curve. The shape of this function could be established by direct experiments, but since such a process is extremely laborious it is customary to arrive at the same end by other means. The curve B, the contrast sensibility, is the first derivative of the sensation curve, hence if the sensibility be measured and the curve B plotted the sensation curve may be obtained by integration. The sensibility at a given adaptation level is determined by measuring the least difference in brightness perceptible under the specified conditions. The least perceptible difference, ΔB , expressed as a fraction of the brightness at which it is determined is a direct measure of the sensibility of the eye to contrast or brightness difference. The data from which the curve B is plotted are from the work of Nutting and Blanchard (*loc. cit.*). The ordinate of curve B at any point is therefore equal to the slope of the curve A at the same value of B. Thus, if S be the sensation, $\frac{d S}{d \log B} = \frac{B}{\Delta B}$. The values of the ordinates of the sensation curve are in terms of sensation units, and the construction of such a sensation scale is based on the assumption that a just perceptible difference at any point on the sensation scale is equal to a just perceptible difference at any other point. The basic unit upon which this scale is established is therefore the least perceptible brightness difference.

It should be pointed out that the curves in Fig. 9 are similar in shape to those given by Renwick (*loc. cit.*) but that the absolute values of log brightness are very different. This is due undoubtedly to the uncertainty in the value of the unit used by König from whose data the curves in question were plotted. Blanchard (*loc. cit.*) has discussed the question and computed the probable value of König's unit as being .044 ml. (approximately). The millilambert is the c.g.s. unit of brightness and is equivalent to a brightness of ten apparent meter candles or .93 apparent foot

candle. The region of maximum sensibility is therefore from 3 to 250 foot candles (approximately) instead of from 20,000 to 400,000 as indicated by the curves published by Renwick. In order to determine the sensibility for a given adaptation level it is important that the correct abscissae values be used.

Now, if we consider a specified brightness difference in the object viewed with the eye adapted to some brightness level A_o , it is possible from curve A (Fig. 10) to find the corresponding sensation difference; and if the brightness difference between the corresponding areas of the material reproduction be known together with the adaptation level (A_{mr}) of the observer viewing this material reproduction, it is possible to determine also the

FIG. 10

The Relation between Sensation and Stimulus

magnitude of the resulting subjective contrast. A comparison of the magnitudes of these two contrast values namely: (a) the subjective contrast resulting from observation of the object at a given adaptation level, which subjective evaluation it is convenient to refer to as the subjective object; and (b) the subjective contrast due to the observation of the material reproduction at a specified adaptation level, which subjective evaluation will be termed the subjective reproduction; determines the exactness with which the subjective sensation resulting from the observation of the object is reproduced by observation of the material repro-

duction (the illuminated positive) under the conditions specified. It is also possible by similar methods to determine the magnitude of the contrast necessary, at any point in the tonal scale of the material reproduction, for the exact reproduction of the subjective contrast of the object, assuming of course, that the values of A_o and A_{mr} are known

A_o = Adaptation level while observing object

A_{mr} = Adaptation level while observing material reproduction

For instance, in Fig. 10, consider an increment of brightness, $\Delta \log B_1$ for which the corresponding increment in the sensation is ΔS_1 . At any other point take a second increment in sensation ΔS_2 such that $\Delta S_1 = \Delta S_2$. Let the increment in $\log B$ corresponding to ΔS_2 be represented by $\Delta \log B_2$. Assume that the increment $\Delta \log B_2$ applies to some point in the object and that the value of B_2 fixes the adaptation level of the observer looking at that object, while for the material reproduction the adaptation is conditioned by the value of B_1

$$A_o = B_2$$

$$A_{mr} = B_1$$

Now the average slope of the curve (Fig. 10) over the range $\Delta \log B_2$ is given by,

$$\text{Slope (2)} = \frac{\Delta S_2}{\Delta \log B_2}$$

And the average slope over the interval $\Delta \log B_1$ is likewise,

$$\text{Slope (1)} = \frac{\Delta S_1}{\Delta \log B_1}$$

Since $\Delta S_1 = \Delta S_2$ it follows that

$$\frac{\text{Slope (2)}}{\text{Slope (1)}} = \frac{\Delta \log B_1}{\Delta \log B_2}$$

But the average slope of the sensation curve over any given interval is given by the average value of the ordinate, D , of the contrast sensibility curve (Curve B, Fig. 9) over the same interval. Hence, we may express the values of the slope by the corresponding values of D and the equation becomes

$$\frac{\text{Average } D_2}{\text{Average } D_1} = \frac{\Delta \log B_1}{\Delta \log B_2}$$

It is evident, therefore, if $\Delta \log B_2$ be the objective brightness difference at some point in the object that the equation will give the value of the $\Delta \log B_1$, the objective brightness difference necessary in the photographic reproduction for the exact reproduction of subjective contrast. In the case illustrated, the interval $\Delta \log B_2$ is less than the interval $\Delta \log B_1$ thus indicating that a greater objective contrast in the reproduction will be required to reproduce the subjective contrast due to the smaller objective contrast in the object. Changing the numerical subscripts therefore so as to indicate that the various factors apply to object and material reproduction the exposure becomes,

$$\frac{\text{Average } D_o}{\text{Average } D_{mr}} = \frac{\Delta \log B_{mr}}{\Delta \log B_o}$$

By allowing these finite increments to approach zero as a limit we may replace the average values of D by values of the slope of the contrast sensibility curve at a point and obtain the expression

$$\frac{D_o}{D_{mr}} = \frac{d \log B_{mr}}{d \log B_o}$$

Since previously an assumption of equality of subjective contrast (sensation increment) was made this equation is a statement of the conditions necessary for the exact reproduction of subjective contrast.

Now the value of $\frac{D_o}{D_{mr}}$ gives the slope of a curve which if plotted in quadrant I, Fig. 5 would be the line of exact subjective reproduction of objective contrast. In the graphic solution, however, it is more convenient in plotting the reproduction curve D and also in the later interpretation of the results to retain the line E (of which the gradient is unity) as the line of exact contrast reproduction. This can be done by plotting in quadrant IV a curve of which the gradient is equal to the reciprocal of the value $\frac{D_o}{D_{mr}}$, that is $\frac{D_{mr}}{D_o}$. This new function will now replace the dummy curve previously plotted in quadrant IV as one step in the graphic solution for the objective phase.

It should be pointed out at this place that this procedure leads to a final expression of the exactness of reproduction as a function

of B_o , the brightness of the object. It is quite possible to obtain the final evaluation of the exactness of reproduction as a comparison between the contrast values of the subjective object and the subjective reproduction, but in view of the fact that the starting point in any tone reproduction problem must be the objective brightness values of the object it seems more logical to make these values the primary base of the computation and to express finally the departures from exact reproduction in terms of these physically measured values of object brightness. This necessitates the evaluation of the subjective contrast of the reproduction in terms of the subjective contrast of the object and a final expression

FIG. 11

A General Case of the Complete Solution Including the Subjective Phase

of this complex relation as a function of the object brightness B_o . The final comparison must therefore be made between the actual measured (objective) contrast values of the object and the corresponding contrast values of the subjective reproduction evaluated in terms of the subjective object. The scale on which the points representing the various areas of the reproduction as evaluated in terms of this relative subjective contrast function

must occupy the line OY in order that the curve representing the final reproduction may be graphically constructed with values of B_o as abscissae, Fig. 11. The required scale constructed on line OY will be termed the $\log B_z$ scale and the relative subjective contrast function which is used to determine the distribution of the points on the $\log B_z$ scale will be referred to as the Z function and its gradient will be designated by G_z .

The slope of this function (Curve C Fig. 11) at any point is given therefore by $G_z = \frac{D_{mr}}{D_o}$.

Now it can be shown that the relation between the gradients of the several curves (Fig. 12) is expressed by the relation,

$$G_n \cdot G_p \cdot G_z = G_r$$

Where G_n = Gradient of negative (Curve A)

G_p = Gradient of positive (Curve B)

G_z = Gradient of Curve C.

G_r = Gradient of reproduction (Curve D)

If any three of the four functions be known or are assumed the fourth can be obtained either by the graphic method or by computation. In the most general case such as is represented in Fig. 11 no assumption is made as to the constancy of the adaptation level of the observer as attention shifts from regions of high to those of low brightness in the object and reproduction, and hence the value of G_z may not be constant. However, it is probable that the value of G_z is in the great majority of cases practically constant in which case the curve C becomes a straight line of which the slope is specified by the value of $\frac{D_{mr}}{D_o}$.

It is well-known that other factors than the brightness of the area upon which the attention is fixed (foveal image) influence to some extent the adaptation level of the eye at any instant. Such factors include the brightness of the surrounding objects (i.e., the peripheral images) and the length of time during which the attention has been fixed on the area considered. In practice, however, the picture being observed occupies a very considerable portion of the field of vision, and, further, in the great majority of such pictures the actual range of brightness is relatively limited.

This is especially true of surfaces viewed by reflected light. Further, under the majority of conditions the field of vision not filled by the reproduction being considered does not contain any area contrasting extremely with brightness of the reproduction. It seems reasonable, therefore, to assume that the adaptation level will be fixed in practice by the brightness of the reproduction itself and likewise that the level when viewing the object will be conditioned by the object considered.

The question then arises as to what particular brightness in object and reproduction will determine the adaptation level in each case. Considering the reproduction as a reflection surface the average range of brightness may be taken as 1 to 40 (1.6 in $\log B_2$) which even at the steepest part of the sensibility curve (Fig. 9) does not correspond to an excessive change in value of D . The change in adaptation as attention travels from highlight to shadow probably is not so great as that indicated by the brightness range, being limited to some extent by the stabilizing effect of the peripheral images as well as to the time lag of adaptation behind the changing foveal stimulus. It seems logical, therefore, to assume that A_o and A_{mr} are conditioned by the average brightness of object and material reproduction and this assumption will undoubtedly hold for a large percentage of the normal cases, although it may be necessary under extreme conditions to take into account the change in adaptation (and consequently in the value of D) which occurs as attention shifts from an area of one brightness to that of another.

A special case, therefore, which will probably fit most practical conditions depends upon the assumption that the adaptation level is conditioned by the brightness of object and reproduction half way between (on the $\log B$ scale) the highest and lowest brightness existing in these things. Such a case is shown in Fig. 12 where curve C, the relative subjective-contrast function is a straight line and D is the curve expressing the quality of final subjective reproduction as a function of B_o .

Now if

$$\begin{aligned} D_o &= D_{mr} \\ G_z &= 1.0 = G_d \end{aligned}$$

FIG. 12

Special Case of the Complete Solution Including Subjective Phase

This is the gradient thus far used in the construction of the curve C. It is evident, therefore, if average B_o and average B_{mr} are such that they fall between the limits (Fig. 5) $\log B = 0.5$ ($B = 3.2 \text{ ml}$) and $\log B = 2.2$ ($B = 166 \text{ ml}$) that the subjective reproduction of contrast will be identical with the material reproduction curves already discussed.

If however, the brightness, B_o , of the object and the consequent adaptation level, A_o , of the observer viewing that object is relatively high, while the brightness of the material reproduction, B_{mr} , (the illuminated positive) and the corresponding adaptation level, A_{mr} , is low, the subjective reproduction will be different from the objective reproduction. In this case the contrast sensibility D_o is greater than D_{mr} and hence the gradient, G_s of the relative subjective contrast curve is less than unity.

$$G_s = \frac{D_{mr}}{D_o}$$

The reproduction curve, D , constructed in the usual way will also have a decreased gradient. This indicates that under such conditions a loss of contrast occurs due to the subjective factors and in order to obtain exact reproduction it will be necessary to enhance the objective contrast in material reproduction in order to compensate for the loss due to the subjective effect. It is evident from these considerations that a picture of a brilliantly lighted scene which is to be viewed under relatively low illuminations such as exist in interiors at night should be somewhat more contrasty than the scene itself. That is, best subjective reproduction will be obtained by a positive in which the actual objective contrast is somewhat enhanced. This condition may be stated symbolically thus:

If,

$$\begin{aligned} D_o &\text{ is greater than } D_{mr} \\ G_s &\text{ is less than } 1.0 \end{aligned}$$

When G_s is less than unity there will be a loss of contrast due to the subjective factors.

On the other hand if,

$$\begin{aligned} D_o &\text{ is less than } D_{mr} \\ G_s &\text{ is greater than } 1.0 \end{aligned}$$

and there will be an enhancement of contrast due to the subjective factors.

Many interesting relations between the various factors may be derived and applied to practical problems but the discussion of such details will not be taken up at this time. One point deserving mention at this time, however, is relative to the values of adaptation of the eye upon which depend the sensibility values from which the slope of the subjective relative-contrast function is computed. Few data are at present available as to adaptation levels when the visual field is filled by areas of different brightnesses such as exist under practical conditions. Experimental work is at the present time in progress in this laboratory from the results of which it is hoped more reliable evaluations of A_o and A_{mr} may be obtained for certain specified practical conditions. When these data are available it will be possible by the application of the general principles outlined in this paper to arrive at more certain conclusion relative to the exactness of reproduction in any particular case.