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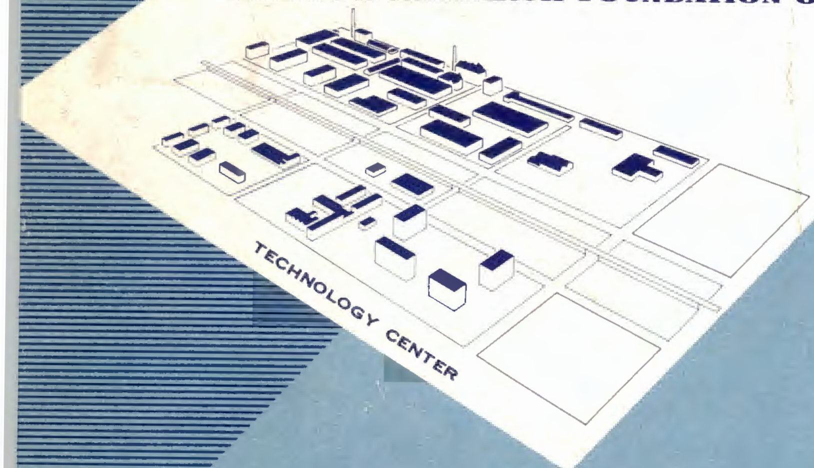

ARF Project No. E154

SELF ORGANIZING NETWORKS

Annual Report

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ARMOUR RESEARCH FOUNDATION
of
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Chicago 16, Illinois

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SELF ORGANIZING NETWORKS

ANNUAL REPORT

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ADAPTIVE LOGICAL NETWORKS EMPLOYING OPTICAL TECHNIQUES

I. INTRODUCTION

This report describes the initial phases of a program directed toward the realization of complex adaptive logical networks by optical means. The logical networks with which the research is concerned are comprised of threshold devices in various configurations. The general hypothesis which underlies the program is that networks of threshold devices can be designed which will be capable of useful application to pattern recognition problems of several types, provided that we can discover simple, inexpensive means for their manufacture. Still another notion which we accept is that effective solutions to such problems will be found not in terms of networks of fixed behavior, but in terms of networks whose parameters can be easily altered by suitable "action principles" or adaptive strategies.

This point of view is by no means unique to or original with the Armour Research Foundation, and is perhaps best represented by the work of Rosenblatt on the Perceptron. What characterizes our work is the particular interest in optical means for the realization of such networks and in the theoretical problems associated with the discovery of adaptive strategies within a frameworks constrained by the properties of the optical structures.

While the program has been aimed at problems of both a theoretical and "hardware" nature, the major effort during the initial phase has been directed at the realization of a simple optical device for adaptive pattern recognition. This report will therefore be confined entirely to a discussion of this aspect of the program and will reference theoretical results only when necessary to explain some aspect of the design.

II. AN OPTICAL THRESHOLD OPERATOR

We define a picture P as a two dimensional array consisting of N finite-area elements each of which has an optical transmission from the two-valued field consisting of t^0 and t^1. The values t^0 and t^1 correspond to the values 0 and 1 in the usual binary field, or the values opaque and clear from the subjective visual field. Note that if we place such a picture in the path of a uniform, collimated beam of light, the total flux passing through the picture may be computed as follows:

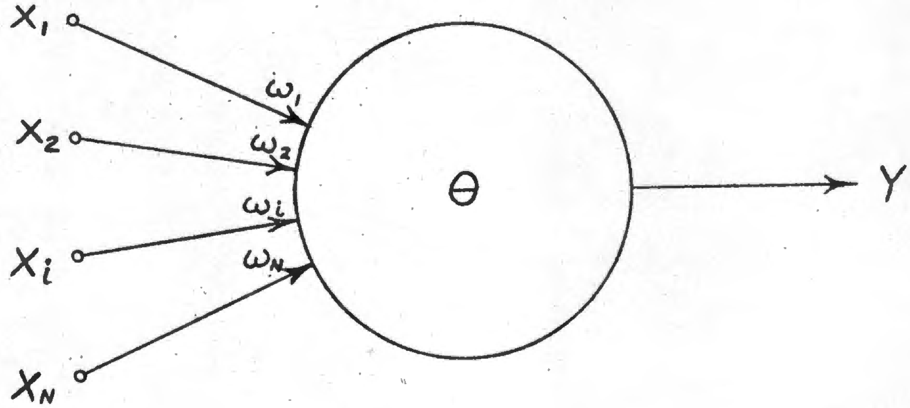
$$F(P) = f \sum_{i}^{N} t_i, \qquad (1)$$

where F (P) is the total flux passing through the picture, f the flux incident on each element of the picture, and t_i the transmission of the i th picture element according to some arbitrary labeling of the elements of the set P. If we place a second picture W in the optical path and designate the optical transmission of its constituent elements as w_i, where the w_i are in the range $0 \leq w_i \leq 1$ and the i th element of W has incident upon it the flux transmitted by the i th element of P, we may compute the total flux passing through P and W as:

$$F(P, W) = f \sum_{i}^{N} w_i t_i . \qquad (2)$$

If further we arrange to collect the total flux passing through P and W and cause it to impinge on a flux sensitive photodetector, we may obtain an electrical signal proportional to $\sum_i^N w_i t_i$. This electrical signal can be compared with a threshold value, say Θ, and a two-valued indication, say y established which depends on the sign of $\left[\sum_i^N w_i t_i - \Theta\right]$. We note that such an apparatus may be interpreted as a threshold operator having a number of inputs equal to the number of elements of resolution in the picture P and having weights confined to the range of $0 \leq w_i \leq 1$. The "threshold operator" notion is one of central importance in much of the work on pattern recognition and is an operation, the properties of which are becoming increasingly well known. For the sake of those who may not be familiar with this notion, however, or prefer a different language, Fig. 1 has been included to define the threshold operator as a formal operator on a binary array.

Because of the fact that the power of a threshold device having only positive weighting values is very much smaller than one having both positive and negative weights (in terms of the number of different functions of which it is capable), we should like to remove the restriction on weighting values which confine them to the positive range. This restriction may be removed by either of two techniques which may be implemented as follows. In the first implementation, we arrange for the weighting transparency, W, to have two elements of resolution for each element of resolution in the original picture P, say w_{1i} and w_{2i} corresponding to the element i in the picture P. We then employ some technique (for example, a transforming bundle of optical fibers) to cause the flux from the set of elements $w_1 = \{w_{11}, w_{12}, \ldots, w_{1i}, \ldots w_{1n}\}$ to impinge on one photodetector and the flux from the set $w_2 = \{w_{21}, w_{22}, \ldots, w_{2i}, \ldots, w_{2n}\}$ to impinge on a second photodetector.



$$Y = 1 \quad \text{IF} \left(\sum_{i}^{N} \omega_i x_i - \theta \right) > 0$$

$$Y = 0 \quad \text{IF} \left(\sum_{i}^{N} \omega_i x_i - \theta \right) \leqslant 0$$

$$x_i = 0, 1$$

$$Y = 0, 1$$

$$-1 < \omega_i < +1$$

FIG. 1 -- THRESHOLD OPERATOR

If E_1 is the electrical output of the first photodetector and E_2 the output of the second detector we see that the quantity $(E_1 - E_2)$ is obtained as follows:

$$(E_1 - E_2) = kf \sum_i^N w_{1i} t_i - kf \sum_i^N w_{2i} t_i = kf \sum_i^N (w_{1i} - w_{2i}) t_i, \qquad (3)$$

where k is proportional to the detector sensitivity.

Thus the quantity playing the role of the weight in the threshold operator formulation of the above device is device is $w_i = (w_{1i} - w_{2i})$. Clearly w_i can now take on values from the range $-1 \leq w_i \leq +1$.

Note that we eliminate the requirement for the transforming bundle of optical fibers if we employ instead a replica of P and duplicate systems to obtain the quantities E_1 and E_2. Note further that if we add to both copies of the picture P (and in fact to both copies of every picture which will be an input to the device) a region in which the transmission is always t^1 (for example a clear border), and designate the transmission of the weighting transparencies in the corresponding "border" areas as Θ_1, and Θ_2, then the quantity $E_1 - E_2$ will be modified as follows:

$$(E_1 - E_2) = k \left[\sum_i^N (w_{1i} - w_{2i}) t_i - A t^1 (\Theta_2 - \Theta_1) \right], \qquad (4)$$

where A refers to the area of the "border" region of P relative to the area of an element of resolution.

Making the obvious substitutions above, and adding a subscript j to indicate the identity of the jth picture, eg. the picture P_j having elements with transmissions t_{ij}, we see that

$$\text{Sign} \left[E_{1j} - E_{2j} \right] = \text{Sign} \left[\sum_i^N w_i t_{ij} - \Theta \right]. \qquad (5)$$

Having indicated how the structure described above provides a realization of a threshold operator with optical input, we pose two additional questions. First, "Can we elaborate the above structure so as to provide networks of threshold operators rather than single operators the logical potential of which is so extremely limited?", and second, "Can we discover convenient means whereby the structure, either in its original form or in an elaborated form, can be rendered adaptive?". It is primarily the second question with which this report will deal. Further consideration of the elaboration of the structure must await developments in the theory of such adaptive networks as well as the quantitative results of the effort to render the single operator adaptive.

III. ADAPTIVE TECHNIQUES FOR OPTICAL THRESHOLD DEVICES

The work of Rosenblatt, Joseph, Widrow, Stafford, and others, has demonstrated the fact that a number of adaptive strategies exist which will cause a single threshold device to converge to any desired behavior within its structural limitations. Most of the adaptive strategies are of the error-correcting variety, i.e. a sequence of samples from the set of all inputs is presented to the threshold device, the threshold device is caused to evaluate each input (assign it a name) based on the existing weight and threshold values, and the device is modified if and only if the device response (the assigned name) is not in accord with the "desired" response. Clearly in this case "error" simply means that the device response to a particular input picture is not what we should like it to be. It can be readily demonstrated that a strategy which calls for a positive increment in all weights whose increased value would have "tended toward" the correct response, together with a negative increment in those weights whose decrease will "tend toward" a correct response, is an effective strategy. By "effective strategy" we mean one which will result in a finite number of errors for any initial values of the weights. While the fact that such a strategy will converge is an interesting result, the strategy is not one that can be considered for any practical optical device since the absolute value of the weights required may be extremely large. A more practical formulation of a strategy is one in which each "increase" takes the weight some fraction of the way from its present value to a "maximum" value, and each "decrease" takes it some fraction of the way toward a "minimum" value, eg.

$$\Delta w_i \text{ (increase)} = \alpha \left[w_{max} - w_i(t) \right]$$
$$\Delta w_i \text{ (decrease)} = \alpha \left[w_{min} - w_i(t) \right] \qquad (6)$$

Such a strategy has also been described as having "decay" since we may think of the change in weight as being comprised of two parts, a fixed increment equal to $\pm \alpha$ and a "decay" equal to $\alpha w_i(t)$. While such a strategy can be shown to converge in the same sense that the fixed increment strategy will converge, it will not do so for all functions if we additionally require that the quantity $\left| \left[\sum_i^N w_i t_{ji} - \Theta \right] \right|$ be greater than some positive quantity for all j. Such a requirement corresponds to the demand that the response be unambiguous since, if we had no such requirement, we might regard as acceptable a set of weights which for some inputs yielded values of the quantity $\left[\sum_i^N w_i t_{ji} - \Theta \right]$ the sign of which could be altered by arbitrarily small changes in Θ. Let us refer to the modified strategy as described in equation 6 as an "exponential" strategy. The term "exponential" is used to suggest the way in which the weighting values approach their limiting value as a result of a sequence of equal-sign changes.

The particular approach to an adaptive optical structure which is being investigated at the present time leads to a strategy of the "exponential" variety. The problem of adaption in the context of the optical scheme previously discussed is that of finding a scheme to generate the weighting transparencies appropriate to a specified behavior of the device. The approach being pursued can be most easily explained with the aid of Fig. 2. Figure 2 also serves as a diagrammatic representation of the experimental apparatus with which this technique is being evaluated. Before attempting to describe Fig. 2, however, we should discuss the general properties of the material being utilized as the weighting transparency. This material is known as a photochromic or phototropic material and has the property that its transmission in a portion of the visible spectrum may be reversibly altered by exposure to relatively high intensity radiation in other portions of the spectrum. The National Cash Register Company has been extremely active in the development of these materials and has supplied the films or transparencies used in the equipment to be described. To be more specific relative to the properties of the films, Fig. 3, curve A, shows the transmission of a sample of a particular film supplied by NCR in its "clear" state, while curve B shows its transmission after it has been exposed to high intensity radiation confined to the blue end of the spectrum (in fact essentially a white source passed through the filter of Fig. 4, curve B).

After subsequent illumination with high intensity "yellow" light, eg. a white source passed through the filter of Fig. 4, curve Y, the transmission of the photochromic again becomes that of Fig. 3, curve A. Thus we see that if we "read" the condition of the photochromic film by means of a low intensity source operating over the spectrum defined by the filter indicated

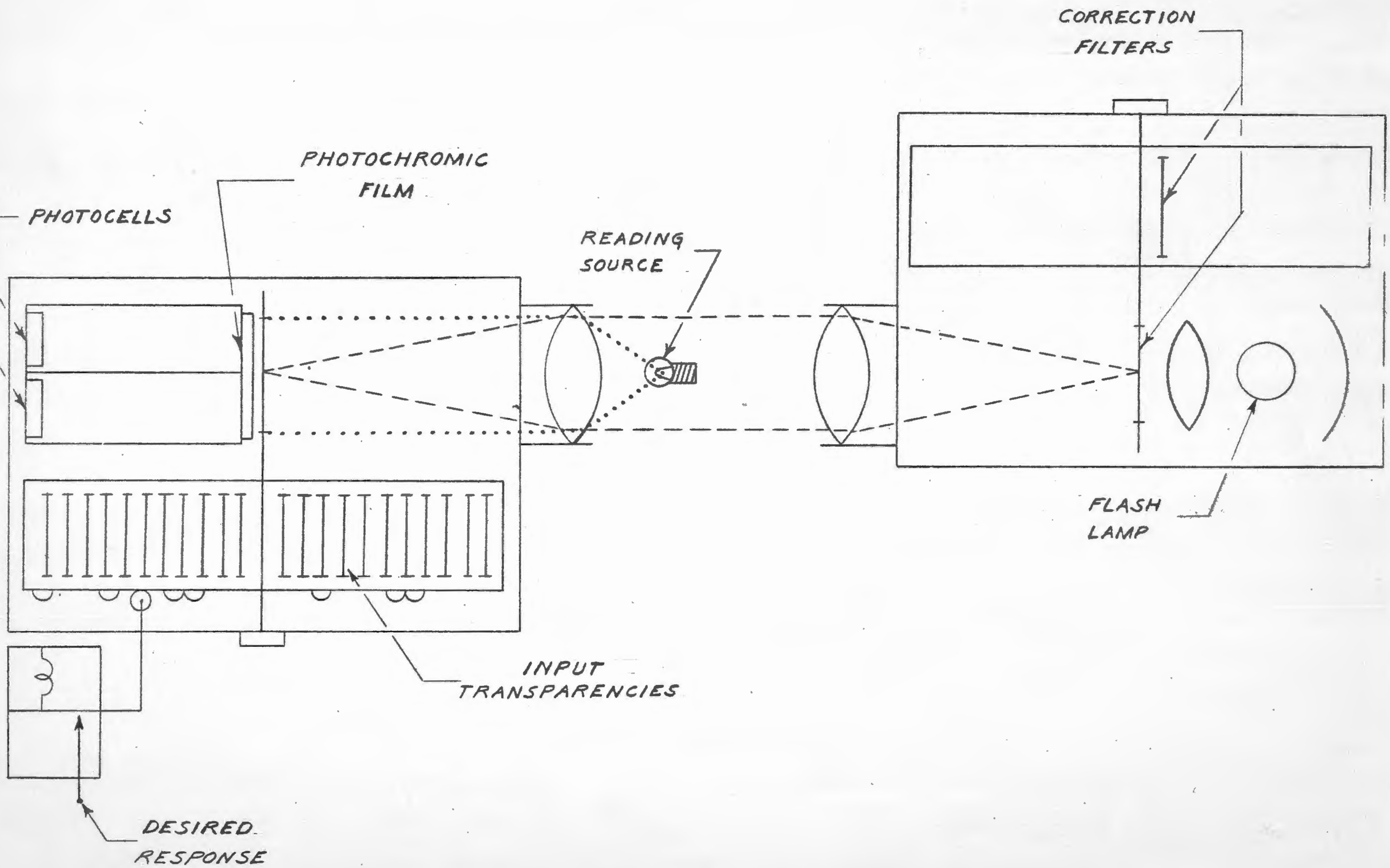


FIG. 2 -- SCHEMATIC REPRESENTATION OF EXPERIMENTAL APPARATUS

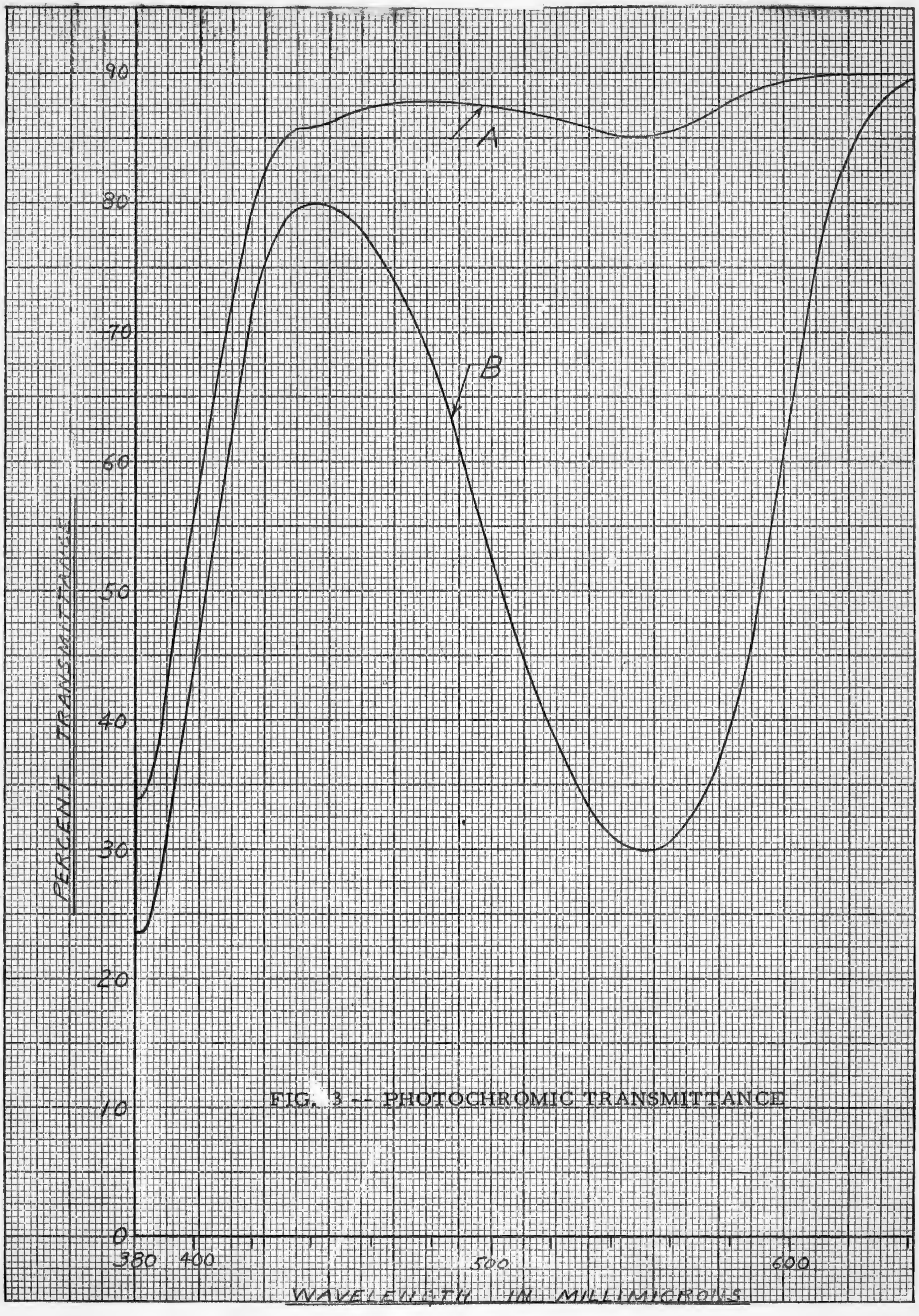


FIG. 3 -- PHOTOCHROMIC TRANSMITTANCE

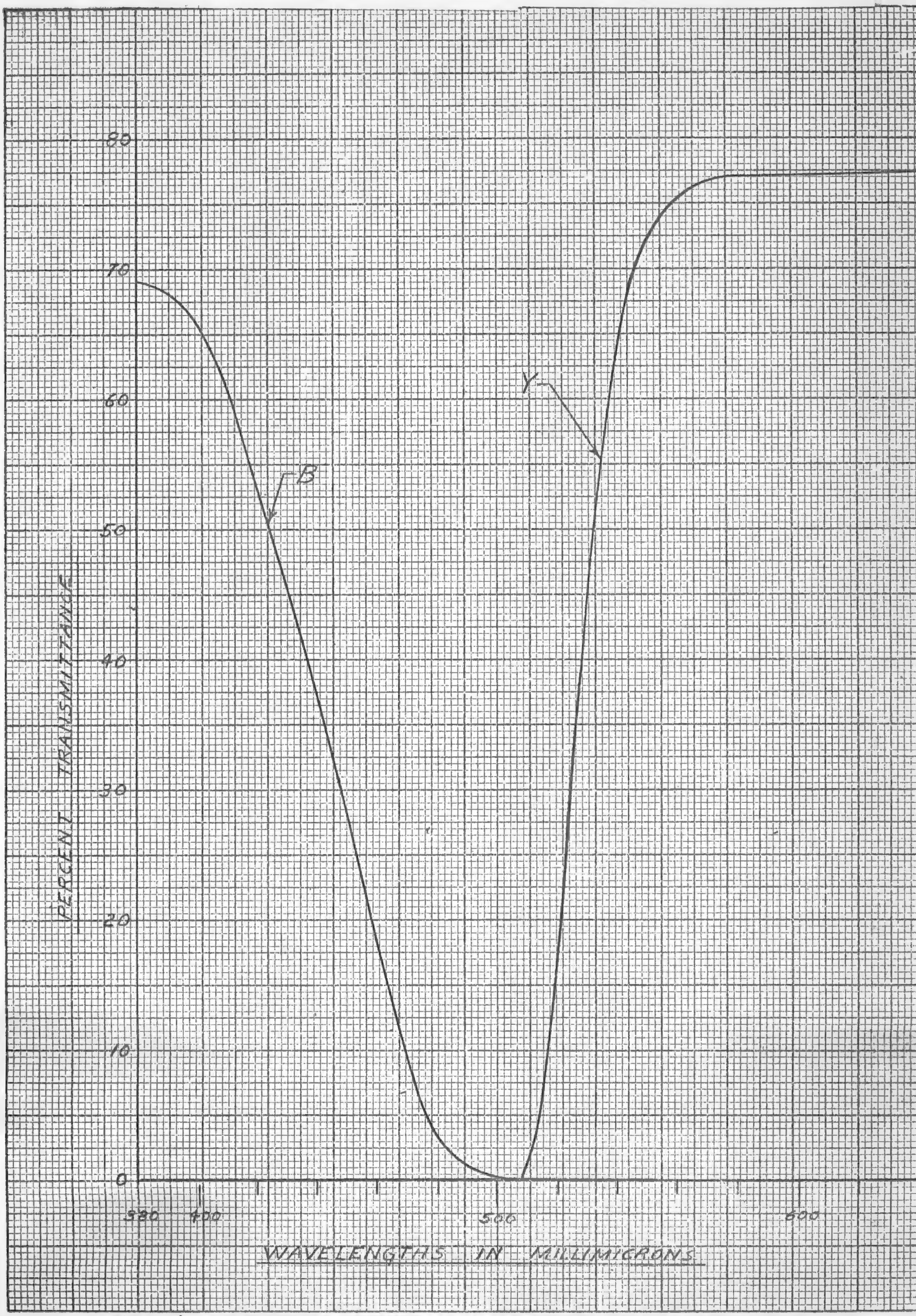


FIG. 4 -- WRITING AND ERASING FILTER TRANSMITTANCE

as curve A in Fig. 5, the observed transmission can be anywhere from roughly 0. 3 to roughly 0. 8, depending on the previous history of the exposure of the transparency to blue and/or yellow radiation. It should also be remarked that although the material is relatively stable (in the dark at room temperature it will decay toward an equilibrium with a time constant of the order of hours), we are to some extent faced with a kind of macroscopic uncertainty principle. If we should like to determine the state of the photochromic by measuring its transmission, the measuring process itself alters the transmission we seek to measure. The saving feature is found however in the energies required. The energy required to "read" the film is so small compared to that required to "write" or "erase" the film that the reading energy may for all intents and purposes be ignored.

Returning now to Fig. 2, we note that the input transparency (actually a 35 mm slide) is introduced into the optical path from the slide magazine of a modified commercial slide projector with automatic slide changing features. The picture consists of two side by side versions of the same pattern plus a "border" region. The "desired" response corresponding to each input picture is sensed by means of a mechanical switching arrangement actuated by the slide magazine. After a transparency has been inserted the reading source, which is placed at the focus of the projection lens associated with the lefthand projector of Fig. 2, is turned on. The reading source illuminates the input transparency and the photochromic weighting transparency with a uniform collimated beam. The flux through each of the two halves of the transparency is collected separately and caused to impinge on the two photodetectors. The two detectors (actually photoresistors) are wired into a bridge circuit so that the direction of bridge unbalance indicates the sign of

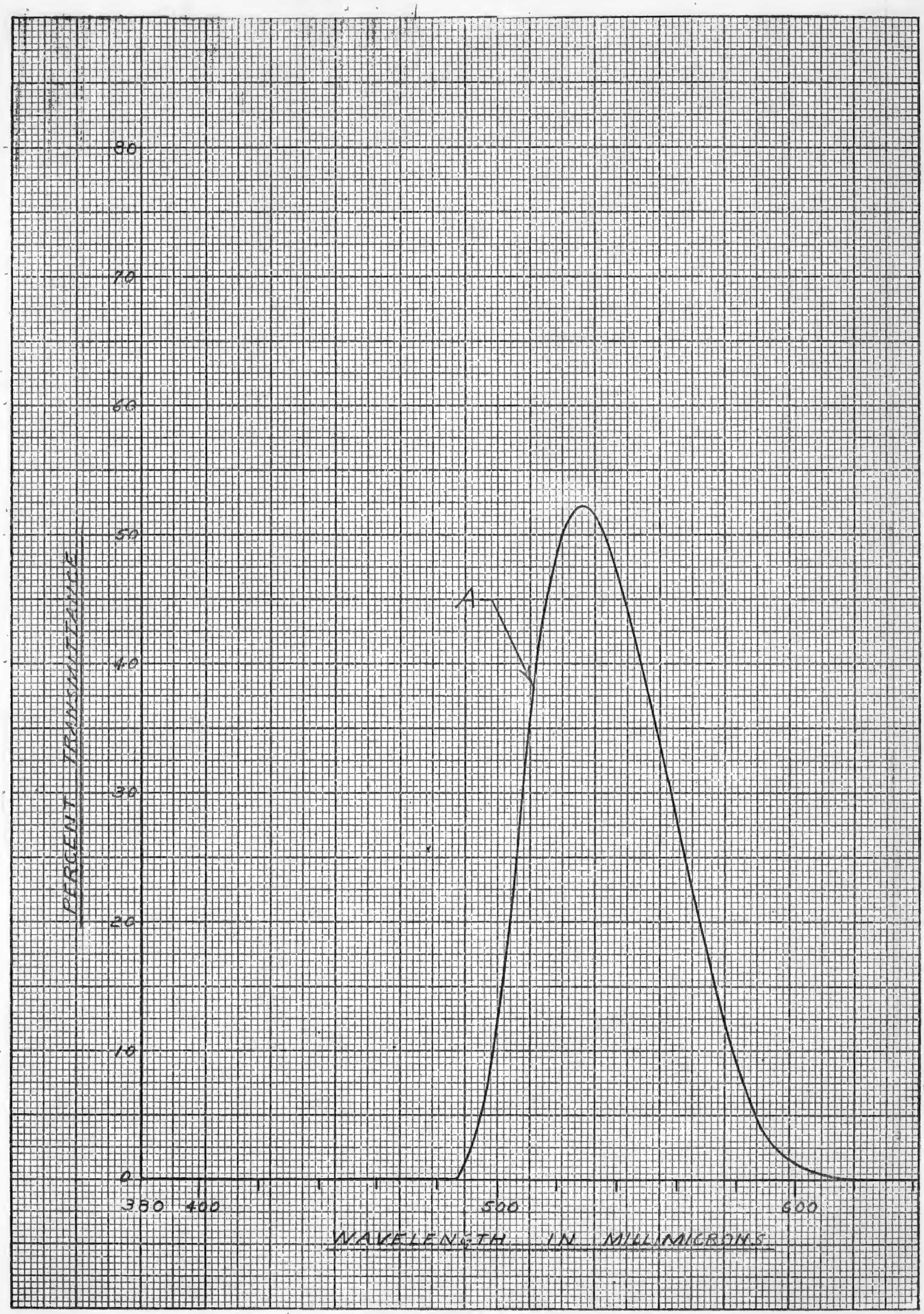


FIG. 5 -- READING FILTER TRANSMITTANCE

$\left[\sum_{i}^{N} w_i t_i - \Theta\right]$. If the sign of $\left[\sum_{i}^{N} w_i t_i - \Theta\right]$ is in accord with the desired response, as indicated by the mechanical sensing finger, the picture or transparency is withdrawn and the next transparency inserted. If however the response is in "error", the high energy gas discharge lamp located in the right hand projector is fired before the transparency is withdrawn. The right hand projector slide magazine contains two filter arrangements, one of which is inserted in the projector prior to the firing of the high energy source. The selection of the filter actually inserted in each instance is based on the nature of the "desired" response. The filter arrangements each consist of two, side-by-side filters, one "blue" (having the character indicated in Fig. 4, curve B), and one "yellow" (having the character indicated in Fig. 4, curve Y). The two filters are different in that they are mirror images of one another. Whichever filter arrangement is in the projector is imaged by the pair of projection lenses onto the photochromic film (through the input transparency) so that the right-hand picture is flooded with blue light and the left-hand picture with yellow light (or the reverse) whenever an "error" is committed by the device. It can be demonstrated that this structure implements an adaptive strategy of the "exponential", error-correcting variety discussed earlier. The device is designed so that it will automatically and repeatedly sequence through the set of input pictures until it has gone through the entire set once without error, at which point it terminates the experiment.

IV. EXPERIMENTAL RESULTS

Unfortunately no experimental results of any interest have as yet been obtained. One of the major problems associated with the design described above was due to the fact that the high intensity flash from the gas discharge lamp is also incident on the photodetectors. Although the photodetector output is not significant at the time at which the flash lamp is ignited, all detectors investigated suffered in some way from the exposure to such high energy flashes, so that it was found necessary to add a shutter to protect the detectors. The particular shutter design created still other problems as a result of the vibration it introduced in the equipment. Still another problem resulted from our inability to obtain photodetectors which were sufficiently well matched over the necessary dynamic range of incident "reading" illumination. For the above reasons, among others, a portion of the optical system has been redesigned to employ a single detector and a chopper. In this design the single detector views the right and left half fields alternately. Also the present chopper design eliminates the need for a separate shutter to protect the detector from the high intensity flash. It is anticipated that the improved instrumentation will provide experimental results more nearly in accord with the results of the computer simulation experiments on which the design has been based.

Respectfully submitted,

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