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GRAPHICAL DATA PROCESSING RESEARCH STUDY AND EXPERIMENTAL INVESTIGATION

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Prepared for:

U.S. ARMY SIGNAL RESEARCH AND DEVELOPMENT LABORATORY
FORT MONMOUTH, NEW JERSEY

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SRI Project 3192

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FORT MONMOUTH, NEW JERSEY

Contract DA 36-039 SC-78343
SCL-4087 (18 November 1958)
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Objective: To conduct a research study and experimental investigation of techniques and equipment characteristics suitable for practical application to graphical data processing for military requirements.

Approved:

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PURPOSE

It is the objective of this project to conduct a research study and experimental investigation of techniques and equipment characteristics suitable for practical application to non-alphanumeric graphical data processing for military requirements. All phases of the graphical data processing art will be considered, including the treatment of the raw graphical data, identification, programming, selection, indexing, access to storage, and presentation. The studies and demonstrations of feasibility will be designed to evaluate the practicability of the proposed techniques and systems, with sufficient detail to be useful in establishing the design criteria necessary for equipment procurement.

The program of work will proceed in three phases, with an evaluation of the most promising lines of investigation to take place at the six-month and twelve-month marks. The general lines of thought governing the various phases are as follows:

Phase 1—A broad survey of (1) the state of the art and (2) new methods.

Phase 2—A more detailed survey of the sections which seem to be especially relevant, with additional experimental investigation of the more promising lines of attack.

Phase 3—A further limitation of the field, with special emphasis on the methods and devices most likely to find application, including experimental verification, if possible, of their practical value.

The scope of Phase 1 has been divided into five relatively independent tasks:

Task A—The use of photographic processing techniques and their electronic analogues for the simplification of input data.

Task B—A survey of electronic methods of performing pattern recognition.

Task C--The construction of a small pattern recognition machine capable of modification to various schemes of logic.

Task D--Mathematical investigations.

Part (a)--The possible application of certain theorems of integral geometry.

Part (b)--The logic of practical wiring systems for the improvement of the performance of machines of limited capacity in specific situations.

Task E--Data storage and retrieval in relation to the special problems of non-alphanumeric graphical data processing.

ABSTRACT

The scope of the work under Phase I has been divided into five relatively independent tasks. These are outlined below.

Task A--This task involves the investigation of photographic processing techniques and their electronic equivalent for the simplification of input data. A study has been carried out on the use of unity gamma photographic transparencies for grey-scale elimination leading to the suppression of fine detail and the creation of a solid outline around significant features of the landscape. The process may be of practical value for the simplification of aerial photographs before they are fed into a pattern recognition machine.

Task B--A survey will be made of electronic methods of performing pattern recognition. In Sec. III an outline is given of the characteristics of current techniques and the "signature" approach. This will be treated in detail in Report 2.

Task C--A small pattern recognition machine will be constructed, capable of modification to various schemes of logic. A compatible set of components based on multi-aperture magnetic cores has been devised, and a general purpose machine is being constructed having an 8-by-8 retina, 65 multi-level stores, and 5 binary outputs. The mechanical construction work is now 40% complete. Perceptron type logic will be used initially. A paper on the simulation of neural networks with multi-aperture magnetic cores is included.

Task D--Mathematical investigations are being undertaken. These are divided into Parts (1) and (2), as outlined below.

Part (1)--The possible application of certain theorems of integral geometry is being investigated. These provide numerical relations governing such properties of geometrical figures as line length, area, and curvature, which are invariant under rotation and displacement.

Part (2)--An investigation is being made of the logic of practical wiring systems for the improvement of the performance of machines of limited capacity in specific situations.

Task E--Data storage and retrieval will be studied in relation to the special problems of non-alphanumeric graphical data processing. In Sec. VI, a brief outline is given of the chief areas of interest; a detailed account is deferred until Quarterly Progress Report 2.

PUBLICATIONS, LECTURES, REPORTS AND CONFERENCES

Two papers were presented at the Illinois Symposium on Principles of Self-Organization held at Champaign, Illinois in June 1960. These are "An Approach to a Distributed Memory," by C. A. Rosen, and "Statistical Properties of Geometric Figures Invariant Under Translation and Rotation," by A. B. Novikoff.

On 26 and 27 April 1960, meetings were held at Stanford Research Institute, Menlo Park, between the sponsor's representative William A. Huber of the Data Transducer Branch, Communications Department, United States Signal R & D Laboratory, Fort Monmouth, and all personnel allocated to the project, for the purpose of discussing the requirements of the contract.

GRAPHICAL DATA PROCESSING RESEARCH STUDY AND EXPERIMENTAL INVESTIGATION

I INTRODUCTION

A. THE PROBLEM

Information relating to the geographical features of the landscape may be stored in many forms—as aerial photographs, as maps, or as a series of numbers in a catalogue. It would be desirable to retrieve this information in classes or in detail with the minimum delay, making use of modern electronic data handling techniques to achieve control over the vast quantity of data that has to be processed. It is the objective of the project to explore the possibility of identifying selected features of the landscape—*e.g.*, road junctions, oil tanks, etc., and storing their locations by a suitable code. All the data within a selected classification and lying within the chosen area would be made available upon interrogation by the appropriate input code.

It is apparent that two mutually independent problems are involved in the above formulation. These are (1) the ability to perform pattern recognition at a speed and a level compatible with the quantity of input data, and (2) the ability to solve the library problem, using mechanical aids to organize the stored material in such a way as to achieve the required access time.

B. THE APPROACH

In the normal course of events, difficult problems are best attacked by a painstaking, thorough analysis, in which all detail is strained through a sieve of critical appraisal and nothing relevant is lost. But if the mesh is too small, and the quantity of material too great, the system is unable to function. In the present instance, the stock of raw data to be processed is enormous, and any system that is to be of value must reject irrelevant detail with the minimum cursory examination. It would appear axiomatic that the most efficient system is the one with the minimum amount of stored data, but at the same time it may be extremely undesirable for the system to miss any of a special class of items that are being catalogued. The balancing of these factors may well be the criterion determining the merit of the system.

The initial problem is that of pattern recognition. In considering the extreme case of the trained observer reading an aerial photograph, it is apparent that recognition of ill-defined features of the landscape is frequently performed by relating them to the context of the surrounding terrain. In many cases, when the sun is shining, the boundary of an object may appear incomplete and be camouflaged by shadow, or the subject contrast may be less than that of the remainder of the landscape. From the point of view of the circuit engineer, this represents a signal below noise level. The problems involved in designing an electronic machine to duplicate the performance of a skilled observer are beyond present day abilities, and are likely to remain so for a considerable period. Assuming the pattern to have been located and to be well defined, two further factors are of major significance: recognition must take place (1) independently of size, and (2) without regard to orientation. It is possible to perform normalization of presentation with the help of mechanical or electrical aids, but it would be preferable for the recognition machine to achieve the generalization as a consequence of its internal function. There is good ground for the belief that this is within the realm of possibility, and work at present in progress in several organizations suggests that generalization under area-preserving transformations will in due course be practically realizable. On initial examination, it appears that detailed serial scanning techniques are incompatible with the rate at which data must be handled in a practical system, and it is considered essential to reduce the information presented to the minimum required for satisfactory recognition. To this end, the techniques of graphic arts will be utilized to effect the maximum elimination of redundant detail.

The general problem of library organization and catalogue file storage appears in many forms in our modern civilization, and the limitations of existing techniques and equipments are fairly well defined. For the storage of a specific number of items and with a specific access time, comparison with previous experience will give an accurate prediction of feasibility. But the amount of storage under a given system is not extensible indefinitely in an upward direction, since access time increases correspondingly until operation becomes impractical. It seems probable that new techniques will be needed to yield the requisite access time for graphical data storage in modern and future systems.

C. THE SCOPE OF THE INVESTIGATION

The ultimate goal of the project is to determine, by study and experiment, techniques suitable for the processing, recognition, storage and retrieval of non-alphanumeric data useful for military purposes.

The program of the present work is limited to the study, the laboratory investigation and the demonstration of feasibility of techniques relevant to the project.

The work is divided into the following three phases, each to be completed with six months:

Phase 1--This will cover a broad survey of the state of the art, including a literature search and the preparation of a bibliography. New methods of performing pattern recognition will be sought, including mathematical analyses in the field of integral geometry, which seem potentially suitable for physical implementation.

Phase 2—After six months, a critical evaluation will be made of the methods brought to light by the Phase 1 survey, and a more detailed evaluation will be made of those sections which seem especially relevant. Experimental investigations will be pursued on the more promising lines of attack.

Phase 3--The field of investigation will be narrowed still further, and special emphasis will be given to the methods and devices most likely to find application in machine construction.

Since some of the tasks to be performed under the contract are an extension of work already in hand, certain sections of the program will run ahead of the schedule outlined above.

It is intended that the construction of a small pattern recognition machine will be involved, but that its function will be limited to the following purposes:

(1) To classify a retinal field pattern as belonging to a category defined by a binary output code

(2) To demonstrate the feasibility of constructing a pattern recognition machine from particular kinds of electronic components

(3) To investigate systems of wiring between the retina and the pattern recognition machine with a view to securing improved performance under less general conditions.

D. THE PROGRAM

In view of the ramifications of the problems involved in the design of a machine to perform the processing, recognition, storage, and retrieval of graphical data for military purposes, it has been found necessary to allocate the available effort to the performance of five well-defined, but relatively independent, tasks. These are discussed below.

Task A—Application of the Techniques of Graphic Arts and Sciences to the Simplification of Input Data

In keeping with the philosophy that it is essential to eliminate redundant detail with the minimum cursory examination, graphic arts techniques will be applied to the simplification of input material, which may take the form of maps, charts, or aerial reconnaissance photographs. Since the photographic data are under least control and probably represent the greatest need, they will be given primary attention. While the techniques investigated will be predominantly photographic, electronic devices which produce equivalent effects by performing analogous functions will also be investigated.

Task B—Survey of Electronic Methods of Performing Pattern Recognition

During the past decade, interest in the development of electronic techniques for performing pattern recognition has undergone enormous expansion, and a large body of material relevant to the present problem is to be found in the literature. A survey and evaluation will be made of existing and proposed techniques and of their application to both the original data and the modified data produced by the methods of Task A.

Task C—Construction of a Small Parallel-Connected Pattern Recognition Machine for Feasibility Studies

In the twelve-month interval prior to the issuance of the present contract by the Signal Corps, an investigation was proceeding in the Applied Physics Laboratory on the basic functional elements required for the construction of potentially useful pattern recognition machines. The work was supported by SRI funds. Considerable progress has been made in achieving a compatible set of magnetic components, and this will now be extended by the construction of a small machine sufficient for feasibility studies. In view of the versatility of the components and the differences of opinion which exist on the merits of suggested schemes of logical interconnection, the machine construction will be organized in a manner which will permit relatively easy modification of the logic. The machine will take its input data from an 8-by-8 retina and initially use 65 multi-level stores to classify the input patterns into a maximum of 32 binary output codes. Its purpose will be limited to the demonstration of the feasibility of constructing a pattern recognition machine from the present components, and to a preliminary evaluation of the logical schemes of interconnection.

Task D—Mathematical Investigations

The studies that fall under this heading have been proceeding for some time under SRI sponsorship, and the work will now be partially supported by the present contract. These studies may be divided into the following two categories:

(1) A mathematical investigation of the relevance to pattern recognition of certain theorems of integral geometry. These theorems provide numerical relations governing such properties of geometrical figures as lengths, boundary curvature, angles, and area, which are invariant under rigid motion. Thus the equations depend only on shape, and are invariant under transformations such as rotation and displacement.

(2) An investigation of the logical interconnection of practical wiring systems, with particular reference to the improvement of the performance of machines of limited capacity in specific situations.

    Since machines of this type are essentially combinational, their work capacity increases with size considerably faster than linearly. Inversely, small machines deteriorate in capability very rapidly with diminishing size. If the range of operation of the machine with respect to a particular variable can be restricted to a narrower interval, a considerable improvement in efficiency may be anticipated. However, in order to achieve this, a specific method of interconnection within the machine would be necessary.

Task E—Data Storage and Retrieval in Relation to the Special Problems of Nonalphanumeric Graphical Data Processing

A survey will be made of the equipment and techniques which are applicable to the present problem. Two types of system will be given primary emphasis: those which are most suited to maximum storage capacity, and those of limited capacity but with very rapid access.

II TASK A—APPLICATION OF THE TECHNIQUES OF GRAPHIC ARTS AND SCIENCES TO THE SIMPLIFICATION OF INPUT DATA

A. STATEMENT OF THE PROBLEM

The most desirable form of pattern-recognition machine would require no preliminary processing of graphic input material. However, the information content of continuous tone material is so great that a preliminary processing operation to remove extraneous information might result in considerable design simplification of the recognition machine.

The basic form of symbol information on maps and charts exists as black lines or figures on a white ground. These are generally of uniform size and well defined in outline. Photographic aerial maps present information of much greater variability.

The work described has concentrated on the processing of aerial photographs, with the object of arriving at photographic techniques capable of converting the continuous tone information into black and white line information. This might then be handled on a common basis with the line material derived from maps and charts.

It is assumed that the pertinent features to be retained and emphasized will consist largely of lines derived from roadways and rivers, and of geometric figures derived from buildings and other man-made structures. The superfluous detail to be eliminated or subdued would be largely textural rendition of natural terrain and vegetation.

B. VISUAL ANALYSIS OF AERIAL PHOTOGRAPHS

The information present in a photographic aerial map is defined primarily by the juxtaposition of areas of differing density, representing the relative light reflectance of the subject. Lines as such are rarely present, but are inferred by the viewer from the edges formed by adjacent density areas. Such "lines" consist of density transitions that range from ratios of over 200:1 to less than 2:1. The density areas defining objects are the result of (1) inherent subject contrast, and (2) light contrast. In most cases a combination of the two effects is operative, though it is easy to find cases where only one effect is present. Where a subject does not have significant spatial relief, a ploughed field for instance, it is defined by its light reflectance value relative to that of the surrounding terrain. In the second case, it is possible to visualize a structure having a reflectance value matching that of the surrounding terrain, where the subject is defined only by light modulation caused by the spatial characteristics of the object. A rectangular building with a roof parallel to the ground and having the same reflectance will be defined by a shadow area falling, at most, on two sides of the subject. Identity can be inferred only from this partial shadow outline.

C. EXPERIMENTAL INVESTIGATION

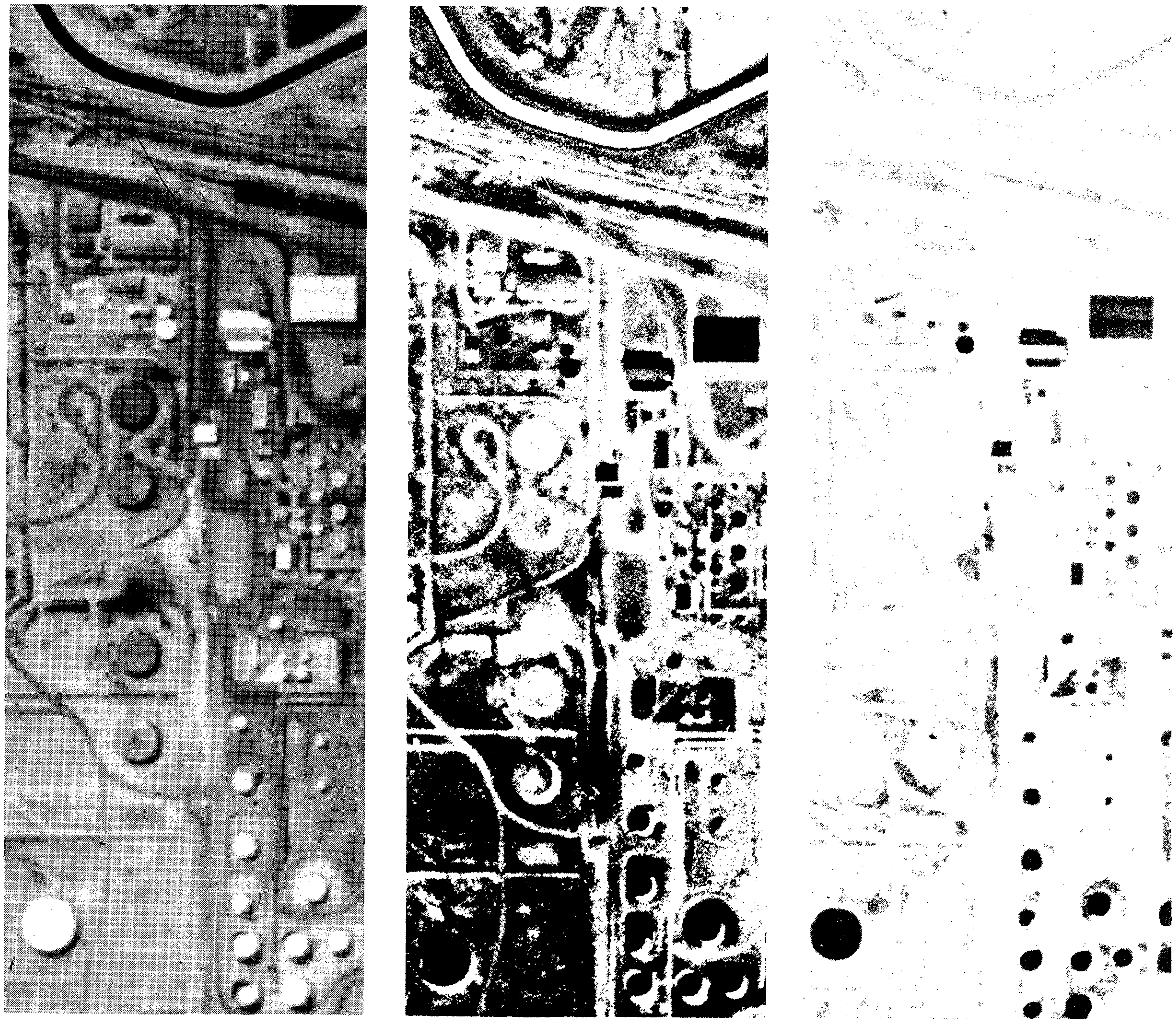
1. Clipping

Selected portions of aerial survey negatives were enlarged so that significant detail was of a visually readable size. The most obvious way of simplifying the tone scale is to increase the contrast of the material until all values are rendered as either black or white. This can be done by printing on high contrast material such as Kodalith film, repeating the steps until all middle tones are eliminated. The crucial point in such a procedure is the exposure given during each step. The final result is defined by a tone contour, representing a transition from black to white at an arbitrary value that is fixed by the exposure. This is demonstrated in Fig. 1, where (a) is a section of the original photograph, and (b) and (c) show the effect of two different exposure times for the first contrast-increasing step. Some gross information is retained, but such a procedure falls short of preserving all the desired information.

Although too much subject matter is completely eliminated to make this technique of great practical value in terms of the ultimate application, it forms a useful reference standard against which other processes may be compared.

2. Grey-Scale Elimination and the Generation of Solid Outlines

In evaluating aerial photographs with a view to construction of a practical pattern recognition system, it is evident that significant information may be located anywhere on the grey-scale density range, and may involve any arbitrary percentage modulation of the transmitted light intensity. It is desired to eliminate the grey scale, and create an image



(a) INITIAL POSITIVE

(b) CLIPPED NEGATIVE MEDIUM LEVEL

(c) CLIPPED NEGATIVE HIGH LEVEL

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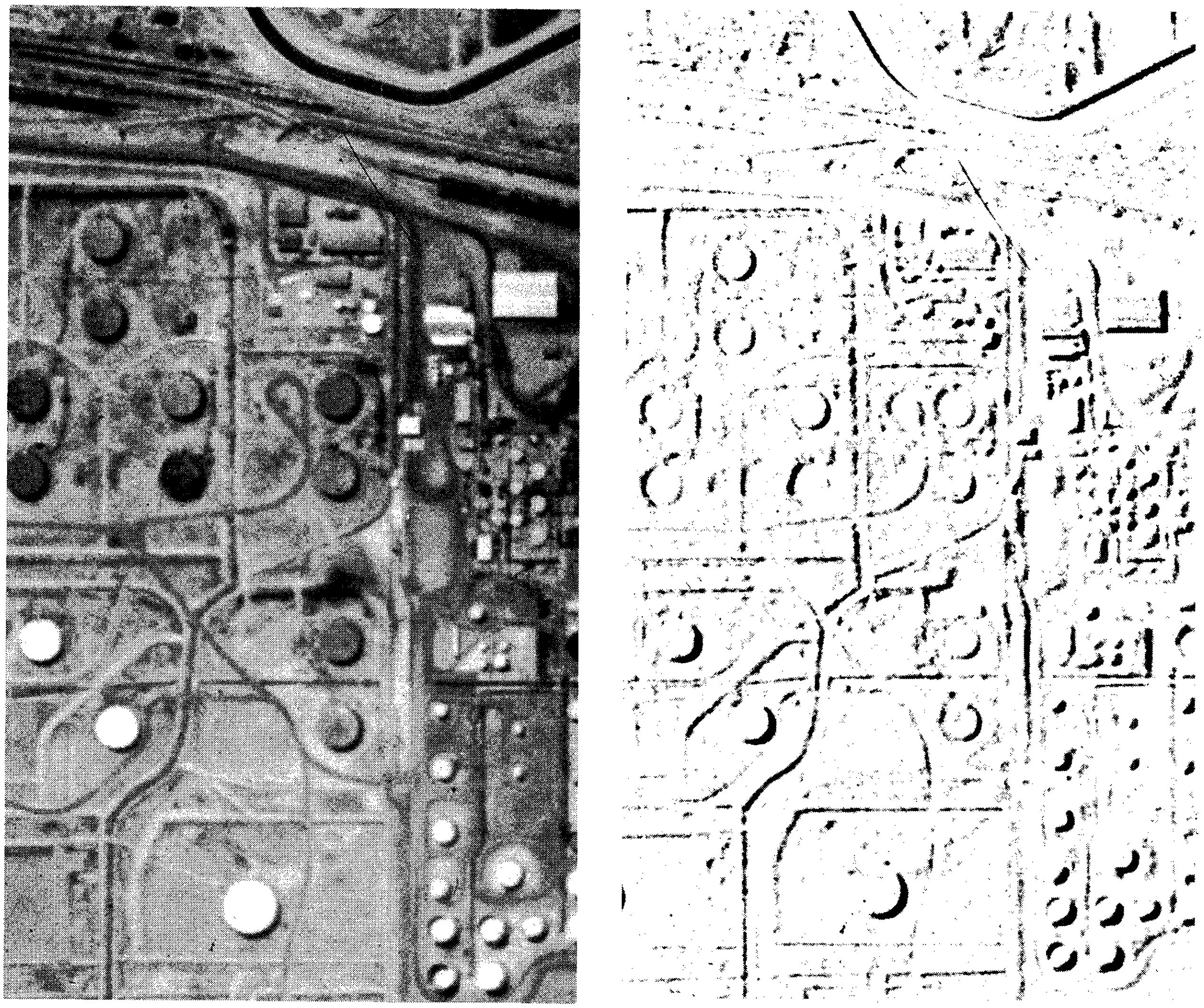
FIG. 1

ELIMINATION OF DETAIL FROM CONTINUOUS-TONE POSITIVE BY VARIATION OF CLIPPING LEVEL with 100% light modulation, while retaining the outline of all significant objects. The outline should be wide enough to cover at least 10% of the enclosed area, since the machine used to examine it will probably have relatively low resolving power as compared with a normal photographic image. It is important to guard against the tendency to evaluate the resulting images on a visual basis, instead of assessing their merit from the point of view of the machine.

In order to eliminate the tone information entirely from a photographic negative it is necessary to make a photographic positive, reproducing the light transmission in precisely inverted order. The two elements in perfect register would result in complete cancellation of the image; this may be achieved substantially in practice, with the exception of certain edge density or border effects. Imperfect cancellation occurs when development by-products accumulate in the emulsion along the boundaries between areas receiving widely different exposures, and the by-products modify locally the rate at which the chemical reactions take place. These effects are trivial, however, in comparison with the density differences resulting from even the slightest misregistration of the negative and positive transparencies. The present investigation is concerned with the effects which arise when such transparencies are misregistered in various ways, and with the possibility of using such effects to advantage.

3. Results

The major portion of the work has concentrated on the use of positive tone masks printed in conjunction with the negative. From an enlarged negative a positive mask was made by contact printing. A step wedge with a transmission density range of 0.2 to 3.0 was included for control purposes. The exposure and development were controlled to give a density range on the positive that gave complete cancellation of the density range of the negative—*i.e.*, the positive was developed precisely to a gamma of unity, reproducing the density steps of the negative inversely. The degree of control required is comparable with that for color film development.
If one of this pair of transparencies is laterally displaced slightly, light is passed chiefly along two sides of the image boundaries. When the combination is printed on a high contrast material, a line image is created which reproduces the original circular shapes as crescents, and rectangles as right angle figures (Fig. 2). This gives the effect of a "bas relief."



(a)

INITIAL POSITIVE

(b)

POSITIVE-NEGATIVE PAIR
WITH LATERAL DISPLACEMENT

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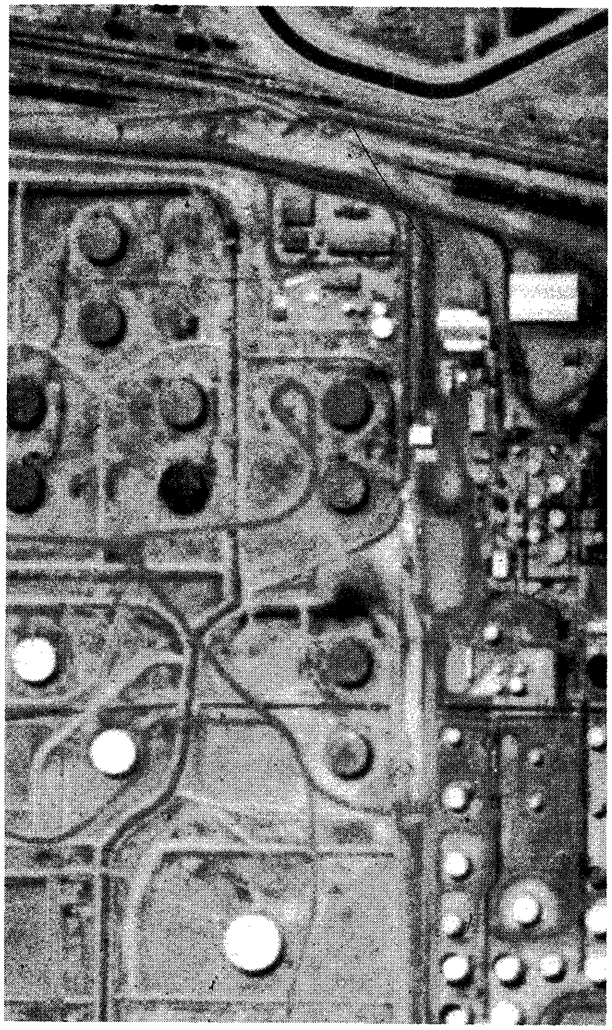
FIG. 2

ELIMINATION OF DETAIL FROM CONTINUOUS-TONE POSITIVE BY COMBINATION PRINTING OF POSITIVE WITH A UNITY GAMMA NEGATIVE, AND LATERAL DISPLACEMENT

To make this half-image outline continuous around the object, light must be passed around the full boundary rather than along the misaligned edge. To accomplish this, equal misregistration is needed around the whole object. The positive and negative are now sandwiched together in register, with the films back-to-back, rather than emulsion-to-emulsion as they were printed. The silver images are thus separated by the thickness of the two emulsion supports. Such a registered pair of transparencies will, when viewed from a point perpendicular to the surface and at a distance sufficient to minimize parallax, appear to be an over-all gray value, with only faint density differences defining edges of strong tone changes. If this pair of transparencies is viewed at an angle of approximately 45 degrees from the perpendicular, it will be seen that light is passed at all image boundaries. To expose a print from this film sandwich, a revolving turntable is used. The negative and positive and the film are placed in a printing frame on the turntable. Exposure is made by a projection light source positioned at a 45-degree angle incident to the surface of the print frame. The exposing light striking the paired films at an angle is passed chiefly at the image boundaries, producing line images of the sharp tone breaks that existed on the original print. The spacing of the emulsions caused by the film support is in this case 0.02 inch. It will be seen that outline images, not only of the objects desired, but also of the fine detail (grain of original print), are reproduced (Fig. 3).

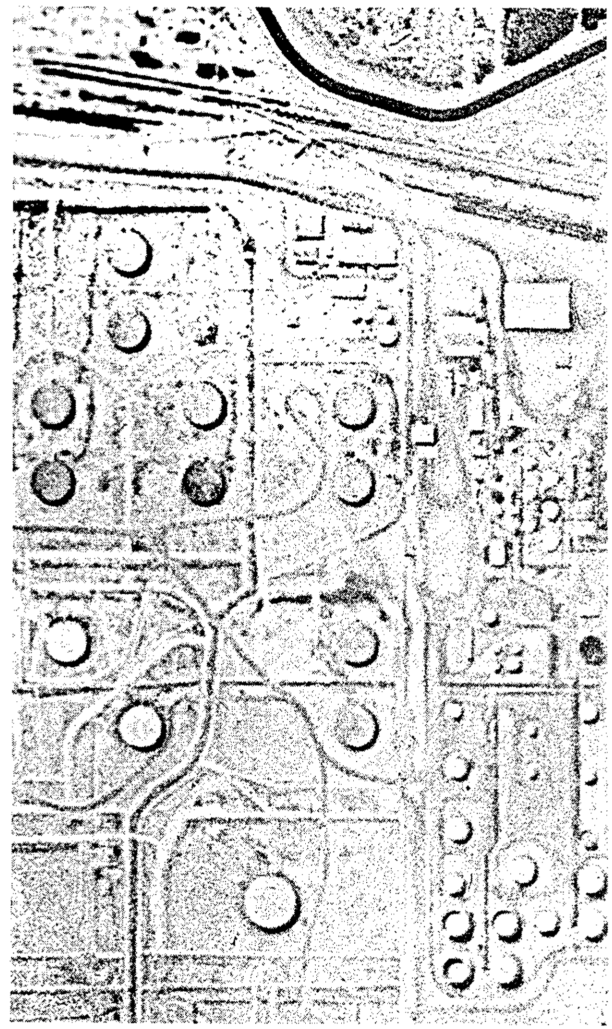
By increasing the spacing between negative and mask the fine detail is minimized, while the lines of the larger detail are broadened and strengthened. In this case the space between emulsions was increased to 0.085 inch (Fig. 4).

The extent to which this line-broadening effect can be utilized is governed by the minimum size of objects to be detected. Objects on the negative that are appreciably smaller in diameter than the spacing between the negative and positive in the printing sandwich are lost. Note the six light-toned circular tanks just below the building on the right-hand edge of Fig. 4(a); the diameter of these tanks on the negative is 0.050 inch, and these are lost on Fig. 4(b). The tanks in the lower right corner of Fig. 4(a) have a diameter of 0.100 inch, and are fairly well defined in Fig. 4(b). It is apparent that where an object is defined almost entirely by its shadow because its primary light reflecting surface matches the background, it is rendered by only a half-outline image. The effect is similar to that created by lateral misalignment when printing through complementary negatives (*cf.* Fig. 2).



(a)

INITIAL POSITIVE



(b)

POSITIVE-NEGATIVE PAIR IN ALIGNMENT, WITH 0.02-INCH SPACING

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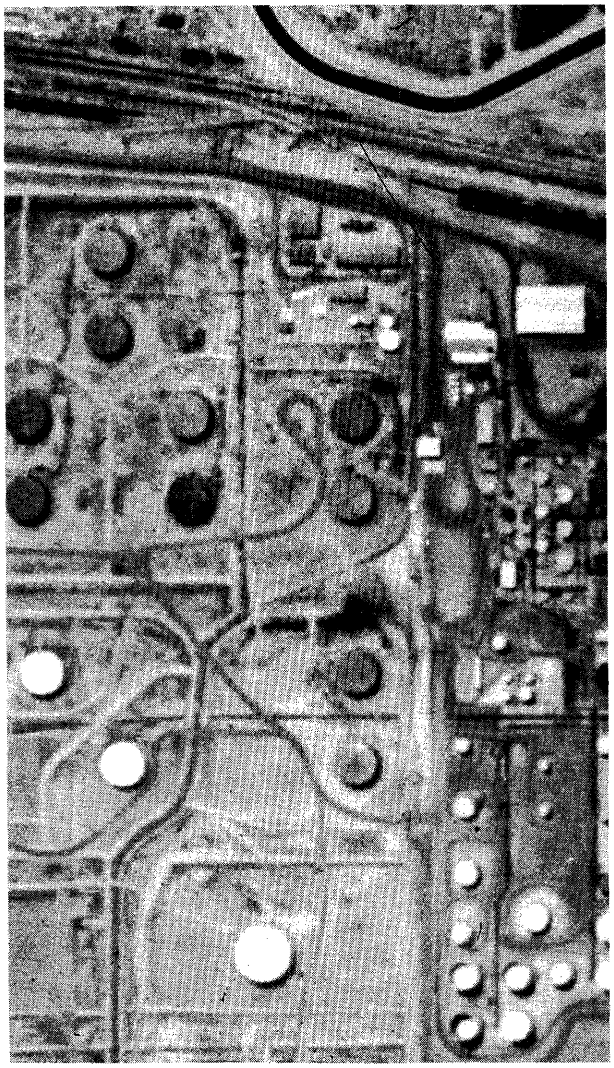
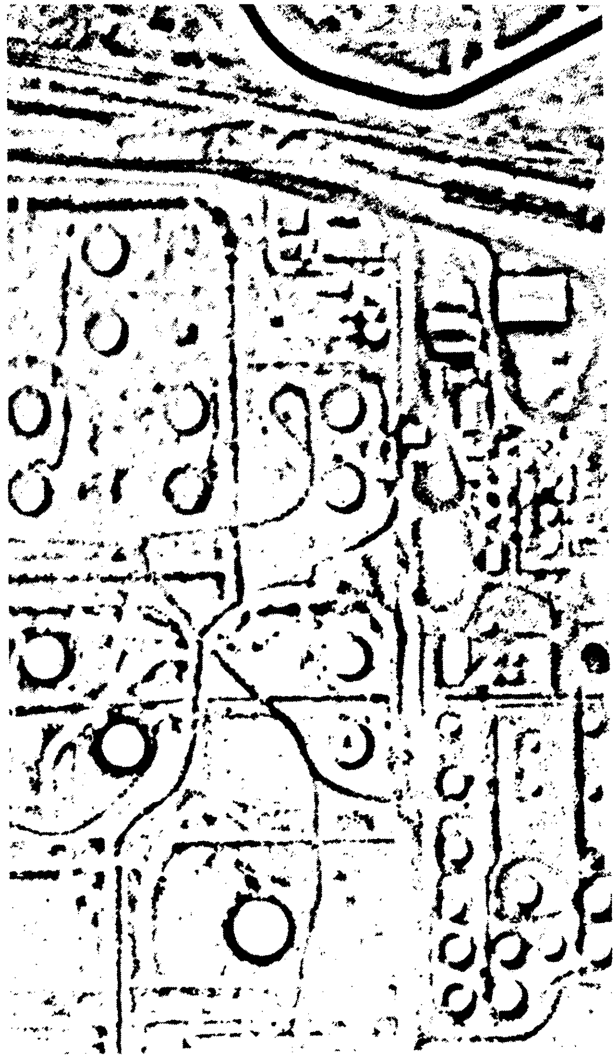
FIG. 3

ELIMINATION OF DETAIL FROM CONTINUOUS-TONE POSITIVE BY COMBINATION OF POSITIVE WITH UNITY GAMMA NEGATIVE IN REGISTER



(a)

INITIAL POSITIVE



(b)

POSITIVE-NEGATIVE PAIR IN ALIGNMENT,
WITH 0.085-INCH SPACING

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FIG. 4

ELIMINATION OF DETAIL FROM CONTINUOUS-TONE POSITIVE BY COMBINATION OF POSITIVE WITH UNITY GAMMA NEGATIVE IN REGISTER, BUT WITH EXTRA SEPARATION

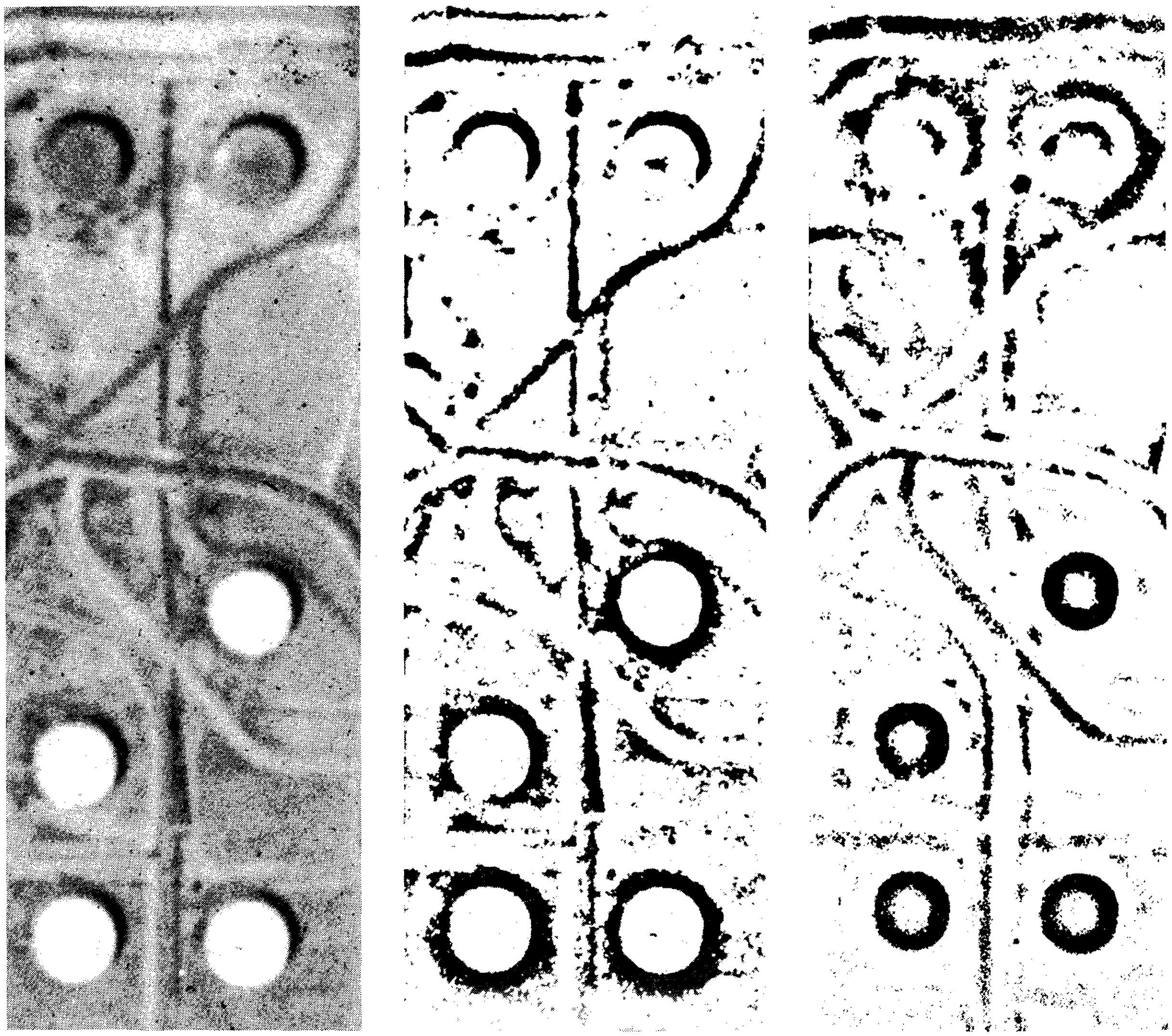
A comparison of Fig. 5(b) shows the difference in effect, depending on whether the negative or its positive mask is in direct contact with the recording emulsion. In Fig. 5(b) the negative is in contact with the recording emulsion; the objects are defined by a dark line outside the actual dimensions of the object. In Fig. 5(c) where the positive mask is in contact with the recording emulsion the objects are defined by a line inside the actual dimensions of the object. It is evident that one of the edges defining the dark outline figures is fairly regular, but the other is quite irregular; on Fig. 5(b) the inside edge is regular, the outside irregular. This effect is caused by the difference in relative position of the two images forming the figure, the image in contact with the recording emulsion giving the regular outline, and the image spaced away giving the irregular outline. When the turntable is rotated relative to the exposure light, the transparency spaced away from the recording emulsion casts a moving image. The outline of a given figure is usually composed of areas of non-uniform density even when the figure is sharply defined. The high contrast of the recording emulsion converts these continuous tone density variations into solid-tone area variations. It is possible that by using a point source for the exposing light, this effect may be minimized.

4. Details of Photographic Processing

The photographic procedures used to obtain these results were as follows: continuous tone duplicates were made on Kodak Commercial Ortho developed in DK60a. The high-contrast line transparencies were printed on Kodalith ortho developed in Kodalith developer. The light source for printing was a Kodaslide projector. For the turntable exposures, the light was positioned approximately four feet above the turntable and displaced laterally four feet from its center. The turntable ran at approximately 12 rpm, and the light source was regulated to give exposures of at least 25 seconds to minimize any directional inequality of exposure. The original survey negatives were enlarged 4 times. The subsequent manipulations were done by contact printing from negatives and positives of this size. The illustrations for this report were enlarged an additional 2 times, with the exception of Fig. 5 which was enlarged 4 times.

5. Conclusions

The methods here outlined are capable of reducing full tone scale information to a simplified black and white representation, simultaneously



(a) INITIAL POSITIVE

(b) POSITIVE-NEGATIVE PAIR IN ALIGNMENT

(c) NEGATIVE-POSITIVE PAIR IN ALIGNMENT

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FIG. 5

ELIMINATION OF DETAIL FROM CONTINUOUS-TONE POSITIVE BY COMBINATION OF POSITIVE WITH UNITY GAMMA NEGATIVE, SHOWING EFFECT OF TRANSPOSING POSITION OF POSITIVE AND NEGATIVE eliminating a large amount of superfluous detail. In addition it has proved to be possible to create a broad outline around objects of significant size.

The process favors the retention of well defined objects with regular boundaries; natural objects do not usually have vertical sides or accurately defined edges, but are defined by composite grouping of small, irregular tone patches, and consequently are considerably suppressed. Oil tanks, buildings, and other man-made structures are very well retained. Although the resulting images present information in a form that is less easily interpreted visually than the original, they probably represent a useful improvement from the point of view of machine processing.

The accuracy of processing control required is comparable with that needed for the development of color film. It is reasonable to predict that there would be no great difficulty in achieving satisfactory results from automatic machinery.

6. Future Work

These tentative conclusions are dependent on further testing on a wider variety of material. A limited amount of such testing will be done.

Consideration will be given to the use of Xerography and Electrofax to achieve equivalent results. The possibility of developing a single-step photographic method of tone conversion utilizing semi-reversal effects will be investigated.

Optical filtering and video techniques for arriving at the necessary tone simplification are now being investigated.

III TASK B—SURVEY OF ELECTRONIC METHODS OF PERFORMING PATTERN RECOGNITION

A. PRESENT TECHNIQUES

Literature relating to graphical processing and pattern recognition is extensive and rapidly growing. Although a general review of this literature might be valuable at the present time, the objective of the current study is to uncover any and all available information which may be useful within the context of the present project. Useful information may relate to basic philosophy, general methodology, specific techniques, or even detailed hardware.

One impetus for pattern recognition work derives from a desire to understand how the human eye and brain perform this function. Much of this work is aimed more at reaching a model which can represent the human system of sensory perception than toward doing a particular job of pattern recognition.[1,2*] Certainly, an understanding of the human process would be a considerable aid to the mechanization of pattern recognition, but it is not yet certain that the best machine method will be an analogue of the human system. At present, our understanding of the human perception process is so meager and the models are so crude that this question of basic philosophy is wide open. For our purposes, a machine technique must be judged by its ability to perform a task in relation to the cost of instrumenting and operating it.

The short period during which digital computers were revered as "giant brains" is apparently past, and such machines are now viewed as useful tools within a limited sphere of activity. Because they are available, conventional digital machines have been programmed to demonstrate various techniques applicable to graphical data processing, pattern recognition, and learning. The complexity of such programs and the time consumed in performing relatively simple tasks of pattern manipulation, as reported in the literature,[3,4,5,6] indicate that their use for such purposes on a routine basis would be highly inefficient. Their major function in the present line of research is to simulate the performance of machine concepts

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* All references are listed at the end of the report.

which might be mechanized in some form which would be efficient (smaller, faster, cheaper, etc.).[7] The general-purpose digital machine thus appears as a research tool rather than as a final device for pattern recognition.

Much of the literature is concerned with the recognition of alphanumeric characters.[8,9,10,11] In general, the more restrictions one can place on the shapes, positions, and orientations of the characters, the simpler the recognition problem becomes. Little of this work will have direct utility in a pattern-recognition environment in which patterns may be greatly distorted in size and shape, in which they may occur with random positions and orientations, and in which they are presented on an extremely noisy background. Various component techniques reported in this work may be useful, however, and an attempt is being made to "log in" these ideas even though the basic systems described may not be applicable to the present project.

Pattern recognition within a limited environment is a decision problem.[12] In response to a given input field, the decision must be reached as to which, if any, of a finite number of outputs will be energized. Decisions result from operations performed on data. Two fairly distinct approaches to the questions of what data to obtain and how to use these data appear in the literature.

One approach makes an *a priori* analysis of the noise-free patterns the machine is to detect and selects certain characteristics which distinguish the various input patterns from each other.[8] For example, only certain letters of the alphabet will have full length vertical strokes. Another non-exclusive group will have curved sections which are concave downward, etc. Each of these definitive characteristics performs a "cut" which narrows the choice, and the final decision may be reached by a logic tree. The main burden on the machine and its designer is to provide positive recognition of a limited number of these primitive characteristics in the presence of noise, distortions, and misregistration.

A distinctly different and potentially powerful approach is initiated by asking what data can be most easily obtained by available techniques.[13] In this approach, some thought is given to the pertinence of the data to the recognition problem, but there is no attempt to make any given datum definitive. After a large number of operations have been defined, they are applied to representative input material for which the correct decisions have been independently obtained. Relative frequencies of the various data states, treating the several operations either as independent or in combinations, permit the assignment of weights relating every operation to every output. Thus the importance of a given operation is determined *a posteriori* from typical, rather than ideal, input material. Once the weights have been assigned, the data obtained from new input material are operated on by the weights to produce a number (voltage, current, etc.) for each possible output. The decision is based on which number is largest or whether one or more exceed predetermined thresholds.

Machines have been constructed and/or simulated which can demonstrate the ability to learn to recognize patterns.[1,14] At present, these machines are severely limited in the number of patterns which can be differentiated in the presence of noise, distortions, or misregistration. The variety of such machine concepts and the incompleteness of current theories of their operation would make generalization at this time difficult and possibly misleading. Their performance to date is encouraging. The predicted performance of much larger machines operating on similar principles is an unsettled and controversial question. It is the opinion of the writer at this time that although the final step in pattern detection or recognition may be performed by a machine of the Perceptron type, several stages of graphical processing and perhaps decision logic may be required to produce a useful result in an efficient manner.

The above discussion is based on a study of the literature, which is continuing. References cited should be considered representative rather than complete.

B. THE "SIGNATURE" APPROACH

In searching beyond the literature for useful techniques, effort has been devoted to the problem of obtaining an identifiable "signature" for a pattern or class of patterns. The word "signature" is introduced here to mean a derived pattern of some sort containing information sufficient for positive identification or classification of the primary pattern, and exhibiting some degree of invariance with respect to translation, rotation, magnification, or allowable distortion of the primary pattern. The ideal signature would retain its essential characteristics irrespective of the position of the primary pattern in the input field, rotation of the primary pattern around any point in the input field, and the size of the input pattern (within limits).

One approach which has been studied is the use of a retinal device which would provide outputs relating to the connectivity of the input pattern. The retina, in this sense, is the optical-to-electrical transducer which provides electrical input to the recognition circuitry. It is usually conceived as a matrix of photo-sensitive devices which simply maps the input pattern onto an array of electrical terminals or as a scanning device mapping the spatial pattern onto a time axis. The output of the retina need not necessarily constitute a map of the input function, however; a signature, in the sense defined above, might be more desirable.

One retinal configuration might consist of a sheet of photoconductive material with islands of conductive material arranged in some regular array on one or both sides. Voltage applied to selected conductor elements would set up a pattern of currents and voltages throughout the retina, due to the finite dark resistance of the photoconductor. Light shining on part of the retina would lower the resistance between adjacent conductors in that region and modify the current and voltage patterns. The basis for studying such a configuration is the hope that by some choice of driving electrode configuration, and of voltage or current monitoring, a signature can be obtained which is representative of the connectivity of the input pattern. Initial studies have not proven very promising, but only a small fraction of the many possibilities has been investigated.

A signature may be obtained by one or more steps of graphical processing. One process which has been studied is the formation of the autocorrelation function of the input pattern. With black-and-white copy, the autocorrelation function is essentially the area of overlap of the pattern with an exact copy of itself as a function of the linear displacement between the copy and the original. In cartesian coordinates, the independent variables of the correlation function are the displacements along the rectangular axes. The chief advantage of the correlation function as a signature is that it is always centered at the origin of coordinates and is independent of translation of the primary pattern in the input field. The autocorrelation function as defined here, is not independent of rotation, however, and work is continuing in an effort to develop an analogous process which will preserve the information necessary for recognition or classification while removing the dependence on orientation.

IV TASK C—CONSTRUCTION OF A SMALL PARALLEL-CONNECTED PATTERN RECOGNITION MACHINE FOR FEASIBILITY STUDIES

A. BACKGROUND

Early in 1959 it was decided that the newly-formed Applied Physics Laboratory of the Engineering Division at Stanford Research Institute would take the subject of "learning machines" as one of its fields of primary interest, with particular emphasis on the problems of "reducing to practice," and the construction of a useful machine. The subject was attractive for several reasons. In itself it was challenging, and appeared ripe for development. Further, it had considerable bearing on the logic of machines which may ultimately be fabricated from components developed through the Applied Physics Laboratory's micro-electronics program. When this latter investigation comes to fruition it may be possible to fabricate inexpensive, active elements in quantities of the order 10^9 per cubic inch. Computers using such unrepairable components will contain many parallel channels, and be highly redundant. Pattern recognition by statistical decisions based on the information appearing simultaneously in numerous input channels would seem to make an ideal application for the micro-electronic computer. Such a computer would have available the enormous storage capacity essential for a comprehensive graphical data processing system. However, it will be several years before the development reaches a stage at which computer systems can be realized from micro-electronic components. In the interim, work will continue on highly parallel machines, and their practical implementation in terms of somewhat more conventional components.

It was very soon apparent from a search of the literature that a substantial body of theoretical effort had been engaged on the analysis of systems constructed from neuron-like elements, but that such numerical results as were presented came from simulations run on digital computers. Our philosophy is that a digital computer which treats its input data in serial fashion has a recognition time which increases linearly with the number of input channels, whereas the period required by a parallel machine is independent of the number of inputs. The difference may be of little consequence and overshadowed by other factors when one is considering relatively small machines, but for a retina of 300-by-300 picture elements and detail resolution comparable with a television picture, the advantage of a parallel machine is obvious.

The only strictly parallel machine now in operation is Rosenblatt's Mark I Perceptron. This machine was built primarily for the purpose of testing theoretical results, and has enabled an experimental check to be made of conclusions that were drawn regarding the possibilities latent in machines of this type. However, the multi-level storage was performed by motor driven potentiometers, and the operating speed was consequently very slow. This form of construction did not appear to be extensible to meet our concept of a "useful machine." On examination it was evident that the main obstacle impeding the construction of parallel machines was the high cost of the multi-level storage elements, and these would be needed in large numbers. Since one of the primary assignments of the Applied Physics Laboratory is the application of new devices, it seemed that a useful contribution might be made by a search for inexpensive methods of implementing the required logical functions.

Various schemes of recognition logic[15,16,17,18] were examined for the purpose of defining a minimum set of logical operations essential for the performance of pattern recognition. The operations of summation, threshold, control, gating and multi-level storage appeared to have the necessary generality. If a compatible set of circuit elements could be achieved to perform the required operational functions, a general purpose machine could be made into which the various schemes of logical connection might be programmed.

Such a compatible set of circuit elements, based on multi-aperture magnetic cores, has already been devised and an embryonic machine is being constructed. The four basic operational functions of summation, threshold control, gating and multi-level storage have been achieved at relatively low cost, since the components use magnetic cores and copper wire only; with the addition of a diode, it has been possible to achieve power gain and compatible input-output connections, thus permitting multi-layer logic. These components are fully described in the paper entitled "The Simulation of Neural Elements by Electrical Networks Based on Multi-Aperture Magnetic Cores," which is included as Appendix A in this report.

B. A BASIC DESCRIPTION OF THE SMALL PATTERN RECOGNITION MACHINE FOR FEASIBILITY STUDIES

The machine at present under construction will operate initially with logical connections of the Perceptron type as described by Rosenblatt;[15] however the components will be organized in a way which will permit modification of the logic in a relatively straightforward manner. A simplified diagram is given in Fig. 6.

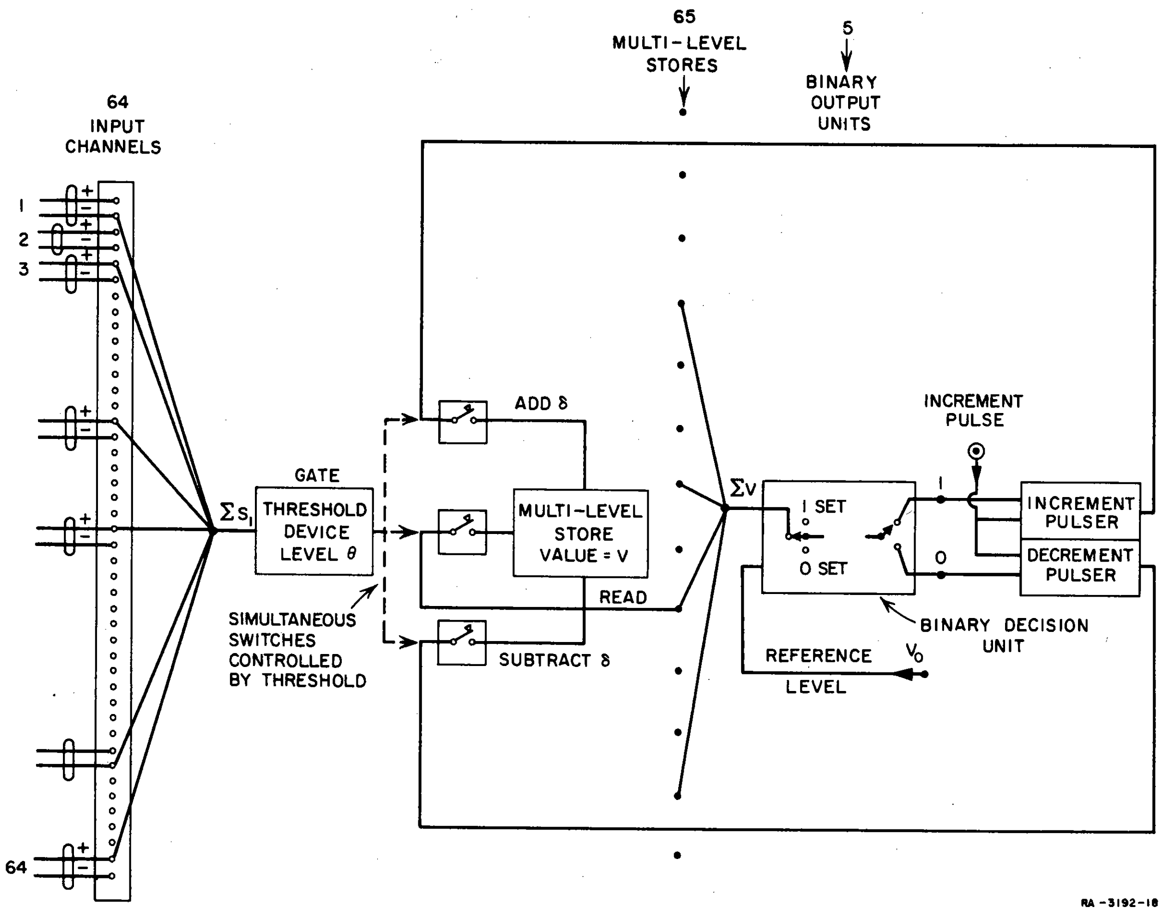


FIG. 6

SCHEMATIC DIAGRAM OF SMALL PARALLEL-CONNECTED LEARNING MACHINE

Initially the input data will be provided as DC signals appearing in 64 input channels; the source will be either an 8-by-8 photocell array or a switch panel of similar dimensions, and the power level will be of the order of 5 ma at 0.4 volt, per element.

The threshold-controlled gate and multi-level storage circuits immediately following the input channels are described in Appendix A of this report.

The input data will be sampled simultaneously by 65 gate circuits, each of which will sum the signals taken from perhaps 10 of the photocell circuits. Thus it will be necessary to provide for $64 \times 65 = 4160$ possible connections, of which 650 will be operative.

The summed inputs to the gate circuits will be compared with threshold levels, and those circuits for which the threshold has been exceeded will go to a condition described as "active," Circuits for which threshold has not been exceeded will remain quiescent, and take no further part in events until such time as they become active. At any instant it is unlikely that more than one-third of the units will be active; in a large machine it would be less than one-tenth.

When a unit becomes active, the multi-level store that is associated with it gives out a signal whose amplitude depends on the information "learned" by the machine. It is characteristic of machines of this type that the memory is not located uniquely—*i.e.*, a particular stored bit leaves a trace in several memory cells, but it shares the cells with other bits. When the proper group of cells is sampled in order to regenerate the stored bit, the output contributions created as a consequence of the bit act in unison, but the interference signals are of the nature of noise. If the circuit constants have been properly chosen, the correct decisions will be given when a choice is made as to whether the stored data corresponded to a one or a zero. Thus, the bit has been accurately regenerated. Two features of this method of storage should be noted: (1) it is statistical, and liable to give erroneous results even when the machine is functioning perfectly, and (2) it is possible for parts of the memory to fail without necessarily introducing error.

Initially there will be 65 multi-level stores each having at least 20 useful levels, and the output from these will be sampled by 5 decision units. Each decision unit sums its set of signals, compares that sum with a reference level, and determines which is greater. If the sum is greater, the decision unit shows a one; if less, a zero.

The machine may be looked upon as a classifier or a code converter. It classifies the data appearing simultaneously in the 64 input channels without serial analysis, and allocates one of 32 output codes on the basis of the cooperation between the input information and the content of the 65 multi-level stores.

It is now necessary to describe the process by which the learned information is introduced into the multi-level stores. Initially it will be assumed that the 8-by-8 retina is connected to the 65 gates by random sets of input connections having equal numbers of wires, and similar assumptions will be made with regard to the connections between the multi-level stores and the decision units. Consider an input pattern in the form of a square with unit line thickness lying one square in from the edge of the retina. This covers 20 squares out of 64. There are 10 wires from each of the 20 squares, and each wire contributes a unit level towards overcoming the threshold level of its controlling gate. Of the 65 gates perhaps 20 become active if the threshold level is 2.5. Initially all the stores are half full, and the reference signal against which the decision unit makes comparison is set equal to the average summed input. The output code is, under these conditions, arbitrary.

At this point a choice is made regarding the output code which the operator has selected to represent the classification of the input pattern. The decision units now have their inputs transferred from the output circuits of the multi-level stores to a switch bank which provides signals corresponding to the selected output code. The pulse generators controlled by the decision units are tied back to the multi-level stores by the increment and decrement circuits, and some of these have active gates selected by the input pattern. The *one* and *zero* pulse generators in each channel control reciprocal sets, so that when the increment button is pressed the active units which are tied onto a *one* channel, when a *one* has been set for that binary, receive an increment to their stores. However, if a *one* has been set and the store is contributing to the *zero* channel, the store output receives a decrement. It is important to appreciate that active units only are affected; inactive units play no part at all until they do become active. When information is being stored, the active units are determined by the selection exercised by the inputs from the retina and the threshold levels at the gates. It is reasonably obvious that discrimination and accuracy are strongly dependent on the presence of a high threshold level and an adequate number of multi-level stores.

While the machine under construction will be adequate for testing the magnetic elements to determine whether they are suitable components to use as the foundation for a unit of significant capability, it is appreciated that 65 multi-level stores represent a very small memory capacity. A rough estimate of the minimum desirable number of stores can be found by a simple calculation. It is efficient to set the threshold control on the gates at a high level so that only the most significant stores become active--say, one out of ten. There are five binary outputs, and for good cancellation of interfering signals a decision should be based on a sample derived from at least twenty stores. There is a further reason for requiring such a large sample: If the stores have twenty levels, it is desirable that the absence of one store should not prejudge the issue. However, it is legitimate for a store to contribute to more than one binary. Assume that each contributes to two. Thus the required number of stores is $10 \times 20 \times 5 \times \frac{1}{2} = 500$. A machine of significant capability would involve numbers that are very much larger.

The mechanical and electrical layout of the machine have been organized in a manner which will allow straightforward modification of the machine logic from the Perceptron type described above. Several other schemes will be tried. It appears probable that very specific methods of interconnection will show a substantial improvement in performance over the random sampling technique.

V TASK D—MATHEMATICAL INVESTIGATIONS

A. THE POSSIBLE APPLICATION OF CERTAIN THEOREMS OF INTEGRAL GEOMETRY

We have proposed a method of pattern recognition based on a novel application of a branch of mathematics called integral geometry, which is not very well known to workers in the pattern recognition field. The suggested method of pattern recognition has the advantage over some of the previously advanced schemes in that the pattern does not have to be placed in some standard position in order to be recognized. If a photograph is to be examined for the presence of a specified pattern, the photograph need not be subjected to a preliminary recognition which decides the orientation of the photograph with respect to the recognition device before the recognition phase. Since a complete and self-contained exposition of the mathematical details of this method is to be found in Appendix B of this report, and will also be presented in later reports, we limit ourselves here to a brief description of the general procedure and of the problems which arise in an effort to implement this procedure.

Essentially this is a method of discriminating between specified patterns—for example, five or six alternative patterns or indeed any finite number. It is assumed that the designer of the device knows beforehand the nature of every one of this finite set of patterns. For example, on a photograph he may have to distinguish between an empty dock and a dock with a ship in it. In this case, he must know what the empty dock looks like and at least approximately what the dock with a ship in it looks like. The device proceeds by "scanning" the pattern which is presented on its retina and to this extent resembles many other existing pattern recognition devices. The word "scan" in this context does not necessarily refer to a serial process, but is merely an abbreviated way of describing sampling along a line by any means whatever. The chief novelty is that the scanning pattern is not a specified left-to-right linear scan nor a large collection of parallel left-to-right linear scans, but rather scans which to begin with are not necessarily restricted to being straight lines, and secondly are performed not parallel to one another but in random direction with respect to one another.

To limit ourselves first to the case of linear scans—once the pattern to be recognized is presented on the retina, the device might scan this pattern with a straight line crossing from one border of the retina to another. It would then scan a second time along a second straight line chosen quite independently of the first. Then a third scan independently of the first two, and so forth, until a large number of scans had been accomplished whose net arrangement was that of a random collection of straight lines crossing the retina. There is a great deal of flexibility as to the kind of information that may be gathered from each scan. For example, it can be asked (1) whether a given scanning line crosses the pattern at all, or (2) if it crosses the pattern, how many times it intersects, or (3) what is the length of the intersection of the scanning figure with the pattern when the pattern is a solid figure. One of these possibilities is discussed in Appendix B, and a large number of them will be discussed in the appendixes to future reports.

If now we know a theorem which tells us what to expect as the average consequence of our random scanning procedure, when applied to each of the several alternative patterns, we have a means of deciding which pattern has actually been scanned. Suppose, for example, we are distinguishing between precisely two patterns by scanning along random straight lines, and we are in possession of a theorem that tells us that for Pattern 1 the average number of intersections of a scanning line of a figure is 0.5, and for Pattern 2 the average number is 2.6. Then, having performed our random scan, if we get an answer of 2.3 we will decide that it was the second pattern which was actually presented. The use of integral geometry permits us to obtain a large body of such theorems. These differ from one another in that they discuss scanning patterns of different shapes, not always straight lines, and ask the scanning device to tally different kinds of information—for example, numbers of intersections, and distance between intersections, etc. It is intuitively clear, as well as a provable theorem, that this method is independent of the orientation and location of the pattern to be recognized on the retina of the device, since the very method of scanning treats all locations and orientations equally alike. By contrast, the method of parallel scanning would regard the letter "a" upright and the letter "a" on its side as having quite different properties.

The first phase of work has naturally been devoted to the gathering of the available theorems with a view to examining them for practical application. Since these theorems arose in a completely abstract mathematical context, many questions which are natural for the designer of a recognition device have not been previously asked, and there has been some search of the literature to find out if, in addition to the basic theorems of integral geometry, there are laws of supporting theorems, or supporting calculations, which would aid the designer. For example, the nature of the classical theorems in integral geometry is to predict--given the pattern to be scanned, and given the scanning figure which is to be used repeatedly in random locations and orientations, and given the information to be tallied on each scan--what an average effect is of scanning in all possible locations and orientations. It is, of course, impossible to scan more than a finite number of times, and a device would be regarded as unfeasible if it requires too large a number of scans in order to arrive at a decision. Hence it is important to know what reliance can be placed on a practical measurement using only a finite number of scans, when the theorems are based on using all possible scans. There is very little literature available on this question and, in fact, it may be that the only workable way to answer this question is by actually building a device and examining it for reliability.

Questions of reliability versus number of scans, and degradation due to errors are the main subject of the present inquiry. To this end, a notion of "noise" suitable for pattern recognition problems is being examined. This corresponds to a random set, rather than a random location or orientation of a given set.

B. THE LOGIC OF PRACTICAL WIRING SYSTEMS FOR THE IMPROVEMENT OF THE PERFORMANCE OF MACHINES OF LIMITED CAPACITY IN SPECIFIC SITUATIONS

The pattern recognition machine which has been proposed will accept, process, and store information in a parallel manner. As a consequence, a major problem that must be solved is how to interconnect the various functional parts to achieve the desired performance economically, with due regard to such engineering considerations as speed of operation, reliability and simplicity. There are, grossly, three main areas of investigation:

(1) Interconnections between input units and the first (and perhaps only) layer of logic-performing units. It may very well be that in this area, some processes of information "filtering" are accomplished, such as the "spatial filtering operation" of Taylor,[16] in which the information is reduced to more tractable and simple

form for subsequent processing. Here, too, one might impose a specific scheme of connections to extract invariant features of the input patterns, such as that suggested by the use of the Integral Geometry studies.

(2) Interconnections between the logical functional units themselves. This area is least understood, but work now being carried on by Rosenblatt[19] on cross-coupled "perceptrons" indicates that it may be possible to "teach" such a machine generalized transformations, such as are involved in rigid motions of objects in a plane.

(3) Interconnections between the logical units and the output units. These interconnections serve two purposes: they permit flow of desired information after internal processing to indicators (which may perform some final logical functions), and they also enable "forcing" or "teaching" the machine classification information, which is then stored in some manner amongst the inner layer of logical units.

For the present, our studies have been restricted to the first and third items outlined above. As described in Appendix B, various theorems in Integral Geometry are being developed and their use for pattern recognition is being explored. In the third item, initial work was started six months ago to attempt to answer certain questions which are applicable to this problem. In this work it is assumed that we will use the non-destructive-read-out, multi-level analog store (see Appendix A), capable of being incremented and decremented in unit steps. It is further assumed that binary information is to be stored in a distributed manner—*i.e.*, each bit will leave its trace in more than one multi-level store. The questions we are trying to answer, then, are the following:

(1) How are the stores to be connected to n binary outputs so that any arbitrary choice of the 2^n binary patterns can be read into the stores and subsequently read out correctly, each process being a parallel process?

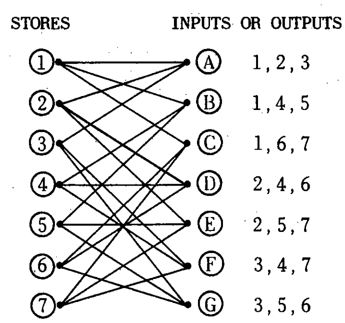
(2) What is the minimum number of stores required for a given number of binary outputs, and how sensitive to failure or error is such a system?

Initial work on these problems has consisted of a paper study starting with multiple random interconnections between stores and output-input units, and imposing successive constraints, by a process of intuition and inference, to derive a systematic structure with specific rules for its organization and operation. This work was reported[20] at a symposium held in Champaign, Illinois, June 1960, the proceedings of which will become available late this year.

A relatively simple interconnection scheme which appeared promising is illustrated in Fig. 7, and is described below.

In Fig. 7 the multi-level stores labelled 1 to 7 are connected to the input-output units labelled A to G. Each such connection shown represents two pathways. An arbitrary set of binary numbers to be stored is assigned to the A, B, C, ..., G units. Each such unit will originate either an increment of *one* for an assigned binary one, or a decrement of *one* for an assigned binary zero. On read-in, operating from right to left, increments or decrements of *one* originating from each input-output unit can be imposed on the multi-level stores, all increments or decrements being summed algebraically, the net increment or decrement constituting the change in store level. On read-out, operating from left to right, the previously summed stored values are summed algebraically at the input-output units and are interpreted, or converted to binary outputs.

For example, on Trial (a), the binary numbers 1,0,0,0,0,0,0 have been assigned to the input-output units A to G respectively. Thus increments of *one* are forced on Stores 1, 2, and 3 to which Unit A is connected,



TRIAL	OPERATION	INPUT OR OUTPUT						
		A	B	C	D	E	F	G
(a)	Read In (Binary)	1	0	0	0	0	0	0
	Read Out (Sum)	-3	-7	-7	-7	-7	-7	-7
(b)	Read In (Binary)	1	1	0	0	0	0	0
	Read Out (Sum)	-1	-1	-5	-5	-5	-5	-5
(c)	Read In (Binary)	1	1	1	0	0	0	0
	Read Out (Sum)	+1	+1	+1	-3	-3	-3	-3
(d)	Read In (Binary)	1	1	1	1	1	1	1
	Read Out (Sum)	+9	+9	+9	+9	+9	+9	+9

STORE NO.	SUM OF INCREMENTS AND DECREMENTS FOR TRIAL NO.			
	(a)	(b)	(c)	(d)
1.	-1	+1	+3	+3
2.	-1	-1	-1	+3
3.	-1	-1	-1	+3
4.	-3	-1	-1	+3
5.	-3	-1	-1	+3
6.	-3	-3	-1	+3
7.	-3	-3	-1	+3

FIG. 7

WIRING DIAGRAM OF DISTRIBUTED MEMORY

decrements of *one* are forced to Stores 1, 4, and 5 to which Unit B is connected, and so on. The net sum of increments and decrements forced on Store 1 in this example is −1, consisting of one increment from A and two decrements from B and C. On read-out, at Unit A, the net increments and decrements from Stores 1, 2, and 3 are summed, and total −3. We thus obtain the whole set of read-out quantities—namely, −3, −7, −7, −7, −7, −7, −7—for Units A to G respectively. One simple method of conversion back to binary outputs, would be to find the algebraic average of all multi-level outputs [in this case −(45/7) = −6(3/7)] and then compare the magnitude algebraically of each output sum with this average. Thus the output for A (−3), is greater than −6(3/7), and becomes a binary one. The other outputs are smaller, and become binary zeros, thus recovering correctly the original binary input pattern. This simple method of interpretation works for all the 2^7 possible binary input patterns except for two degenerate patterns represented by Trial (d). Other and more powerful procedures of read-in and read-out have been found, which permit some degree of failure of components and yet provide correct operation.

The systematic wiring scheme shown is derived in the following manner: Opposite each input-output unit there is listed a triplet of numbers representing the connections from that unit to the numbered stores. Thus Unit A, connected to Stores 1, 2, and 3 has a triplet of 1, 2, 3 listed opposite it. Each such triplet can be considered as made up of three doublets; thus the triplet 1, 2, 3 can be decomposed into the three doublets— 1,2; 1,3; 2,3. The choice of triplets, and therefore of connections, is made such that all doublets possible in the set from 1 to 7 are represented once and only once. In the set shown, there is an equal number, n, of stores and of input-output units, and there are r connections to each store; similarly there are r connections to each input-output unit. It can be shown that for wiring sets conforming to these rules, $n = r^2 - r + 1$. Thus for the next larger set, when $r = 4$, there are 13 stores and 13 input-output units. The connection scheme for $r = 4$, is shown below in convenient form:

INPUT-OUTPUT UNIT	CONNECTED TO STORE NUMBERS
A	1,2,3,4
B	1,5,6,7
C	1,8,9,10
D	1,11,12,13
E	2,5,8,11
F	2,6,10,13
G	2,7,9,12
H	3,5,9,13
I	3,6,8,12
J	3,7,10,11
K	4,5,10,12
L	4,6,9,11
M	4,7,8,13

Here, too, it should be noted that each quadruplet of numbers can be decomposed into $4_{C_2} = 6$ doublets; thus the quadruplet 1,2,3,4 yields the doublets 1,2; 1,3; 1,4; 2,3; 2,4; 3,4. The doublets in this set number $13_{C_2} = 78$, and each is represented once and only once.

The above connection scheme probably represents one of perhaps many possible schemes which have in common the property of "scattering" connections in an optimum symmetrical manner. Further work elaborating on this initial approach is being undertaken.

VI TASK E—DATA STORAGE AND RETRIEVAL IN RELATION TO THE SPECIAL PROBLEMS OF NON-ALPHANUMERIC GRAPHICAL DATA PROCESSING

The study of the information storage and retrieval aspects is proceeding slowly, and is mainly concerned with planning the major effort and surveying the pertinent literature. In keeping with the original project plans, the level of effort will be increased on this task during the second quarter of the project. The effort will be directed along three major lines: (1) Suggestions for an indexing and classification system for aerial photographs, (2) a study of how the existing techniques for mechanization can be applied to large files of aerial photographs, and (3) a study of newer and less-developed mechanization techniques, such as automatic indexing and classification.

The pertinent literature seems to indicate that no organizations are using classification systems to describe the contents of an aerial photograph in any detail. Nearly all the users file the prints by geographical location or project number, or film reel and frame number. However, if there is an interest in mechanizing the file for subsequent detailed searches, then a careful study must be made to provide an adequate classification or indexing scheme. A good working familiarity with the file contents and the interest of the users is a pre-requisite to the design of the scheme. Because of this, the SRI work on this project must initially be limited to developing the outline of such a system, and pointing out the areas for further study and consideration.

Several system configurations will be given to show how the currently available hardware (*e.g.*, Minicard, Magnacard, data processing equipment, tape searching devices, punched card equipment, etc.) can be applied to this problem. Consideration will be given to systems which store the image and the indexing information together on the same physical item, as well as systems which operate on the indexing data to obtain references to images which are stored at some other physical location.

Consideration will also be given to other associated areas for possible mechanization. Examples of such areas are (1) continued monitoring of the file contents to locate "holidays" (areas for which no photographs or maps are available), (2) the possibility of automatic photo indexing or titling, and (3) the generation of analysis reports which describe in report form the contents of specific geographic areas of interest.

VII CONCLUSIONS

Conclusions which may be drawn from the material presented in this report are presented below.

Task A--Application of the Techniques of Graphic Arts and Sciences to the Simplification of Input Data

It is possible to take continuous tone material, and transform it into a two-valued tone scale representation, simultaneously eliminating fine detail and creating a solid outline around objects of significant size. It is believed that preliminary processing of this type is advantageous from the point of view of improving the effectiveness of electronic pattern recognition machines.

Task B--A Survey of Electronic Methods of Performing Pattern Recognition

In addition to the literature search, consideration has been given to a technique which might lead to the development of a machine to perform pattern recognition independent of orientation. It is based on auto-correlation.

Task C--The Construction of a Small Parallel-Connected Pattern Recognition Machine for Feasibility Studies

A set of compatible components based on multi-aperture magnetic cores will make it possible to construct a general purpose machine, useful for making comparisons between the various systems of logic.

Task D--Mathematical Investigations

Part (a)--Integral geometry provides theorems that give numerical relations between properties of geometrical figures which are invariant under rotation and displacement. It may be possible to use these relations for the purpose of pattern recognition.

Part (b)--In the search that is being made to find useful methods of sampling the data appearing simultaneously in numerous channels, one optimum symmetrical scheme has already been discovered.

PROGRAM FOR THE NEXT INTERVAL—1 JULY TO 30 SEPTEMBER 1960

Task A

A limited amount of further testing will be done on the photographic techniques for the simplification of continuous tone material. This work will be primarily aimed at evaluating the technique for its effectiveness on a wider variety of raw copy.

Consideration will be given to the use of Xerography and Electrofax to achieve equivalent results.

The possibility of developing a single-step photographic method of tone conversion utilizing semi-reversal effects will be investigated.

Optical filtering and video techniques for arriving at the necessary tone simplification will be investigated.

Task B

The survey of electronic methods of pattern recognition will be continued, and an evaluation of techniques described in the literature is scheduled for Report 2.

The study of novel systems which lead to recognition invariant under rotation will be pursued.

Task C

The construction of a small parallel-connected pattern recognition machine will be continued, with particular emphasis on the problems of mutual interference between components. In such a highly interconnected structure, and especially for the increment and decrement channels, the magnitude of such effects is difficult to calculate. Perceptron type logic will be used in the initial tests.

Task D Mathematical Analysis.

The investigation of numerical relationships relating to the properties of geometrical figures which are invariant under rotation and displacement will be extended. A large number of such relations may be found; it will be necessary to evaluate them from the point of view of effectiveness and practical implementation in terms of a pattern recognition machine.

The work on special methods of interconnection to improve the performance of parallel-connected pattern recognition machines will be continued, with particular reference to the small machine being constructed under Task C.

Task E

During the second quarter the rate of work on data storage and retrieval in relation to the special problems of non-alphanumeric graphical data processing will be increased substantially. The effort will be directed along three major lines: (1) Suggestions for an indexing and classification system for aerial photographs, (2) a study of how existing techniques for mechanization can be applied to large files of aerial photographs, and (3) a study of newer and less-developed mechanization techniques, such as automatic indexing and classification.

IDENTIFICATION OF KEY TECHNICAL PERSONNEL

	Hours
Mr. Geoffrey H. Ball *Research Engineer, Applied Physics Laboratory*	108
Mr. Virgil P. Barta *Manager, Graphic Sciences Laboratory*	10
Mr. Charles P. Bourne *Research Engineer, Special Projects Group, Computer Techniques Laboratory*	55
Dr. Alfred E. Brain *Research Physicist, Applied Sciences Laboratory* (Project Leader)	491
Mr. Clyde O. Childress *Graphic Associate, Graphic Sciences Laboratory*	180
Mr. George E. Forsen *Research Engineer, Applied Physics Laboratory*	239
Mr. Marcian E. Hoff, Jr. *Research Engineer, Applied Physics Laboratory*	136
Mr. Louis J. Kabell *Senior Research Engineer, Graphic Sciences Laboratory*	10
Dr. Albert B. J. Novikoff *Mathematician, Mathematical Sciences Department*	133
Dr. Charles A. Rosen *Manager, Applied Physics Laboratory*	78
Dr. Robert A. Tobey *Staff Scientist, Subdivision A*	161
Mr. Loren G. Wright *Development Engineer, Applied Physics Laboratory*	157
Shop and Technician Time	641
Secretarial	76
Total Hours	2,475

Biographies of all key technical personnel follow.

Geoffrey H. Ball - Research Engineer, Applied Physics Laboratory

Mr. Ball received an A.B. degree in Applied Science from Harvard College in 1955 and an M.S. degree in Electrical Engineering from Stanford University in 1960. He is working for a PhD. degree.

From 1955 through 1958, he served as a Line Officer (CIC and Operations) in the U.S. Navy. During the summer of 1959 he was employed by Hughes Aircraft Co. in the Semiconductor Division as a member of the technical staff. In June of 1960, Mr. Ball was employed by Stanford Research Institute for the summer as a Research Engineer in the Applied Physics Laboratory of the Engineering Research Division. His fields of specialty include control systems, applications of probability to machines, and adaptive machines.

Mr. Ball is a Student Member of the Institute of Radio Engineers.

Barta, Virgil P. - Manager, Graphic Sciences Laboratory

Mr. Barta attended Reed College, and received a B.Sc. degree in Physics in 1942 from Oregon State College. He has done graduate work toward a Ph.D. degree at Oregon State College, and was on the faculty of the Physics Department.

During World War II he served as a technical commissioned officer in the U.S. Army Signal Corps, assigned to General Staff duty and liaison with the British and French branches of the Radiation Laboratory, M.I.T.

From 1947 to 1950 he organized and served as Head of the Photographic Department of the State College of Washington. In 1950 he became Head of the Graphic Arts Research Department of the Rochester Institute of Technology, where he organized and directed the research program until 1955.

In 1955 he joined the Technicolor Corporation as Technical Director of the Graphic Arts Division, later becoming Acting Division Manager.

In June 1958 Mr. Barta joined the staff of Stanford Research Institute, as a Senior Research Physicist, to organize and coordinate the Institute's Graphic Arts Research Activities. The Graphic Sciences Group was formally organized in June 1959; in January 1960 the Video Systems Laboratory merged with Graphic Sciences and Mr. Barta was named Manager of the Institute's new Graphic Sciences Laboratory.

Mr. Barta is past National President of the Technical Association of the Graphic Arts, and Chairman of their Board of Directors; a member of the Research and Engineering Council of the Graphic Arts Industry; a member of the Research Committee of the Lithographic Technical Foundation; and was a representative to the Second International Conference of Printing Research Institutes in Sweden (1953). He is also a member of Sigma Xi, Sigma Pi Sigma, Chi Beta Phi, and the Scientific Research Society of America.

Bourne, Charles P. - Research Engineer, Special Projects Group, Computer Techniques Laboratory

Mr. Bourne received a B.S. degree in Electrical Engineering from the University of California in 1957. He is working on an M.S. degree at Stanford University, specializing in data-processing and operations research.

He served in the U.S. Marine Corps during 1950-1951. In 1952-1953 he was an Instructor in Guided Missile Instrumentation, Maintenance, Operation, and Telemetry at Convair Guided Missile Division. While he was a university student he did summer work as an Engineering Aide at Stanford Research Institute on system cooling and component temperature studies for the ERMA computer system.

In June 1957 Mr. Bourne became a Research Engineer on the staff of the Institute. He has participated in a government project to investigate storage, retrieval, and reproduction techniques for a file of several million engineering drawings; engineering and operational evaluations of several new general-purpose digital computer systems for various computer manufacturers; technical planning for the installation of a digital computer system at the Institute; and a government project to design a comprehensive mechanized system for accumulating, reviewing, disseminating, storing, and retrieving abstracts of European technical literature. He also supervised the operation and programming effort and conducted the systems studies that determined programming requirements, choice of computer, and expansion capabilities for a large digital computer system currently used as part of a military reconnaissance system. He has provided product planning assistance in the design of magnetic tape systems for commercial data processing equipment, and has conducted system studies for the design of a vary large memory for information retrieval problems.

Mr. Bourne has written several articles for technical journals, dealing with information retrieval and technical information problems, and with studies in non-linear mechanisms. He is a member of the Institute of Radio Engineers and the Association for Computing Machinery, and was Chairman of the sessions on Information Retrieval and Machine Translation at the 1959 Western Joint Computer Conference.

Brain, Alfred E. - *Research Physicist, Applied Physics Laboratory* (Project Leader)

Dr. Brain received a B.Sc. degree in 1943, an M.Sc. degree in 1948, and a Ph.D. degree in 1952, all in Physics from the University of Sheffield, England. From 1943 to 1946 he served at the Royal Aircraft Establishment, Farnborough, as a Junior Scientific Officer, developing anti-jamming devices and rebuilding captured radar equipment. During the period of 1946 to 1949 he was a Circuit Engineer at the E.M.I. Research Laboratories, Middlesex, England, working on multistage, wideband video amplifiers for high definition television. In 1949 Dr. Brain joined the staff of the Department of Physics of Sheffield University, as Ellison Research Fellow. He carried on research on the magnetic properties of semiconductors and supervised undergraduate teaching laboratories. In 1952 he returned to the E.M.I. Laboratories as a Physicist to set up a section to do work in solid-state physics, and to organize a pilot line to make transistors.

In 1956 he became a Physicist in the Electronics Laboratory of the General Electric Company in Syracuse, working on the design of feedback amplifiers, phase correction of delay lines, photoelectric cells, and thin magnetic films.

In December 1958 Dr. Brain joined the staff of Stanford Research Institute, where he has been engaged in the evaluation of high-speed photographic recording techniques, humidity measurements, and a survey of devices potentially suitable for use in neuron simulation circuits.

Dr. Brain is an Associate Member of the British Institute of Electrical Engineers and a Senior Member of the Institute of Radio Engineers.

Childress, Clyde O. - *Graphic Associate, Graphic Sciences Laboratory*

Mr. Childress studied photography at the Art Center School in Los Angeles in 1943-1944, and subsequently was a photography instructor at that school. He became a free-lance magazine and advertising photographer.

From 1953 until he joined the staff of Stanford Research Institute in 1959, he was a Staff Photographer for the Lane Publishing Company, publishers of Sunset Magazine, in Menlo Park. At the Institute Mr. Childress is performing research in phototechnology with emphasis upon new pressureless printing processes for application in the graphic arts industry.

He is responsible for the original work on "The Childress Process of Correct Tonal Reproduction" which was presented at the Technical Association of the Graphic Annual Meeting in June of 1958. His patent assignments are in the field of photographic tone reproduction.

Mr. Childress is a member of the American Society of Magazine Photographers.

Forsen, George E. - Research Engineer, Applied Physics Laboratory

Mr. Forsen received both an S.B. and an S.M. degree in Electrical Engineering from the Massachusetts Institute of Technology in 1957, and the degree of Electrical Engineer from M.I.T. in 1959.

On the Cooperative Plan with M.I.T. he was employed part time in 1954-1956 by the General Electric Company. While with G.E. he was a member of the Small Aircraft Engine Department (Lynn, Massachusetts), the General Engineering Laboratory (Schenectady, New York), and the Electronics Laboratory (Syracuse, New York), working on standards, non-destructive testing methods, and measurement techniques for heat flow in power transistors, respectively.

In 1958-1959 he was a member of the Communications Biophysics Group, Research Laboratory of Electronics at M.I.T., as a Research Assistant and staff member. There he designed electronic instrumentation for the study of neuroelectric and psychophysical phenomena related to nervous systems. From 1957 to 1959 he was also employed by the Electrical Engineering Department of M.I.T. as a Teaching Assistant.

In October 1959 Mr. Forsen joined the staff of Stanford Research Institute. At the Institute he is currently engaged in the study of field emission and neuron-like devices.

Mr. Forsen is a member of the Institute of Radio Engineers and Sigma Xi.

Hoff, Marcian E., Jr. - Research Engineer, Applied Physics Laboratory

Mr. Hoff received a B.E.E. degree from the Rensselaer Polytechnic Institute in 1958 and an M.S. degree in Electrical Engineering from Stanford University in 1959. He is working for a Ph.D. degree.

During the summer of 1960 Mr. Hoff is a Research Engineer at Stanford Research Institute, working on magnetic core devices for learning machines.

Mr. Hoff is a member of Eta Kappa Nu, Tau Beta Pi, and Sigma Xi, and a Student Member of the Institute of Radio Engineers.

Kabell, Louis J. - Senior Research Engineer, Graphic Sciences Laboratory

Mr. Kabell received a B.S. degree in Electrical Engineering from the University of Colorado in 1944. From 1944 to 1946 he served as a Radar Officer in the U.S. Navy. During 1946 and part of 1947 he was a Development Engineer in the Radio Corporation of America's Victor Division. In 1947 he was employed by Sandia Laboratories, Sandia Base, Albuquerque, as a Test Equipment Development Engineer, engaged in pulse radar system development; FM radar system development; and transistor circuit research, development, and application to digital computers.

In October 1953 Mr. Kabell joined the staff of Stanford Research Institute, where he has been engaged in transistor circuit, color television, and electrostatic image transfer work. His fields of specialty include pulse circuits and transistor circuit research. Patent assignments are in the fields of color television, transistor circuits, and video recording.

Mr. Kabell is a member of the Institute of Radio Engineers, the Scientific Research Society of America, Eta Kappa Nu, and Tau Beta Pi.

Novikoff, Albert B. J. - Mathematician, Mathematical Sciences Department

Dr. Novikoff received an A.B. degree from Brown University in 1945 and a Ph.D. degree from Stanford University in 1949, both in Mathematics. He was an Atomic Energy Commission Pre-Doctoral Fellow in Mathematics. From 1950 to 1952 he was an Instructor of Mathematics at Johns Hopkins University. In 1952 he became a Research Associate in the Radiation Laboratory of that university, where his work included the applications of probability and Fourier methods to noise problems and also the study of signal analysis. From 1956 to 1958 he was an Instructor of Mathematics at the University of California, especially concerned with Lie theory and differential geometry.

In June 1958 Dr. Novikoff joined the staff of Stanford Research Institute, where he has been working on probability applications to antenna measurements, theoretical network analysis, equipment location, and classical mechanics, signal discrimination, and character recognition.

In 1960 he is for the second summer an invited lecturer at the Intensive Course in Random Processes given at the University of Michigan.

Dr. Novikoff is a member of Sigma Xi, the American Mathematics Society, the Mathematics Association, the Canadian Mathematics Congress, the Societie Mathematique de France, the Society for Industrial and Applied Mathematics, and the Institute of Mathematical Statistics.

Rosen, Charles A. - Manager, Applied Physics Laboratory

Dr. Rosen received a B.E.E. degree from the Cooper Union Institute of Technology in 1940. He received an M.Eng. in Communications from McGill University in 1950, and a Ph.D. degree in Electrical Engineering (minor, Solid-State Physics) from Syracuse University in 1956.

During 1940-1943 he served with the British Air Commission as a Senior Examiner dealing with inspection, and technical investigations of aircraft radio systems, components, and instrumentation. From 1943 to 1946 he was successively in charge of the Radio Department, Spot-Weld Engineering Group, and Aircraft Electrical and Radio Design at Fairchild Aircraft, Ltd., Longueuil, Quebec, Canada. During the period 1946-1950 he was a co-partner in Electrolabs Reg'd., Montreal, in charge of development of intercommunication and electronic control systems. During this period he also acted as a self-employed consulting engineer in these fields. In 1950 he was employed at the Electronics Laboratory, General Electric Co., Syracuse, New York, where he was successively Assistant Head of the Transistor Circuit Group, Head of the Dielectric Devices Group, and Consulting Engineer, Dielectric and Magnetic Devices Subsection. In August 1957 Dr. Rosen joined the staff of Stanford Research Institute, where he has been working on applied physics projects.

His fields of specialty include dielectric and piezoelectric devices, electromechanical filters, and a detailed acquaintance with the solid-state device field. He has contributed substantially as co-author to two books, *Principles of Transistor Circuits*, R. F. Shea, editor (John Wiley and Sons, Inc., 1953) and *Solid State Dielectric and Magnetic Devices*, H. Katz, editor (John Wiley and Sons, Inc., 1959). Two patents have been awarded and assigned; application has been made for five more and 15 are in process for application.

Dr. Rosen is a Senior Member of the Institute of Radio Engineers, a member of the American Physical Society, American Institute of Electrical Engineers, and the Research Society of America. He has organized and been the co-chairman of the Dielectric Devices Subcommittee (28.5 IRE).

Tobey, A. Robert - Staff Scientist, Subdivision A

Dr. Tobey received from Yale University a B.S. degree in 1942, an M.S. in 1946, and a Ph.D. in 1948, all in Physics. The subject of his dissertation was "Neutron Production by Cosmic Rays." While an undergraduate he was a Research Assistant. From 1942 to 1945 he was a staff member of the Radiation Laboratory of the Massachusetts Institute of Technology. During 1947-1948 he was an Assistant in Research at Yale. He was Assistant Professor of Physics at Washington State College from 1948 to 1950. From 1950 to 1953 he was employed by the Armour Research Foundation in Chicago as Supervisor, Electricity and Magnetism Research, Physics Department; and Senior Scientist, Electrical Engineering Department.

Dr. Tobey joined the staff of Stanford Research Institute in September 1953 as a Supervisor in the Television Laboratory. He became a Group Head in September 1956 and Staff Scientist in 1959. His fields of specialty include information theory, modulation theory, analysis and synthesis of electronic systems, radar, television, and the application of physics concepts and techniques to engineering problems. Patents pending are in the field of bandwidth reduction.

Dr. Tobey is a member of the American Physical Society, Sigma Xi, and the Scientific Research Society of America.

Wright, Loren G. - Development Engineer, Applied Physics Laboratory

Mr. Wright received a B.S. degree in Electrical Engineering from the Heald Engineering College, San Francisco, in 1949. From 1943 to 1946 he had served in the U.S. Army as a Radio Technician and Radio Operator.

Before he joined the staff of Stanford Research Institute in 1953, Mr. Wright was employed by the Pacific Gas and Electric Company and the California Research and Development Company. At the Institute Mr. Wright worked in the Control Systems Laboratory on the ERMA development which SRI conducted for the Bank of America. He assisted in magnetic ink and magnetic printing research and in the development of a check sorter. Recently he has been working in the Applied Physics Laboratory in the field of ferroelectric and magnetic materials, in the field of ferroelectric and magnetic materials, in connection with fast-neutron irradiation damage.

APPENDIX A

THE SIMULATION OF NEURAL ELEMENTS BY ELECTRICAL NETWORKS BASED ON MULTI-APERTURE MAGNETIC CORES

THE SIMULATION OF NEURAL ELEMENTS BY ELECTRICAL NETWORKS BASED ON MULTI-APERTURE MAGNETIC CORES

1. INTRODUCTION

In the many schemes that have been suggested for the simulation of neural elements by electrical networks,[15,16,17,18] the following characteristic electrical operations recur with considerable regularity and form the building blocks from which comprehensive simulations may be devised:

(a) Multi-Level Storage

The strength of an output signal is to be dependent on the previous history of the neural element. In the simulation this appears as a "weight" or "stored value." Since the weight is to receive increments and decrements at intervals throughout the period of operation of the system, it is desirable that read-out should be non-destructive. In some systems it is necessary to generate a signal level proportional to the product of two or more weights.

(b) Gating Function

A signal may or may not be present, depending on the presence of controlling signals. This implies a relay, commonly a normally off make-and-break relay, which closes when part of a system becomes "active," and for example allows a signal to be read out from a multi-level store.

(c) A Controlling Threshold Level

A signal is gated either on or off depending on whether the signal level at some point exceeds a controlling threshold level θ. The threshold may control several circuits simultaneously.

(d) Summation

A set of signals is added together to form an input, which may for example be compared with a gating level θ.

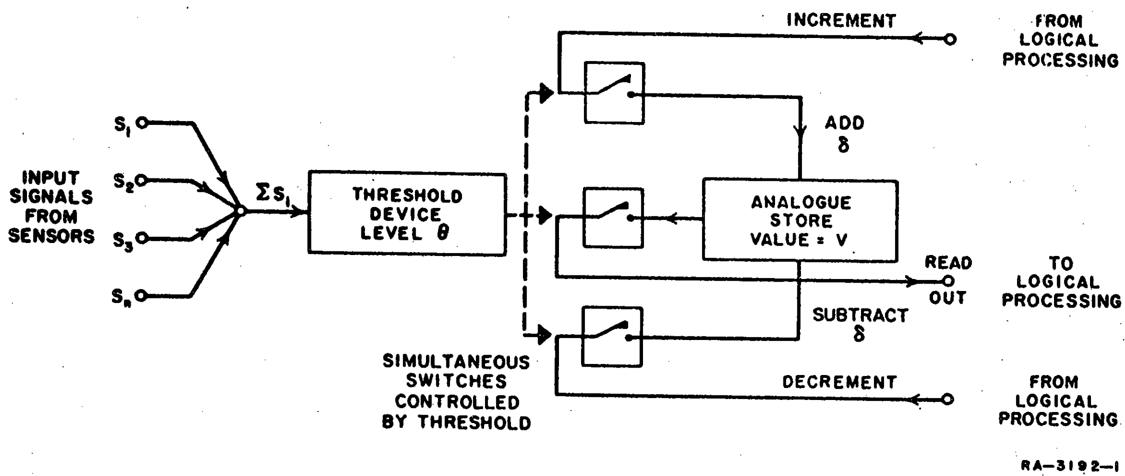


FIG. A-1

SIMULATION CIRCUIT FOR NEURAL ELEMENT

One possible arrangement based on the work of Rosenblatt[15] is shown in Fig. A-1. The inputs from the sensors S_1, S_2, S_3, . . . are summed to generate an input signal, ΣS_1 · ΣS_1 is compared with the threshold θ, and if $\Sigma S_1 > \theta$, the three normally open make-and-break contacts are closed. The unit is said to be active. A signal level proportional to the stored weight, of value V, is read out from the analog store of the active unit and processed by subsequent logical elements in the system. On the basis of this processing, the analog store may receive either an increment or a decrement to its store;

both possibilities are available since the threshold has been exceeded and the switches in the increment and decrement lines were closed at the time of read-out. It is required that inactive units are isolated from the active system and do not have their stored weights changed so long as they are inactive.

2. ANALOG STORAGE IN APERTURED CORES

The preliminary investigation of analog storage in apertured cores has been carried out using ferrite cores of the type described by Crane[21,22] (Fig. A-2). The dimensions of the core are characterized by the fact that the cross-sectional area of A is equal to the sum of areas B and C, and also that B and C are equal. Thus, when A is saturated by winding a, both B and C are saturated also in either a clockwise or counter-clockwise direction. However, if there is a winding b as shown, carrying a bias current, it is possible to hold the core material within the dotted circle saturated in a particular direction and to reverse some of all of the material outside it.

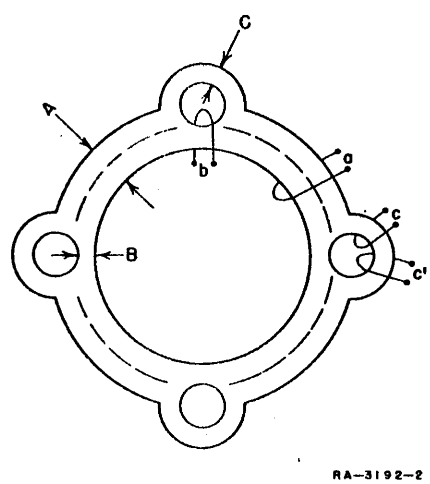


FIG. A-2

CONFIGURATION OF MAD FERRITE CORE OF BENNION AND CRANE

Since the material most easily switched is that with the shortest path length, assuming the core to be homogeneous, when the saturated core of Fig. A-2 is partially switched, the flux distribution changes from that shown in Fig. A-3(a) to the situation in Fig. A-3(b).

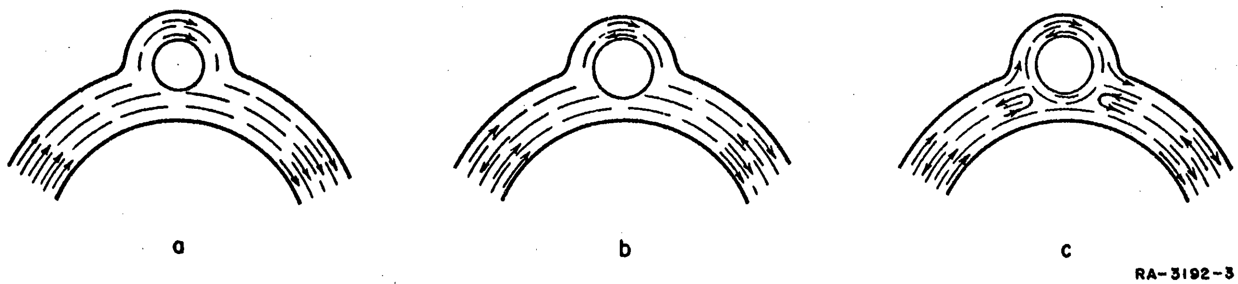


FIG. A-3
PARTIAL SWITCHING OF FLUX AROUND AN APERTURE

If a high-frequency carrier is fed into a winding c in the side hole, and a second winding c' is put on the same leg (Fig. A-2), a signal appears in c' which has a level proportional to the amount of flux which has been switched around the large aperture. Several cycles of carrier may be required before a reversible flux system is reached, since the initial situation shown in Fig. A-3(b) is unstable and reverts to Fig. A-3(c). Once this equilibrium condition is reached, in order to change the output signal level, it is necessary to switch some of the flux around the large aperture; flux trapped around the hole may therefore be sensed non-destructively with relatively high carrier drive without risk of degrading the stored level.

The extent to which the core is switched can be varied incrementally by the use of a very small core ("bucket"), Fig. A-4. However, it is essential that the switching should always occur at a constant reference phase with respect to the carrier drive unless this is removed, since the size of the

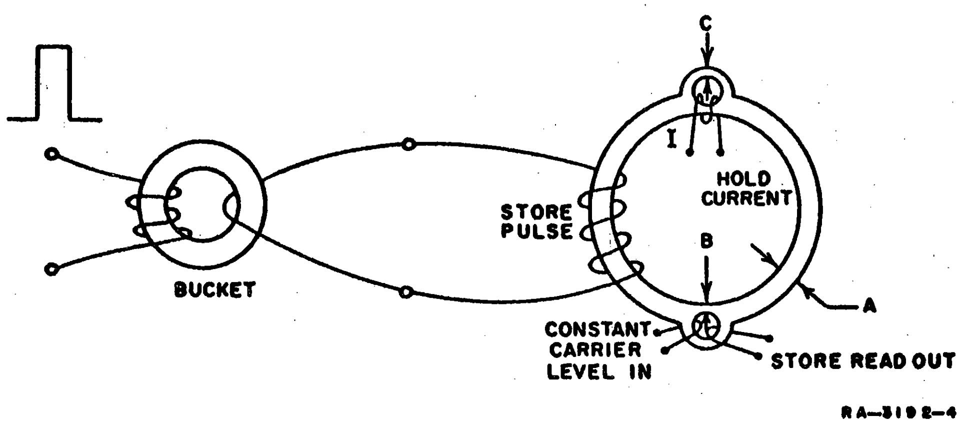


FIG. A-4

MULTI-APERTURE CORE USED FOR ANALOG STORAGE

increment depends on the vector sum of the switching pulse and the carrier. In the practical realization of Fig. A-1, using two similar multi-aperture cores, the bucket core is in fact one of the side holes. Typical measurements are shown in Fig. A-5.

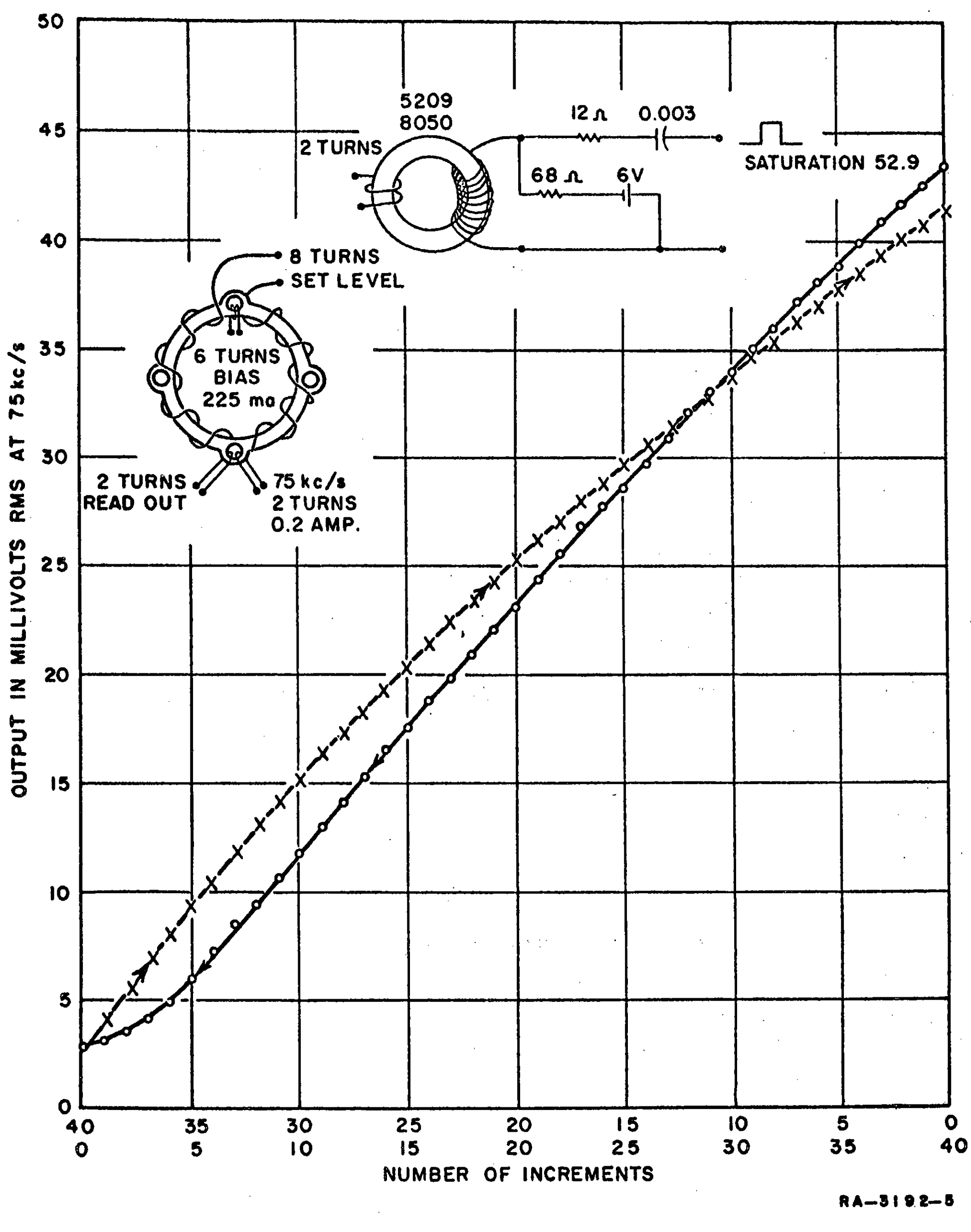


FIG. A-5

STORAGE CHARACTERISTIC FOR MULTI-APERTURE CORE

3. GATE AND THRESHOLD FUNCTIONS

The gate and threshold functions may be performed in a core of the same type as that used for analog storage. A typical configuration is Fig. A-6. A winding a has a steady current passing through it which is greater than the minimum necessary to hold the main leg saturated. There is also a winding b inside one of four similar side holes which receives the current due to the summation of inputs from the sensors. If the current in b is sufficiently large, it will be able to reverse the flux around the center hole within the dotted line shown, in opposition to the field provided by winding a. The winding b therefore behaves as a control winding for a switch, since windings such as c and c' are virtually uncoupled when both annuli of the core are magnetized in parallel, but tightly coupled if anti-parallel. The current in winding a provides the variable threshold control. The three available holes may be used for carrier switching and the increment and decrement control shown in Fig. A-1. It happens that the small side holes are of a suitable magnitude to act as a "bucket" for the increments. An over-all characteristic through a gating core is shown in Fig. A-7.

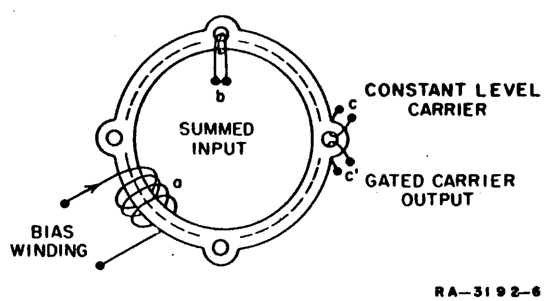


FIG. A-6

MULTI-APERTURE CORE USED FOR GATE AND THRESHOLD FUNCTIONS

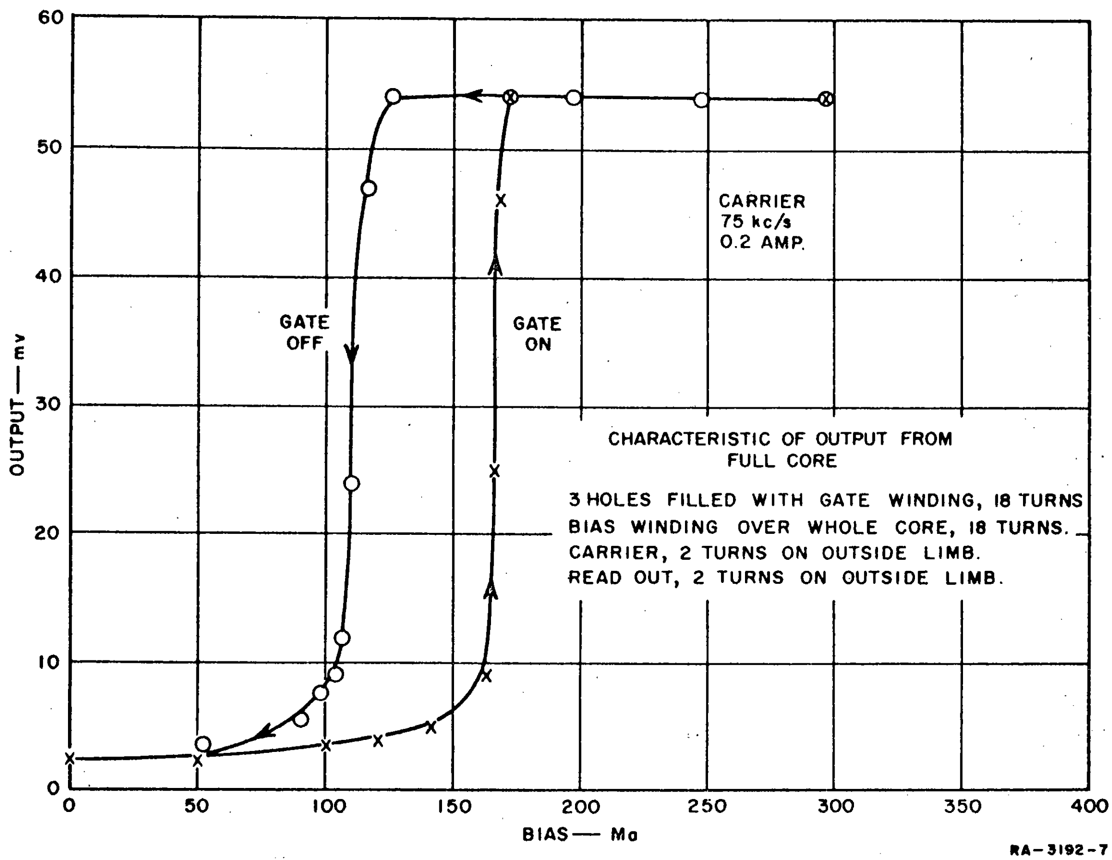


FIG. A-7

GATING CHARACTERISTIC FOR MULTI-APERTURE CORE (SIMPLE ARRANGEMENT)

However, there is a practical difficulty associated with Fig. A-6 which severely limits the application of this arrangement. The side holes are only 20 mil in diameter, and the drive required in winding b is of the order of 2 ampere turns, so that the choice typically lies between supplying 1 amp into 2 turns of 33 gauge wire, or winding 10 turns of 40 gauge in a 20-mil hole and supplying 200 ma. Either way it is not a very attractive situation. Fortunately there is a relatively simple way around this difficulty. The input winding, b, is replaced by a winding through the main aperture which receives the controlling signal, plus a blocking winding on the inner leg of the side hole. The input winding may now consist of 200 turns of 38 gauge wire and is conveniently wound in the large central aperture by a standard toroid winder. The sense of the windings is opposed so that the gating characteristic takes the form of Fig. A-8. The operating current is 10 ma. It is necessary to provide a holding current in the blocking winding to produce a flat top to the gate characteristic of sufficient width to meet the application. The arrangement of Fig. A-6 permits the input signal to be increased arbitrarily, but in Fig. A-8 the allowable range is approximately equal to the ampere turns in the blocking winding.

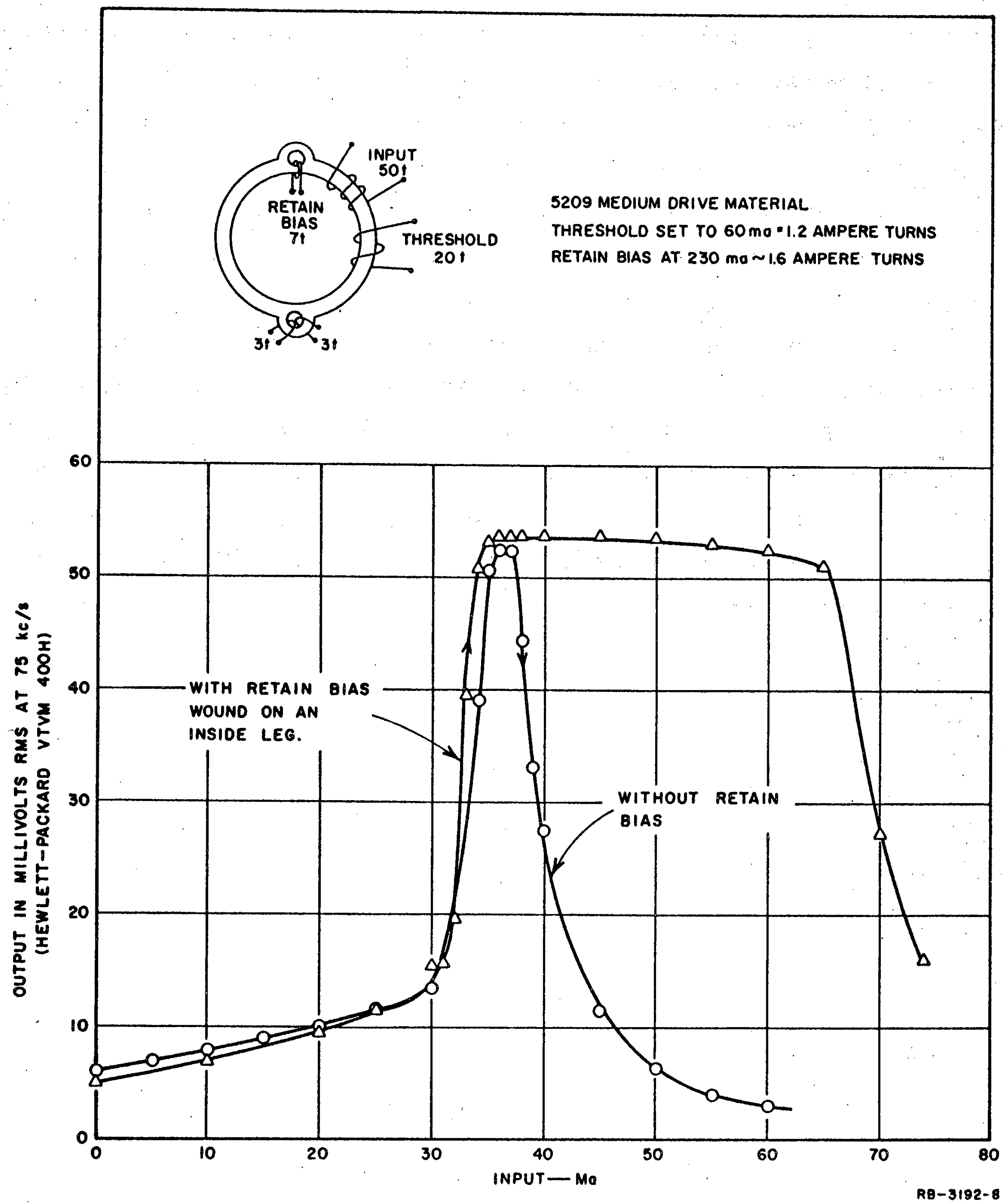


FIG. A-8

GATING CHARACTERISTIC FOR MULTI-APERTURE CORE (MODIFIED ARRANGEMENT)

4. A SIMULATION CIRCUIT FOR A NEURAL ELEMENT

Now that the individual functions of the simulation circuit have been achieved in terms of equivalent magnetic circuitry, it remains to combine them into a mutually compatible system. The completed circuit analogous to Fig. A-1 is shown in Fig. A-9, and makes use of two multi-aperture cores and wire only. It will be appreciated that the design of the flux transfer circuit between the gate and analog cores presents some difficulty, since the flux configuration in the analog core varies from fully saturated to 50 percent reversed. In addition, the side hole which is acting as a bucket drives the analog core in series with its inoperative twin, while there is considerable back-coupling through the carrier loop as well. In the circumstances, it is perhaps remarkable that the arrangement can exhibit linearity of the quality shown in Fig. A-10; an attempt was made to equalize the increments over a greater range by the use of small resistors in series with the pulse generator. The ordinate is a measure of the mean signal level rather than the RMS; this being a characteristic of the circuit of the vacuum tube voltmeter (Hewlett-Packard 400 H). If the simulation behavior demands that the output should increase more rapidly than linearly, a peak reading circuit rather than an average reading arrangement should be used. Multiplication of weights may be effected by using the carrier output from one storage core as the drive for a second core, since both circuits are of low impedance and compatible.

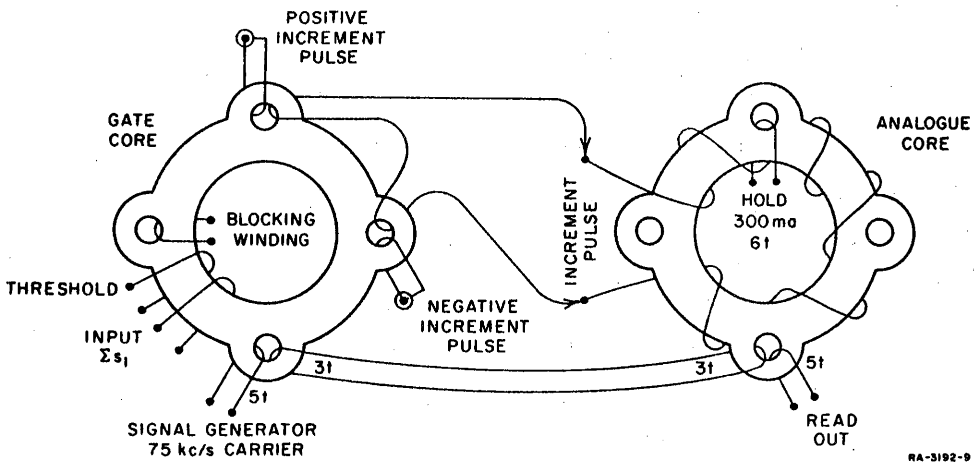


FIG. A-9

MAGNETIC CIRCUIT EQUIVALENT TO FIG. 1

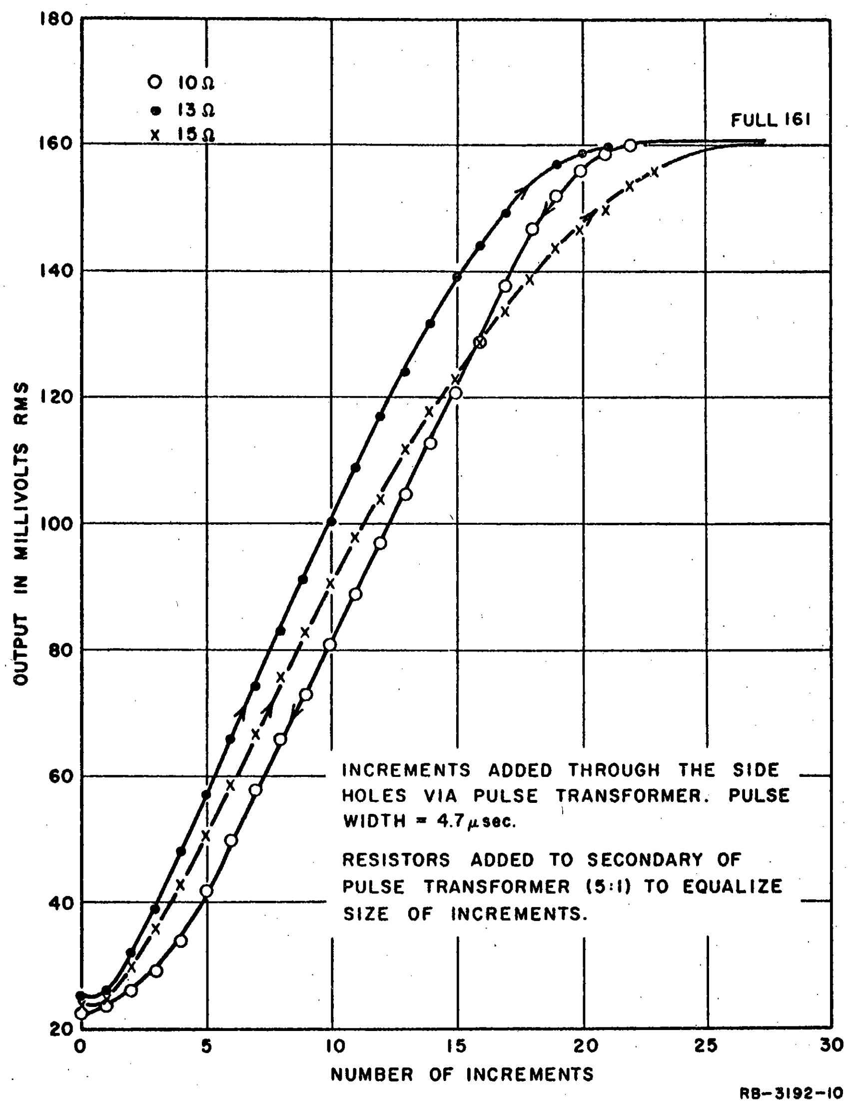


FIG. A-10

STORAGE CHARACTERISTIC FOR NEURON SIMULATION CIRCUIT BASED ON FIG. A-9

5. A LOGIC ELEMENT

It has been found possible to extract more DC current from a winding through a minor aperture than is necessary to operate the control winding of the same gate core. Such an arrangement exhibits two stable states and corresponds in function to a self-holding relay; the remainder of the minor apertures are available for other functions if needed in the manner of independent relay contacts. The measured characteristics of the circuit shown in Fig. A-11 are given in Fig. A-12. If the carrier drive is gated, the circuit will reset to the off condition; a typical ratio for the steady currents in the two stable states is 20 : 1. It should be noted that the threshold current and the extent of the flat top are independently controllable, and in some applications the additional reset to zero at high currents may be employed to advantage.

Since this arrangement exhibits power gain and controlled switching states, and is compatible not only with itself but also with the gate and multi-level storage circuits, it forms an ideal coupling element for use in multi-layer logic systems of neuron simulation.

The work described in this report was initially sponsored by the Division of Engineering Research of Stanford Research Institute, and later was supported by the U.S. Army Signal Research and Development Laboratory, Fort Monmouth, New Jersey.

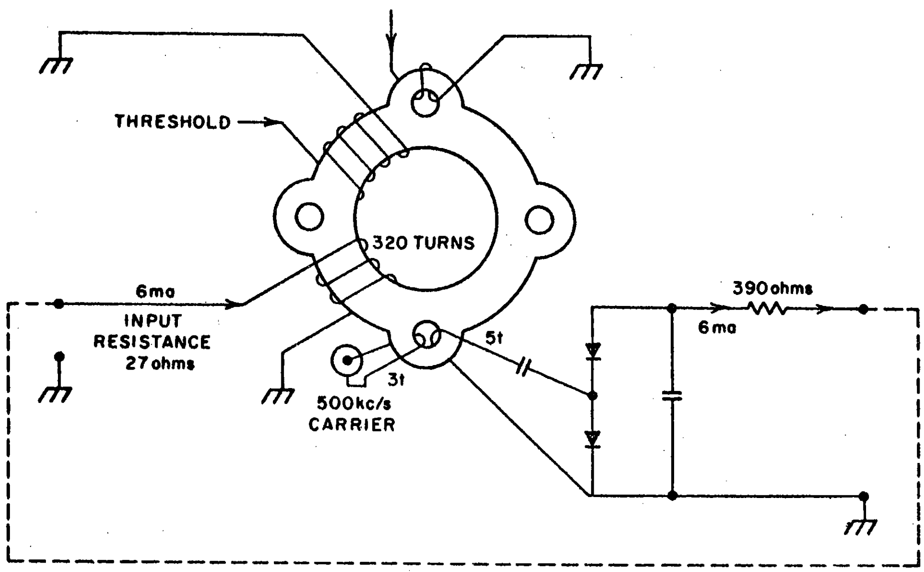


FIG. A-11

A LOGIC ELEMENT WITH TWO-STABLE DC STATES

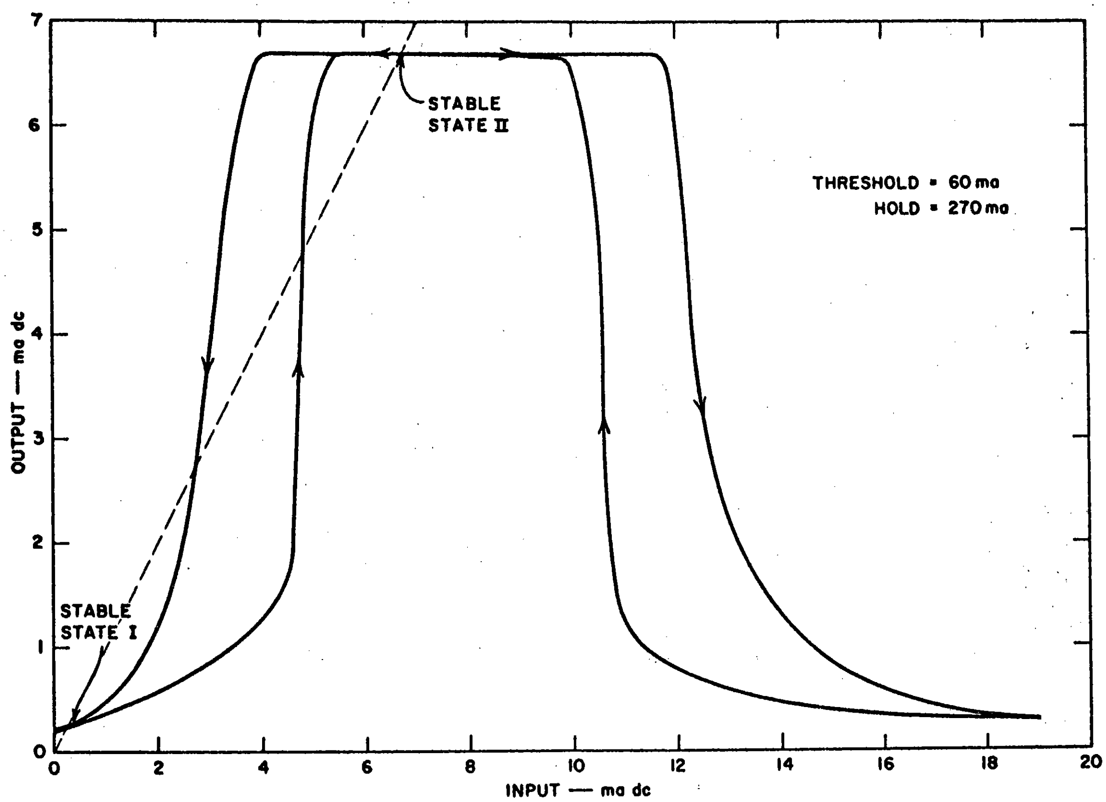


FIG. A-12

THE CHARACTERISTIC OF THE LOGIC ELEMENT SHOWN IN FIG. A-11

APPENDIX B

STATISTICAL AND OTHER INVARIANTS OF GEOMETRICAL FIGURES UNDER TRANSLATION AND ROTATION

APPENDIX B

STATISTICAL AND OTHER INVARIANTS OF GEOMETRICAL FIGURES UNDER TRANSLATION AND ROTATION

1. INTRODUCTION

Integral Geometry, an insufficiently known area of mathematics, seems highly relevant to the problem of automated pattern recognition. Our interest in this area was originally prompted by a study which attempted to clarify certain details of the behavior of Rosenblatt's Perceptron. Results obtained in that study seem to indicate a particular usefulness of the method when:

(1) The designer has sufficient *a priori* information to determine several distinguishing geometrical parameters so that any two patterns are distinct when characterized by these parameters.

(2) It is considered of prime importance to distinguish patterns independent of their location and orientation on the retina of the device.

Before giving a description of the method, the general ideas of integral geometry will be applied in order to familiarize the reader with the general concepts. Though the example is not especially simple in view of the underlying theoretical structure, it is one with which a non-specialist might be familiar and also is intuitively straightforward. This example also gives the flavor of the general method; but it will *not* be of practical interest.

The problem is as follows: Suppose you are asked to distinguish between two sets of evenly spaced, parallel, infinite, straight lines where the spacing interval in the first is d and in the second is d', where $d' > d$--*e.g.*, between two diffraction gratings of different diffractive lengths (see Fig. B-1). The designer is assumed to know d and d' beforehand. All orientations and locations of the two grids are equally likely in the plane.

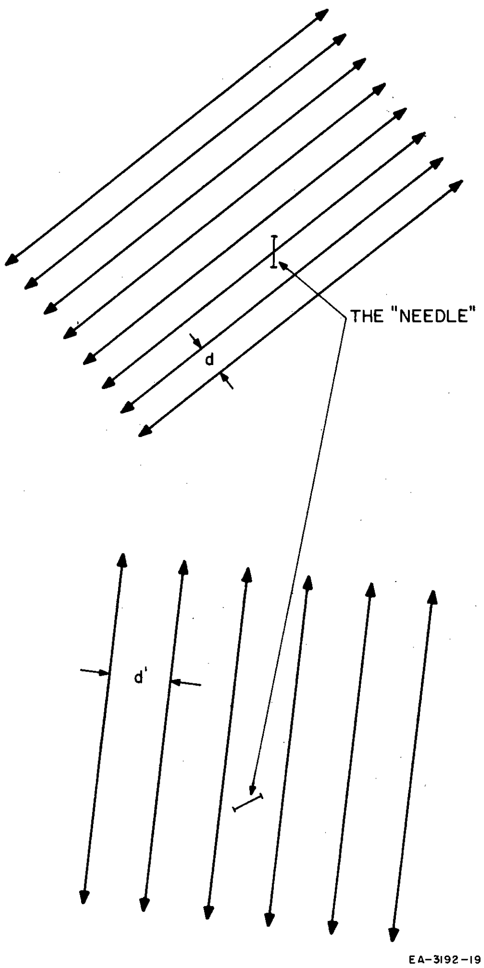


FIG. B-1

ILLUSTRATION OF A NEEDLE "RANDOMLY TOSSED" ON TWO GRIDS OF DIFFERENT SPACING AND ORIENTATION

If we recall the Buffon Needle Problem (first discussed as long ago as 1760) we see an immediate similarity. In Buffon's problem, a needle of length d is thrown "at random"* onto a grid of parallel lines of spacing b where $d \leqslant b$. The probability of the needle intersecting a line of the grid is $2/\pi \cdot d/b$. If we let $b = d$ and $b = d'$, we obtain by substitution the probabilities $2/\pi$, and $2/\pi \; d/d'$, for the first and second grids respectively.

This suggests a recognition device that throws a "needle" randomly N times on a grid. It then counts the number of times the needle intersects the grid. Let the fraction of intersections per trial be denoted by p. Then, by picking a threshold θ satisfying $2/\pi \cdot d/d' < \theta < 2/\pi$, it is possible to assert that unless an event has occurred of less than a given probability the grid is of width d if $p > \theta$. Conversely if $p < \theta$, then the grid would be said to be of width d'. It should be noted that the designer has N and θ at his disposal. The probability that the machine will be in error when this decision criterion is used can be seen, by use of Bernoulli's "weak law of large numbers," to go to zero as N becomes increasingly large. (The quantities $|p - 2/\pi|$, when the grid is of width d, and $|p - 2/\pi \cdot d/d'|$, when the grid is of width d', tend to zero by the same law.)

From the description of the method of discrimination certain properties become evident:

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* As will be shown below the statement "at random" is an inadequate description of the process, unless a further exact definition of "at random" is included.

(1) The method is certainly independent of orientation, at least to the extent that the notion of throwing the needle at random conforms to our intuition that all orientations are equally likely.

(2) A large enough N will reduce the probability of error to as small a value as desired. Note that this probability depends on the value of θ chosen. It should be noted that determination of the actual size of N required for a given probability of error will require further calculations. A thorough consideration of these questions leads to the concepts of statistical decision theory and hypothesis testing.

(3) The method requires the knowledge of a theorem (or set of theorems) to tell us what numbers to expect from the patterns being shown, given a certain figure or set of figures to be used for testing. In the above example, the cited theorem of Buffon was the basic ingredient. The more such theorems that are available, the more patterns it becomes possible to distinguish; and also the more alternative methods we can use for testing these patterns. For instance, it can be shown that exactly the same assertions stated in the previous problem hold if not just a 'needle' but any curve of length d is used as the testing figure—*e.g.*, a circle of radius $r = d/2\pi$. Further variations of the fundamental idea readily suggest themselves.

(4) In the previous example the retinal field used was the entire plane. What if we limit the retinal field considered to a finite area? It will be shown below that this frequently permits the theorems to be interpreted probabilistically (as happened also to be the case in the above example), allowing the usual machinery of laws of large numbers, central limit theorem, moment inequalities, and the like. For example, the use of an infinite straight line, rather than a needle, thrown at random in the plane at large corresponds to one set of theorems in integral geometry which has the mathematical form of evaluating a set of integrals (see Eq. B-3). But if the lines are restricted to intersect a retina, these theorems can be interpreted not merely as evaluating integrals but as giving expected values of a set of random variables, with one random variable associated with each pattern to be recognized (see Eq. B-5).

(5) The following abilities would be required of any machine constructed to carry out the method of discrimination used in the above example:

(*a*) It must perform the act described intuitively as "throwing the needle at random."

(*b*) It must be able to repeat this act often in a short period of time.

(*c*) It must be able to tally intersections.

We see that the requirements of Items (*b*) and (*c*) are engineering problems. By contrast we will see that Item (*a*) requires a much more complete description to be mathematically precise and physically effected.

We conclude these introductory remarks with an example of the dangers implicit in using an inexact definition of geometrical randomness (*i.e.*, of geometric probability). From this example it can be seen that an exact definition (there may be more than one—hence the need for explicitness) is required if we are not to get numerically erroneous results. As before, this example is not chosen as being particularly practical, but rather because it gives the flavor of more complicated examples. It is also well-known and very old, having preceded the general theory by over half a century.

Consider the notion of choosing the chord on a circle randomly. We wish to know the probability that a random chord of a given circle will exceed the length of the side of an inscribed equilateral triangle ($\sqrt{3}\,r$ if the radius is r). There are three answers, each in some way intuitively satisfying:

Answer 1: Since the chord is defined by its two extremities, we can, by symmetry, choose one extremity as fixed, and vary the other. The variable end-point then has an equal chance of being in any of the three arcs which trisect the circumference, two of which meet at the fixed end-point, as shown in Fig. B-2(a). Only the third arc corresponds to success, which therefore has probability 1/3.

Answer 2: Let the direction of the chord be fixed. Then its mid-point lies on the diameter perpendicular to this direction, as shown in Fig. B-2(b). The mid-point should have equally likely chances of being in any of the four equal segments in which this diameter can be subdivided. The central two are favorable, the lateral two are not, so the probability is 1/2.

Answer 3: The chord is uniquely determined by its center which lies at random in the interior of the circle, as illustrated in Fig. B-2(b).

The mid-points of the chords longer than $\sqrt{3} \cdot r$ lie in a concentric inner circle of radius $r/2$. The fraction of the area in which this mid-point must lie for success and hence the probability of success (if all points have equal probability) is $[\pi(r/2)^2/\pi r^2] = 1/4$.

Now each of these three answers corresponds to an appropriate physical device for generating random chords. The first answer is found by choosing, independently, two points at random on the circumference, the first being P, the "fixed" end-point in Fig. B-2(a).

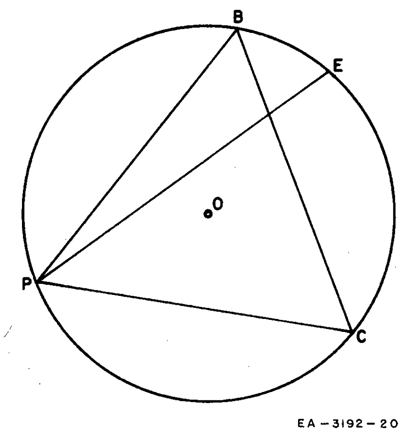


FIG. B-2(a)

ILLUSTRATION OF EQUILATERAL TRIANGLE, PBC, WITH SUPERIMPOSED RANDOM CHORD, $\overline{PE}$, CORRESPONDING TO ANSWER 1

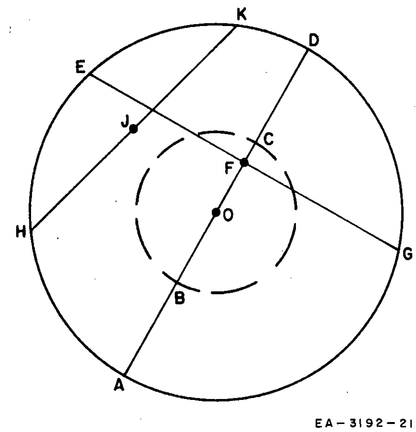


FIG. B-2(b)

ILLUSTRATION OF RANDOM CHORDS FOR ANSWER 2, $\overline{EFG}$; AND ANSWER 3, $\overline{HJK}$

The second answer corresponds to randomly choosing a point uniformly distributed on a diameter after having chosen the direction of the diameter as an angle with uniform density in $(0,\pi)$.

The third answer is obtained by choosing a point at random in a circle--*i.e.*, with uniform area density--where this point is interpreted as representing the mid-point of a chord (whose length is uniquely determined by its mid-point).

These three answers are correct for their corresponding notion of "random chord." The point should be clear. Whatever notion of "random" is used in the statement and proof of the theorems referred to in Item (3) of the above list of properties, the notion must be explicitly stated and consistently adhered to in the interpretation of the results given by the physical device which generates the "randomness." In what follows, there will be no ambiguity in the notion of "random" because only one interpretation can satisfy a certain condition of invariance. This condition corresponds to the requirement that our recognition device not be affected by changes in location or orientation of the pattern being recognized. (It might be noted that in the same sense the figure discussed in Item (3) of the above list randomly samples the pattern.)

2. DESCRIPTION OF THE NOTION OF RANDOM LINE

Since many of the subsequent theorems depend on the notion of random line, we begin with a description of this notion. Let us consider the analogous notion of "random point" in the plane as a preliminary. Whatever the precise meaning of random point might be, we desire of it the property that two congruent point sets (each of which is obtainable from the other by a suitable combination of translation and rotation) be "equally likely." Since the plane is big enough to accommodate infinitely many disjoint congruent replicas of a given bounded point-set, we are forced at once to agree either that the plane as a whole has infinite probability or that each bounded point-set has probability zero. So we abandon the notion of the "probability that a random point lies in a given point-set" temporarily. It will reappear later as desired. In its stead, we seek a way of associating with each point-set in the plane a non-negative number, possibly plus infinity, which resembles a probability in that the number corresponding to a finite or countable union of disjoint sets $\{A_n\}$ is the sum of the separate numbers corresponding to each A_n. We further require that if two sets, A and B, are congruent, then the corresponding number, which we write $m(A)$ and $m(B)$, should be equal (these three conditions are designated (i), (ii), and (iii), below.) It is clear that one such way of associating a number $m(A)$ to the set A is by the formula*

$$m(A) = k \iint_A dx\,dy \tag{B-1}$$

where k is any positive constant, chosen once and for all and independent of A. It is not so obvious, but still true, that no other type of formula

* Even now we are omitting the precise description of the class of sets A for which $m(A)$ is defined. This is unfortunate but not disastrous. We intend to use our results only for relatively simple geometric figures, and so not get caught in a long digression on measure theory (which is not relevant for our applications) when we are aiming at a form of calculus (which is). The class of all open sets and closed sets probably suffices, but the class of Lebesque measurable sets in the plane is easily large enough. No knowledge or taste for the subject known as measure theory will be assumed, despite the appearance of the letter "m" here and the word "measure" later. The best available measure-theoretic discussion of our problems is to be found in an article by S. Sherman.[23]

will do. We call $m(A)$ the *measure* of the set A. Unfortunately there is a free constant k yet to be disposed of. However, in formulas where ratios of measures appear, this drops out. We also call $m(A)$ the measure of the set of random points which lie in A. If we had not required that

$$A \cong B \quad \text{imply} \quad m(A) = m(B)$$

we could have had many other formulas than Eq. (1) which defined functions $m(A)$ satisfying

$$\text{(i)} \quad m(A) > 0$$

$$\text{(ii)} \quad m(UA_i) = \Sigma m(A_i) \quad , (A_i \text{ disjoint})$$

for example

$$m(A) = \iint \phi(x,y)dxdy \quad \text{where} \quad \phi(x,y) > 0 \quad .$$

Returning to the corresponding notions for *random lines* in the plane, we seek a law, associating, to sets A of *lines*, a non-negative number $m(A)$ (called the measure of the set A) such that (i) and (ii) above are true and also

$$\text{(iii)} \quad A \cong B \quad \text{implies} \quad m(A) = m(B)$$

(we say one set of lines A is congruent to another, B, and write $A \cong B$, if it is possible to bring them into coincidence by a combination of rotation and translation).

The first step in finding a law or set-function that has these properties is to introduce coordinates on the space (or more precisely, manifold) of all lines in the plane. To do this, we first select an origin and a pair of orthogonal axes in the plane. Every line can be put in the form

$$\frac{x}{\alpha} + \frac{y}{\beta} = 1$$

where $(\alpha,0)$ and $(0,\beta)$ are the intercepts of the line with the axes. It is necessary to admit $\alpha = \infty$ or $\beta = \infty$ to account for horizontal and vertical lines, respectively. Then we can use the pair (α,β) as coordinates. Or we may write lines in the form $y = mx + b$ (except for vertical lines, which have equations of the form $x = c$) and use the pair (m,b) to describe a typical vertical one. Or we may use the normal form

$$x \cos\theta + y \sin\theta = p$$

where

$$0 < \theta < \pi$$

$$0 < p < \infty$$

Then the pair (p,θ) may be used to describe the line. Geometrically, p is the normal distance of the line from a specified origin 0, and θ is the angle between the line and a specified line through the origin. It is this last coordinate system which is in fact directly useful. We will show that a formula of the type

$$m(A) = \int_A\int dp\,d\theta \qquad \text{(B-2)}$$

assigns to certain sets A of lines a number $m(A)$ which fulfills not only (i) and (ii) above (and so deserves the name "measure" on the space of lines) but also the condition

$$A \cong B \qquad \text{implies} \qquad m(A) = m(B) \quad .$$

It is also true that apart from the choice of the positive constant, k, no other formula for $m(A)$ will do this. For example

$$\int_A\int d\alpha\,d\beta$$

attaches a larger measure to a translate of the set A than to the set A if the effect of the translation is to remove all the lines of A from the origin sufficiently far. In fact it can be shown that

$$d\alpha\,d\beta = p\,dp\,d\theta$$

so that motions which enlarge the coordinate p of all the lines of the set A will enlarge the measure given by

$$\int_A\int d\alpha\,d\beta \quad .$$

At once it may be asked whether the choice of the origin and the axes through it which determine the (p,θ) coordinate system above affects the resulting measure $dp\ d\theta$. The answer is that it does not. The unit of length in the plane, used to determine the normal distance, p, is a scale factor in the resulting measure. Since there is in any case a free multiplicative constant k in the definition of $m(A)$, this scale factor does not change the form of $m(A)$. There is no "natural" choice for k, just as there is no "natural" choice of length in terms of which to measure p.

Let us now show that the measure $dp\ d\theta$ on the set of lines in the plane actually enjoys the invariance property (iii) and that it is independent of choice of location and orientation of the coordinate system. To consider the second statement first: if we have two origina, 0 and 0′, and emanating from each origin, directions OX and $O'X'$ respectively (as shown in Fig. B-3), then every straight line has two sets of coordinates—(p,θ) referred to OX, and (p',θ') referred to $O'X'$. Given one set, A, of lines, we wish to show

$$\int_A\int dp\ d\theta = \int_A\int dp'\ d\theta'$$

where we have indicated by the use of the same letter A in both integrals that the identity of the lines in the region of integration in both cases is the one set A. Of course the description of the set is different in (p,θ) coordinates than in (p',θ') coordinates. It is easy to see that if the point O' has coordinates (a,b) with respect to (OX,OY) axes and the line $O'X'$ makes angle α with respect to OX, then for any given line the (p,θ) and (p',θ') coordinates are related by

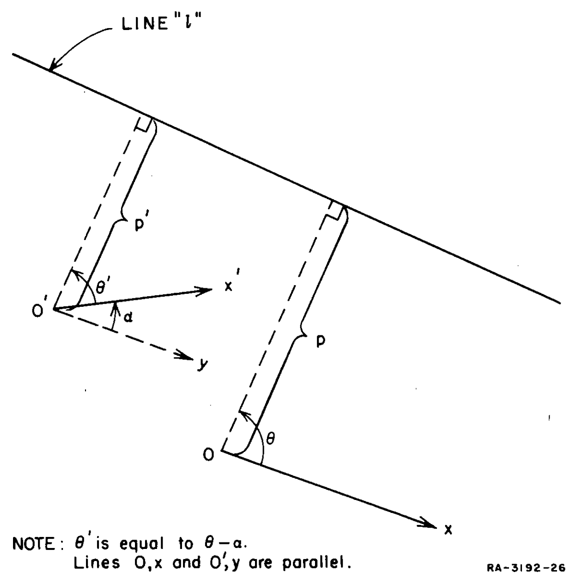


FIG. B-3

EFFECT OF TRANSLATION AND ROTATION ON THE CHOICE OF COORDINATE SYSTEM

$$p' = p - a\cos\theta - b\sin\theta$$

$$\theta' = \theta - \alpha$$

so that $[\partial(p',\theta')/\partial(p,\theta) = 1$. This means exactly that when we change from (p',θ') coordinates to (p,θ) in evaluating $\int_A \int dp'\, d\theta'$ we obtain $\int_A \int dp\, d\theta$ as desired.

As to the proof that $\int_A \int dp\, d\theta = m(A)$ does actually enjoy the invariance property (iii) we now have only to observe that if $A \cong A'$ then the motion which takes A into A' also takes the coordinate system OX into a corresponding coordinate system $O'X'$. By what we have just shown, we have

$$\int_{A'} \int dp\, d\theta = \int_{A'} \int dp'\, d\theta' .$$

But

$$\int_{A'} \int dp' d\theta' = \int_A \int dp\, d\theta$$

since A' with respect to $O'X'$ is indistinguishable from A with respect to OX, so that $\int_A \int dp\, d\theta = \int_{A'} \int dp\, d\theta$, as was to be shown.

Another remark is in order now. Let us return to the notion of random points in the plane. We saw above that we were unable to define a probability measure for a random point in an infinite (unbounded) plane. Fortunately the same situation does not exist when we restrict our considerations to a plane area S which is bounded. We agree to consider only subsets of S as the A's and B's of (i), (ii) and (iii). S itself is of course such a subset. In this case we can define a new measure $m_s(\circ)$* on the subsets of S. This measure continues to enjoy properties (i)—(iii), and is defined as

$$m_s(A) = \frac{m(A)}{m(S)} = \frac{k\int_A \int dxdy}{k\int_S \int dxdy} = \frac{\int_A \int dxdy}{\int_S \int dxdy} .$$

Alternatively this measure can be considered as

$$m_s(A) = k\int_A \int dxdy \quad , \text{ where } \quad k = \frac{1}{\int_S \int dxdy} \quad , \quad \text{a fixed constant} .$$

* $m_s(\circ)$ is essentially the measure $m(\cdot)$, used above, normalized to be one on S, and defined only for sets $A < S$.

It can now be seen that this new measure $m_s(\circ)$ satisfies not only the conditions (i) to (iii) above, but in addition satisfies a fourth condition,

$$\text{(iv)} \qquad m_s(S) = 1 \quad .$$

In other words $m_s(\circ)$ defines a *probability* measure on points in S and the probability that a "point lies in A" is understood to be $m_s(A)$.

Suppose we agree now to consider not the full manifold of all lines in the plane but only the sub-manifold of those which enter a fixed rectangle, R. Within this sub-manifold we agree to use the measure $dp\ d\theta$, where some unit of length has been chosen, and where the constant k has been chosen for simplicity to be 1. Also, again for simplicity, we select the origin O to be the one vertex of R, and the axis through R to be the larger side of R through O (Fig. B-4).

Then the set of all pairs (p,θ) which correspond to lines through R is given by the region R' in Fig. B-5. With these choices all fixed, the problem of selecting lines at random in R by a physical device, reduces to selection of points at random in R', a comparatively routine matter. There is a bona fide probability measure on R', namely $dxdy/A(R')$, analogous to $m_s(\circ)$ introduced above. Thus, by reducing the somewhat tenuous notion of a "random line penetrating R" to the corresponding problem of choosing a point in R', we have obtained a true probability situation. We reiterate, R' here plays the role of S above.

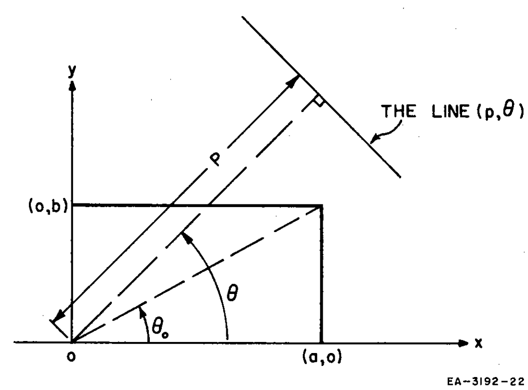
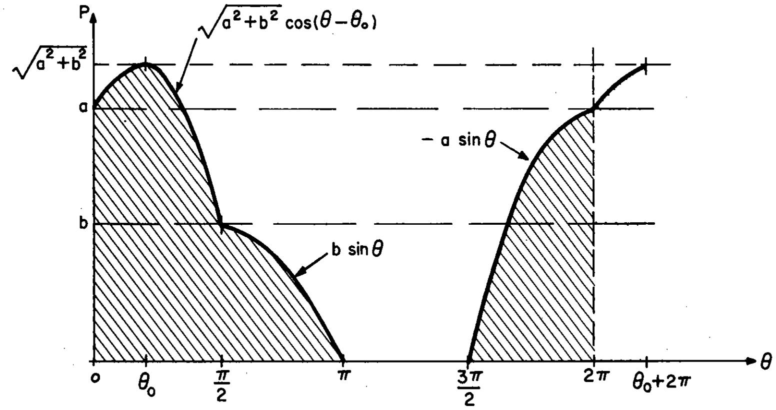


FIG. B-4

ILLUSTRATION OF THE RECTANGULAR REGION, R, IN THE x-y PLANE

We now ask the question, how do we compute $A(R')$ *effectively*, meaning not by brute force. This question is answered by the solution to a far more general question: For any smooth convex curve, C, not merely a rectangle, how do we compute the measure of all the lines which enter C? This can be written in the form

$$\iint_{\{L:L\cap C\neq 0\}} dp\ d\theta$$



NOTE: The shaded area = $(2a+2b)$ = (perimeter of R); $\left[\theta_0 = \tan^{-1} b/a\right]$.

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FIG. B-5

ILLUSTRATION OF THE REGION, R′ (SHADED), IN THE p-θ PLANE CORRESPONDING TO THE REGION, R, ABOVE

The answer to this more general question is contained in a yet more general result: Consider the function, defined on the manifold of all lines with the aid of a rectifiable curve C, by

$$n(L) = n(\beta,\theta) = [\text{number of intersection points (possibly infinite) of } L \text{ with } C] \quad .$$

It can be shown[23,24,25] that $n(L)$ is measurable with respect to the $dpd\theta$ measure, and that

$$\iint_{\substack{\text{all}\\\text{lines}}} n(p,\theta)dpd\theta = \iint_{\{L:L\cap C\neq 0\}} n(p,\theta)dpd\theta = \iint_{\{p,\theta:n(p,\theta)\neq 0\}} n(p,\theta)dpd\theta = 2l(c) \tag{B-3}$$

where $l(C)$ = length of C. In particular, if C is convex, then $n(p,\theta)$ = 0, 1, or 2, and the set where $n(p, \theta)$ = 1, the points of tangency, are of measure zero with respect to (p,θ)—hence negligible in the integration—so that n is either 0 (contributing nothing), or 2, so that

$$\iint_{\{(p,\theta):n(p,\theta)\neq 0\}} n(p,\theta)dpd\,\theta = 2\iint_{\{(p,\theta):n(p,\theta)\neq 0\}} dpd\theta = 2\,l(c)$$

or

$$\iint_{\{(p,\theta):n(p,\theta)\neq 0\}} dpd\theta = l(c) \quad . \tag{B-4}$$

Returning to the rectangle, we see that

$$\iint_{\substack{L \text{ enters} \\ \text{rectangle } R}} dp d\theta = \iint_{\{(p,\theta):n(p,\theta)=2\}} dp d\theta = l(R) = A(R')$$

and that on the sub-manifold M_R of those lines entering R, we have now an easily automated bona fide probability measure, $(dp\ d\theta)/l(R)$, which is *uniquely* singled out as invariant under rotations and translations. Let me now draw several corollary assertions. The theorem applies, first of all to the random variable $n_c(p,\theta)$ defined on the manifold M_R with respect to the probability measure $(dp\ d\theta)/l(R)$. The curve C may even be a finite union of rectifiable curves, $C = UC_i$ (see Fig. B-6), as long as C appears within the "retina" R. R must be convex but is otherwise arbitrary (see Fig. B-7). Stated in the language of probability the theorem says that the expected value of n_c is

$$E[n_c] = \iint n_c(p,\theta) \frac{dpd\theta}{l(R)} = \frac{2l(C)}{l(R)} \quad . \qquad \text{(B-5)}$$

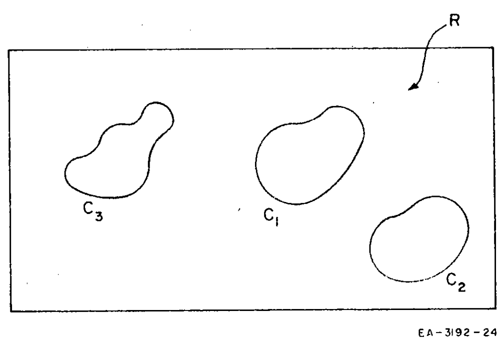

FIG. B-6

ILLUSTRATION OF A SET,$\{C_i\}$, OF RECTIFIABLE CURVES IN R

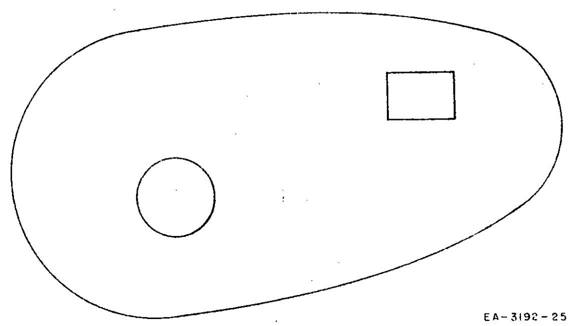

FIG. B-7

ILLUSTRATION OF A POSSIBLE "RETINAL"AREA, NECESSARILY CONVEX, WITH PATTERNS SUPERIMPOSED

If we compute the expected value experimentally, by taking samples of the random variable, we get, by the well-known "laws of large numbers," the fact that for large N, the average number of intersections of N lines tossed on an R containing C is approximately $2l(C)/l(R)$. If we are asked to distinguish between the appearance of two patterns, C and C', both of which are rectifiable curves, and $l(C) \neq l(C')$, we may use this variant of the Buffon needle to do the job.

To estimate the size of N needed to safely distinguish between the hypothesis that C or that C' is presented we need more knowledge of the random variable n_c . For example, an estimate could be given using the second moment of n_c (and $n_{c'}$)—that is, the quantity

$$E[n_c^2] = \iint n_c^2 (p,\theta) \frac{dpd\theta}{l(R)} \quad . \tag{B-6}$$

To my knowledge, this has never been calculated even for simple choices of C. To compute Eq. (B-6) is trivial for a semi-circle and for a linear segment. Unfortunately, knowledge of the second moment of the semi-circle and of the linear segment is not sufficient to permit even the calculation of the second moment of a D composed of the segment and the semi-circle, since the random variables n_{c_1} and n_{c_2} corresponding to a semi-circle C_1 and its diameter C_2 are correlated and hence their second moments do not add to give the second moment of a semi-circle closed by a straight line (a "D"-shape).

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STANFORD RESEARCH INSTITUTE, MENLO PARK, CALIFORNIA
GRAPHICAL DATA PROCESSING RESEARCH STUDY AND EXPERIMENTAL INVESTIGATION
A. E. Brain, C. O. Childress, A. R. Tobey,
A. B. Novikoff, C. A. Rosen, and C. P. Bourne
Report No. 1—Quarterly Progress Report 1, 1 April to 30 June 1960, 88 pp., 27 Illus.
(Contract DA 36-039 SC-78343) SCL-4087(18 Nov. 1958) File No. 40001-PM-60-91-91(6500), DA Project 3A99-22-001-02 Unclassified Report

Task A—This task involves the investigation of photographic processing techniques and their electronic equivalent for the simplification of input data. A study has been carried out on the use of unity gamma photographic transparencies for grey-scale elimination, leading to the suppression of fine detail and the creation of a solid outline around significant features of the landscape. The process may be of practical value for the simplification of aerial photographs before they are fed into a pattern recognition machine.

Task B—A survey will be made of electronic methods of performing pattern recognition. An outline is given of the characteristics of current techniques and the "signature" approach.

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Task C—A small pattern recognition machine will be constructed, capable of modification to various schemes of logic. A compatible set of components based on multi-aperture magnetic cores has been devised, and a general purpose machine is being constructed having an 8-by-8 retina, 64 multi-level stores, and 5 binary outputs. Perceptron type logic will be used initially. A paper on the simulation of neural networks with multi-aperture magnetic cores is included.

Task D, Part (1)—The possible application of certain theorems of integral geometry is being investigated. These provide numerical relations governing such properties of geometrical figures as line length, area, and curvature, which are invariant under rotation and displacement.

Task D, Part (2)—An investigation is being made of the logic of practical wiring systems for the improvement of the performance of machines of limited capacity in specific situations.

Task E—Data storage and retrieval will be studied in relation to the special problems of non-alphanumeric graphical data processing. In Sec. VI, a brief outline is given of the chief areas of interest; a detailed account is deferred until Quarterly Progress Report 2.

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