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6 MEMBER SIGNATURE

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X

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CHARGE INTERCLUB NAME	INTERCLUB MEM. NO.	INTERCLUB MEMBER SIGNATURE	DATE
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IMPORTANT PLEASE DO NOT GET THIS CARD DAMP OR WET. IT IS USED FOR COMPUTER INPUT

PCS 10032

O.K. DATA, DARIEN, CONN.

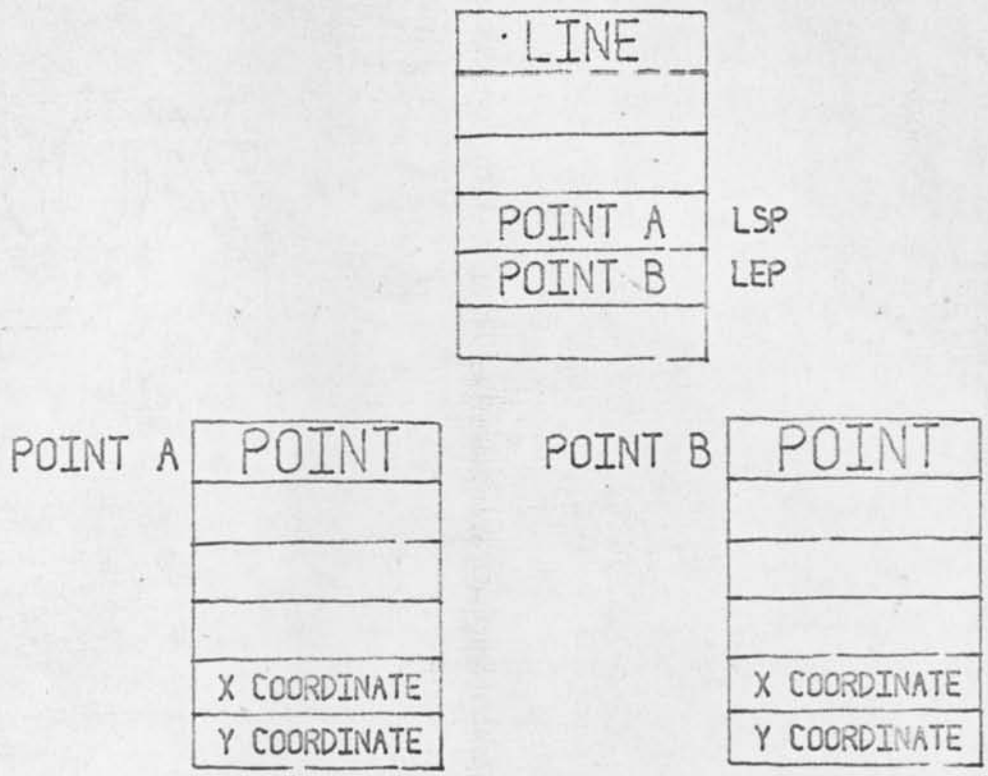


FIGURE 1. N COMPONENT ELEMENTS

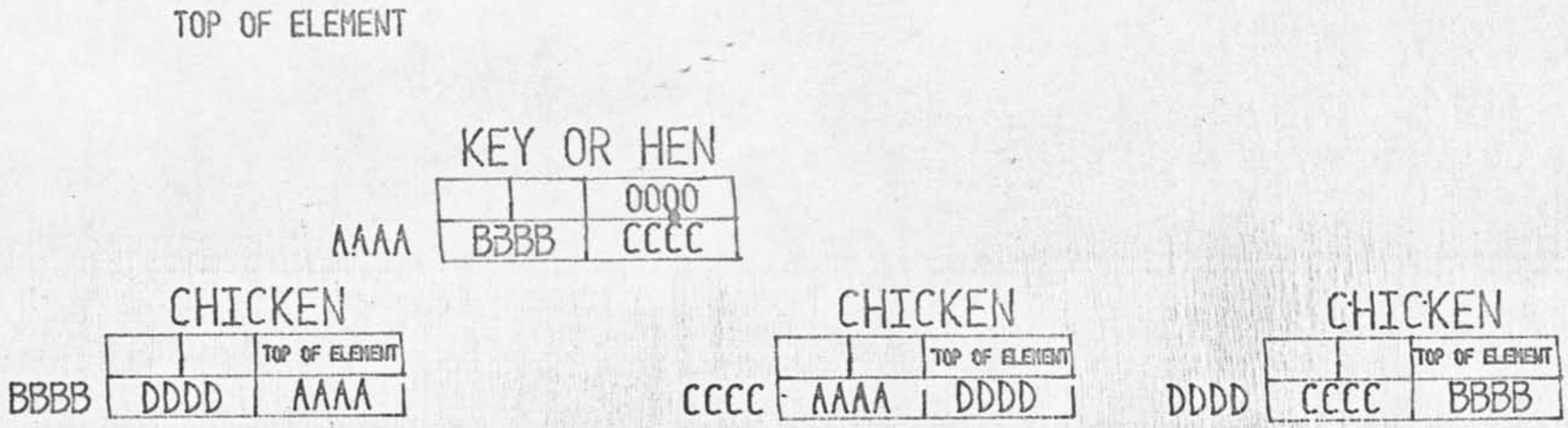


FIGURE 2. BASIC RING STRUCTURE

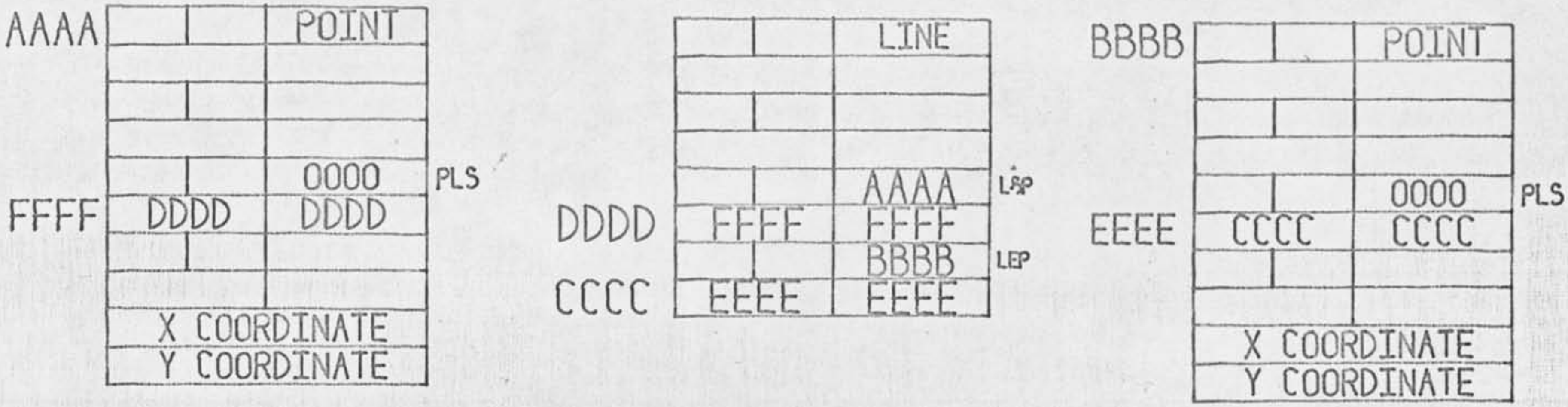


FIGURE 3. LINE AND TWO END POINTS
IN RING STRUCTURE NOTATION

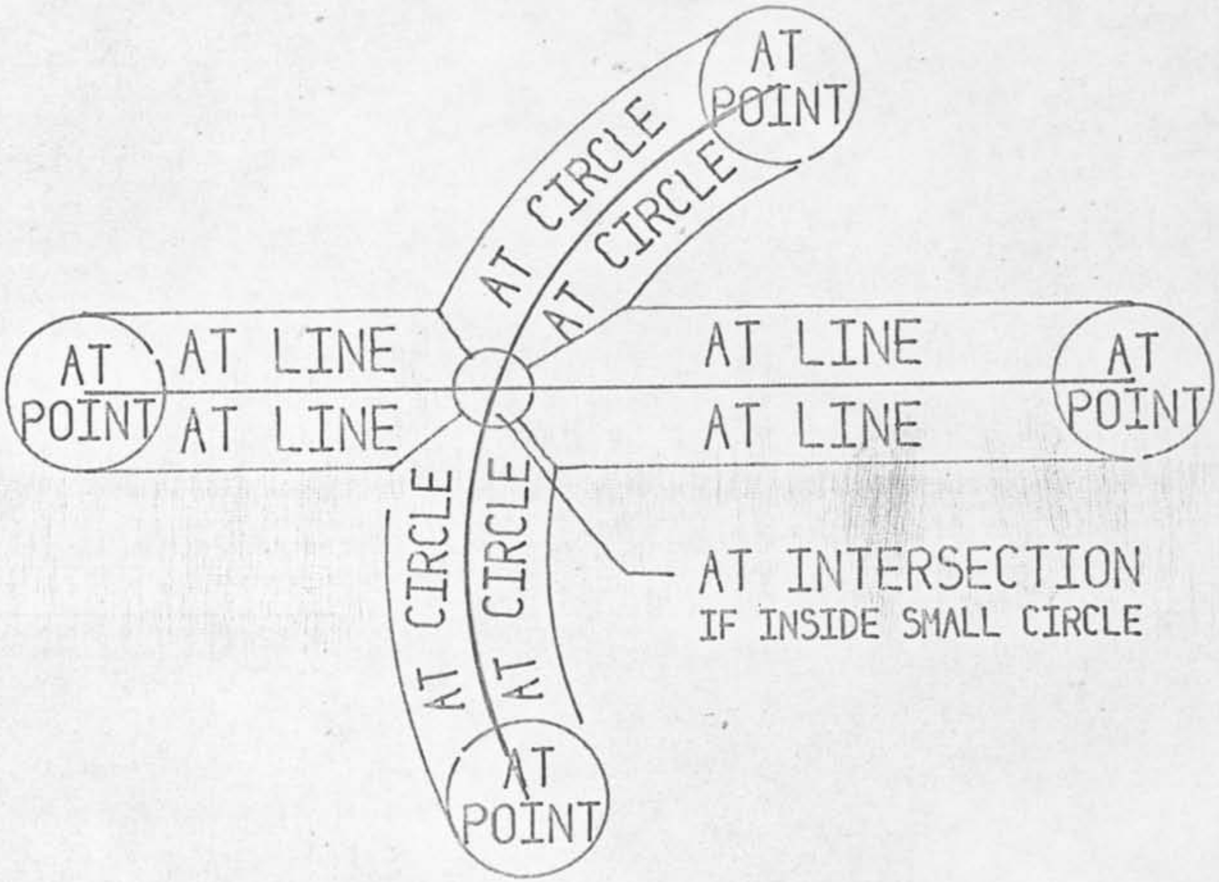
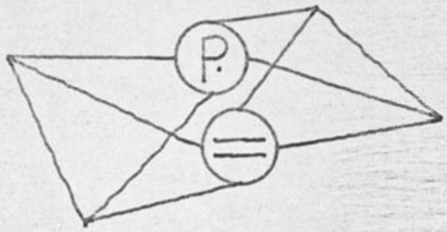
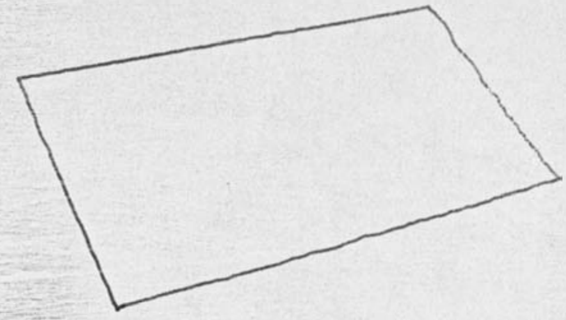


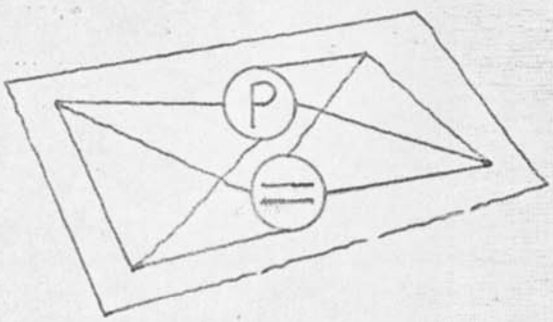
FIGURE 4. OBJECTS POINTED AT FOR VARIOUS LIGHT PEN LOCATIONS



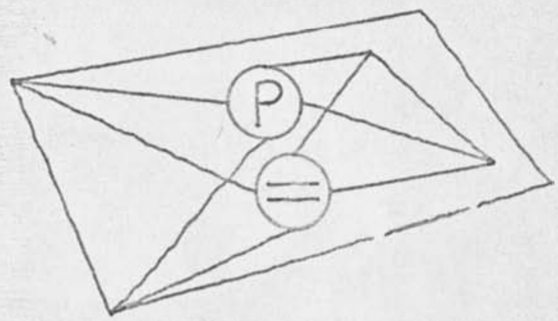
A. OPERATION DEFINITION



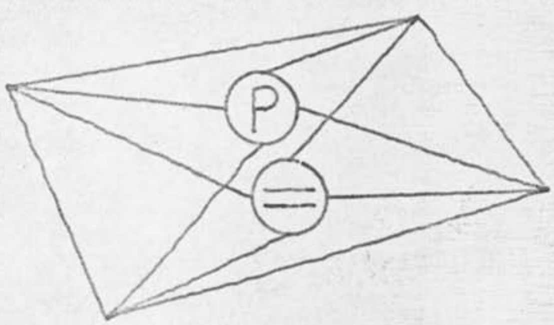
B. PICTURE TO CONSTRAIN



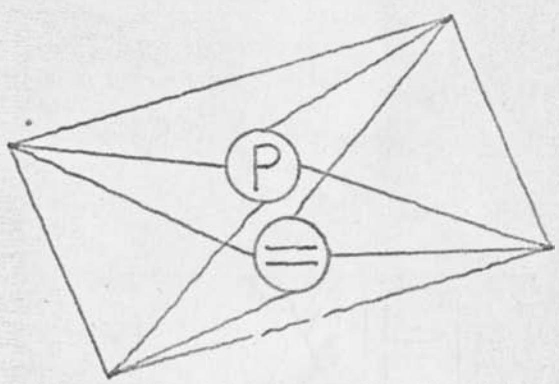
C. DEFINITION COPIED



D. FIRST LINE MERGED



E. SECOND LINE MERGED



F. CONSTRAINTS SATISFIED

FIGURE 5. APPLYING TWO CONSTRAINTS INDIRECTLY TO TWO LINES

P PARALLELISM = EQUAL LENGTH

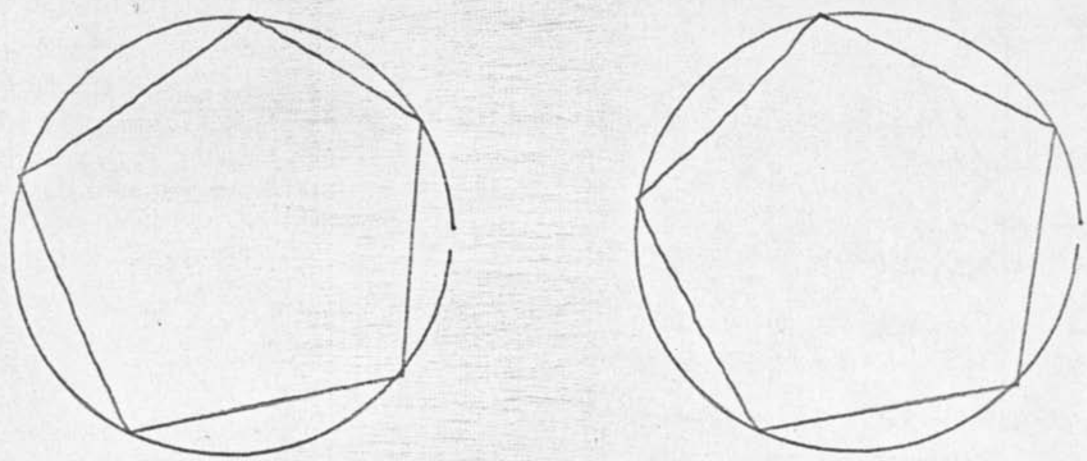


FIGURE 6. CONSTRUCTION OF PENTAGON

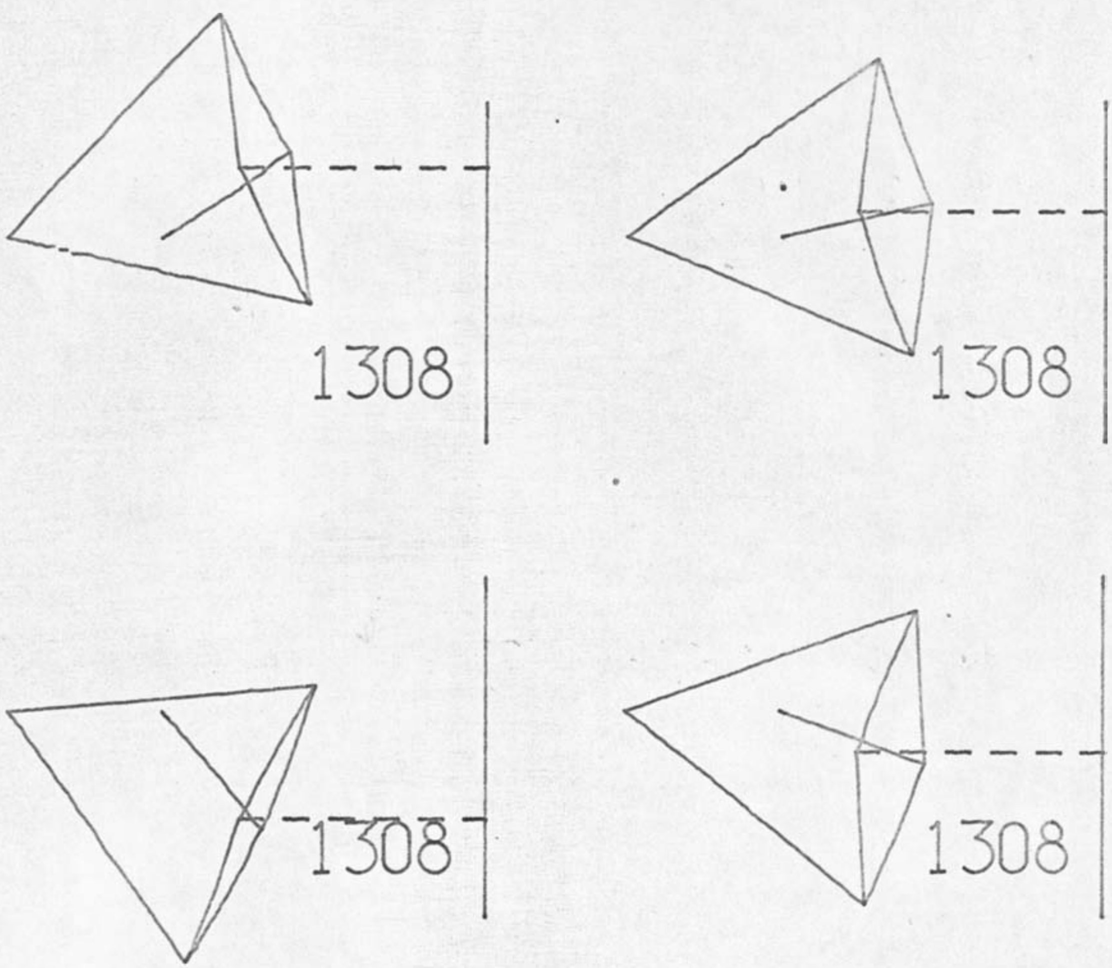
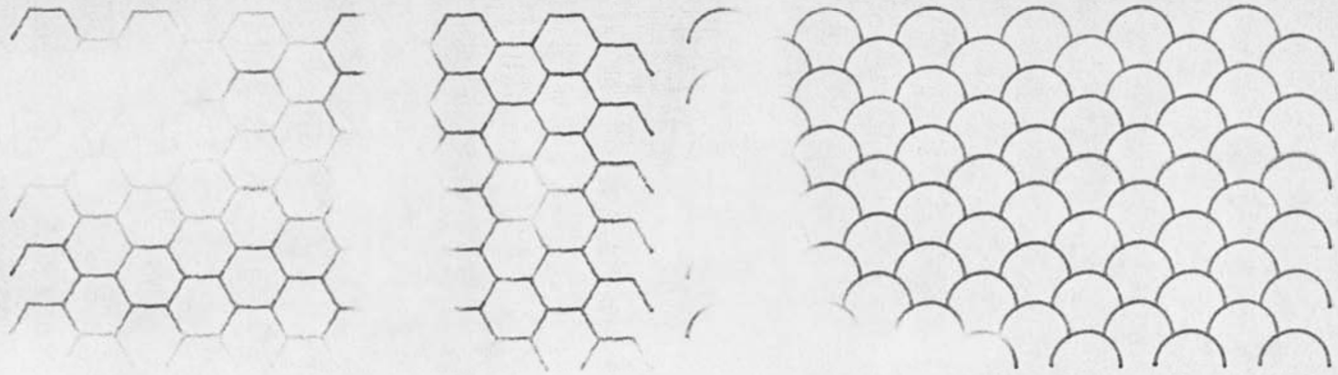


FIGURE 7. FOUR POSITIONS OF LINKAGE
NUMBER SHOWS LENGTH OF DOTTED LINE



IGURE 8. AND SAME LATICE

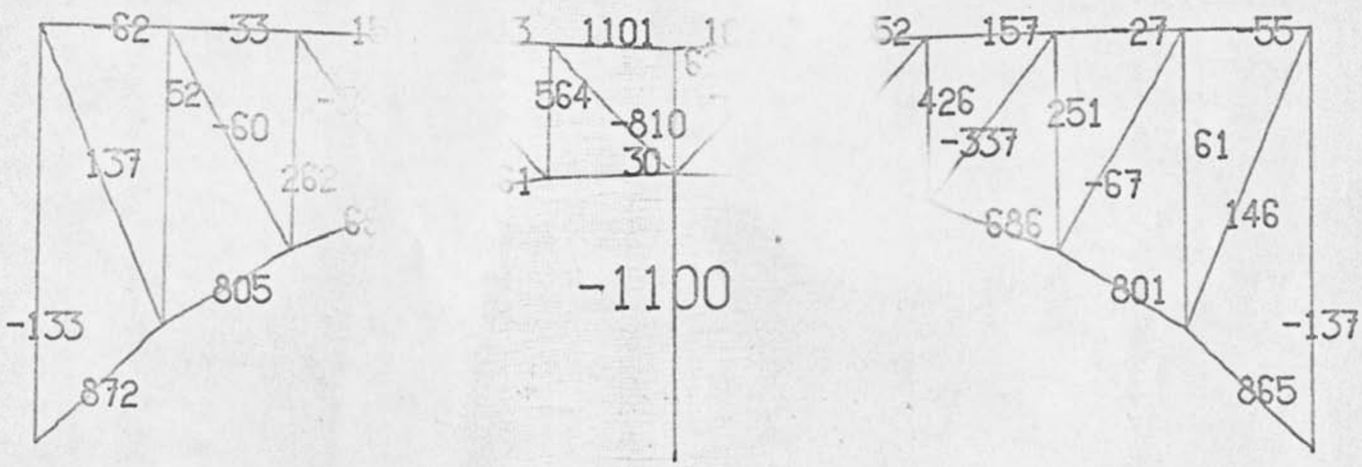


FIGURE 9. FORCES IN ARCH BRIDGE

SKETCHPAD, A GRAPHICAL MAN-MACHINE COMMUNICATION SYSTEM

By

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ABSTRACT

The Sketchpad system developed for the TX-2 computer at MIT Lincoln Laboratory is a general purpose graphical input, output, and drawing manipulation system intended for real-time construction of line drawings. The system has been used for electrical, mechanical, scientific, mathematical and artistic drawings, showing most usefulness for making small changes to existing drawings and for observation of motion of parts of a drawing, for example, of a linkage or a bridge under load. The figures in this report were all prepared with Sketchpad. A modified list structure storage of drawings gives flexibility for editing and for future expansion of the system. A demonstrative light pen language permits the user to describe the parts of a drawing to be changed by pointing to them; no written language is used.

Although the basic system contains only the simplest operations, complex operations and geometric relationships can be built up using the same drawing language used for making object pictures. Similarly, no symbol definitions are included, but any drawn symbol may be reproduced at will: symbols such as transistors appropriate to the particular user are drawn by him and used as he wishes. Geometric conditions imposed on the system by the user are automatically satisfied, if possible, by relocating picture parts soon after the

* This work supported in part by the U.S. Army Signal Corps, the Air Force Office of Scientific Research and the Office of Naval Research.

** Operated with support from the U.S. Army, Navy and Air Force.

conditions are applied; the program assists in turning a sketch into a finished drawing. A maze solving technique is used to provide one-pass satisfaction of conditions in many cases.

STORAGE STRUCTURE

Since the drawing contains large populations of relatively few types of objects: points, line segments, symbols, etc., and since these objects are related to each other primarily in a topological rather than numerical way, the storage representation of the objects is in the form of "n-component elements." Each object is represented by a group of consecutive registers in storage, an n-component element, whose registers contain the addresses of other n-component elements related to it. For example, the n-component element for a line segment contains two registers which indicate the addresses of the end point elements of the segment, as shown in Figure 1. The use of symbolic names for the registers of an element which contain various types of information makes it possible to easily rearrange the format of any type of element.

In order to facilitate the manipulations to be made on the n-component element structure as the drawing is changed, extra pointers are provided which, since they close in loops or rings, give the structure its name, "ring" structure. The additional pointers required to form the ring structure make it convenient to form each entry of a ring with a pair of registers. The ring is composed of a key pair, or "hen," and any number of subordinate pairs, or "chickens," as shown in Figure 2. The chickens indicate, with the "top of element" pointer shown, the address of the n-component element which contains their hen. The orientations of the pointers for the cases of no chickens and one chicken are arranged so that the ring manipulation programs operate without making exceptions for these cases. Basic ring manipulations operations permit adding new members to the ring anywhere in it, deleting any ring entry, combining two rings, and visiting all members of a ring, performing some subroutine for each.

The n-component elements used by the Sketchpad system for representing the topological relations in the drawing use the ring structure pairs as elements. Thus the n-component element for a line segment contains two chickens which are in rings whose key pairs, or hens, are a part of the start and end point elements for that line segment. It is easy, therefore, to perform some operation on all the line segments which terminate at a particular point by following such a ring; moreover, the "top of element" pointers in the chickens which are contained in the line segment element make it easy to go directly from a line segment to its end points. See Figure 3.

USING SKETCHPAD

To create drawings with the Sketchpad system a user may indicate position information with the light pen and specific commands with a set of push buttons. For example, to draw a straight line segment, the user points to the place where the line segment should start and presses the "draw" button. A straight line segment will appear from the indicated place to the light pen, following subsequent motions of the pen as would a rubber band until the termination signal is given. To obtain position information from the light pen, the computer spends about 10% of its time following light pen motions with a tracking display.

To modify existing drawings, the user may indicate specific commands with the buttons which are to be applied to whatever drawing part he points to with the light pen. For example, to delete a line segment, the user points to the line and presses a button labled "delete." The position information taken from the light pen may be modified slightly whenever the user is pointing to an existing object on the drawing. For example, if a new line segment is being drawn, its end point will attach directly on to the end point of an existing line if the user points to that end point when giving the termination signal. Figure 4 shows which objects are pointed at for light pen positions in areas near an existing line and circle segment and their end points. Since only objects which fall within the field of view of the light pen can possibly be pointed at, the computer need search through only a few objects to decide which is being pointed at; objects not seen by the pen are not considered.

RECURSIVE FUNCTIONS

The ring structure organization of the drawing storage in the Sketchpad system has led naturally to the use of some recursive functions for making changes to the structure. Recursive functions for deleting parts of the picture, combining newly created picture parts with existing parts, and for displaying subpictures within subpictures are included. The recursive nature of the deletion and combining operations is never used more deeply than two levels because no chains of inference exist among the geometric things represented by Sketchpad longer than two levels. Considerations of three dimensional objects may well lengthen the chains of inference. The recursive function which displays subpictures is regularly used to about ten levels of recursion. Any subpicture which attempts to be a subpicture of itself is recursed only once, avoiding infinite chains of recursion.

The recursive nature of the deletion and combining routines came about naturally from the ring structure used in the representation of the picture. For example, if a point is to be deleted, any line segments which end at that point will be deleted also, since otherwise they would have no end point, an inconsistent condition. Similarly, if two line segments are to be topologically combined (the result will occupy the position of the historically older line segment), their two pairs of end points must also combine into one pair upon which the resultant single line segment will terminate. Recursive combination makes it possible, for example, to make line segments parallel even though the parallelism operator applies only to their end points, since the location of these points controls the appearance of the line segment. Figure 5 shows the simultaneous application of the parallelism and equal length operators, explained in the next paragraph, to two line segments by copying into the object picture a definition containing these two operators and using recursive combination.

CONSTRAINTS AND CONSTRAINT SATISFACTION

A drawing in the Sketchpad system is more than just a group of marks made on a sheet of paper; it contains explicit representation of some conditions, usually geometric, relating the variables of the drawing. Recursive combination, described above, permits these conditions to be treated as if they applied to non-variables such as line segments. Each condition is represented by an n-component element which indicates the variables related and constrains the values of these variables in some way. The representations of the conditions are called "constraints," and appear on the drawing, when needed, as coded circles with arms drawn to the variables constrained, as in Figure 5. Since they appear on the drawing, the demonstrative light pen language can be used for deleting, applying, replacing, or relocating them.

In many geometric constructions a final variable can be located to completely satisfy all the conditions imposed upon it. If this be so, then the constraints on this last variable need not be considered in locating the just previous variables, and the number of conditions these variables must satisfy may be sufficiently reduced so that they may be used to completely satisfy all conditions. The freedom to completely satisfy all conditions imposed may spread in this way throughout the variables, making it possible to satisfy all conditions in just one computation pass. Sketchpad uses this method of freedom whenever possible to satisfy the conditions imposed without requiring assistance as to how to do so.

In cases where the method of freedom does not provide a solution, relaxation is used to arrive at better and better approximations to a solution. Over-constrained drawings, of course, never satisfy all the constraints applied, a fact which is evident from their appearance. The relaxation method is sufficiently fast for simple cases that it makes a powerful addition to geometric constructions. For example, to draw a pentagon one has merely to sketch five lines inside a circle and insist that they all be of equal length as shown in Figure 6. Similarly one can trisect an angle, etc.

The basic definition of a constraint type is a subroutine for computing the absolute error (a scaler) introduced into the system by the existing values of the variables constrained. This subroutine is usually so easy to write that special purpose constraints can be added to the system. For example, the computation routine which gives two points the same x coordinate, to make a line segment between them vertical, merely computes the difference in the x coordinates. A MACRO language is provided which makes operations like computing the distance between two points easy to describe.

APPLICATIONS OF THE SKETCHPAD SYSTEM

The major benefit of the Sketchpad system has been in providing understanding of graphical processes not normally seen in motion, and for making small changes to drawings previously entered into the system. The inclusion of constraints in a drawing makes it possible to observe the implications of a local change throughout the drawing. For example, rotation of the short central element of the linkage shown in Figure 7 is supposed to move the left end of the dotted line vertically. The numbers show that this is indeed the case.

The extensive use of subpictures makes it possible to generate regular arrays of similar figures, changing the basic shape at will. Figure 8 shows several shapes displayed on a hexagonal latice. The understanding of geometric relationships that can be brought by such dynamic use of a drawing system is invaluable and could justify the present relatively high cost of computer time.

The relaxation method used for satisfying constraints when the one-pass method fails can also serve to solve many engineering problems commonly handled by relaxation. For example, pin-connected trusses can easily be drawn and analyzed by constraining the length of each member to remain constant and indicating the change in length numerically. Changes in the design can be made whose implications are rapidly evident. Figure 9 shows an arch bridge with single central load analyzed in this way.

It has not yet been found economical either in terms of cost or even man time to produce complicated circuit drawings or complete detailed engineering drawings with the system, although a few such drawings have been made to try out the system. The illustrations for this paper were all prepared using the Sketchpad system and put on paper by a computer-controlled plotting system.