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A Ruling Engine for Making Zone Plates

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A RULING ENGINE FOR MAKING ZONE PLATES.

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About a century ago the corpuscular theory of light was falling into disfavor among scientific men in general and the wave theory was taking its place. Among the many contributions to the subject we find the writings of Fresnel. It was he especially who struck the decisive blow at the dying hypothesis. That part of his work which is of particular interest to us is his application of Huyghen's principle to phenomena of diffraction.

According to this principle, every particle on the wave-front, I B, figure 19, may be regarded as the source and center of a new wave. Suppose our figure were a section through a wave. A is the center of the disturbance; I B part of the wave-front, and F some particle on the straight line passing through A B, and farther from A than the wave-front. We know that, in a homogeneous medium, I B, the section through the wave-front, will be an arc of a circle. If there is no opaque obstacle on the line between A and F, the wave will in time reach F, for light travels in straight lines in such a medium. But, suppose we had an obstacle between A and F. Why is it that we will not receive light from the other particles on the wave-front if, as we have said, each particle there acts as the center of a new wave? In other words, why will light not travel in a crooked or curved path in a homogeneous medium? Fresnel's explanation is not the most satisfactory but is sufficient for the present purpose.

He divides the wave-front into a number of zones. In the figure these are shown as arcs of a circle. The line I F is equal to B F plus one half a wave-length. The next line is half a wave-length longer than I F, etc., every line is half a wave-length longer than the preceding. We will not go farther into these details since they are now too well known. Suffice it to say that, by simple mathematical means we can show that the motions given to F by any half zone are exactly balanced by the motions from the succeeding half zone as a result of destructive interference. There is one exception to this, *i. e.*, the motion transmitted by the particles in the immediate vicinity of B. The motion from these particles is what causes the motion of F. It is evident that when we interpose some obstacle, like the dark film of a photographic negative, so that the motions from each alternate zone cannot arrive at F, we will have the motions from the remaining alternate zones arriving a F, practically, at the same time and in the same phase. A negative of this kind will have a series of concentric circles whose radii are proportional to the square roots of the respective numbers of the circles. Soret, in 1875, produced a plate of ninety-eight dark circles and obtained some very satisfactory results. In 1898 Prof. Wood, then of the University of Wisconsin now of Johns Hopkins, made a plate of 115 dark circles. He also produced phase-reversal plates, *i. e.*, plates which were entirely transparent but in which the alternate zones would retard the motion by one half a wave length. His results, in addition to a plate, were published in the *Philosophical Magazine* for that year. His plates were made by first producing a drawing and photographing it afterwards. He used an ordinary beam-compass. Now, anyone who has had the fortune to manipulate one of these instruments can appreciate the value of a steady hand, when he obtains good results. It was with the intention of producing these plates with greater ease and accuracy that an engine, or rather machine, was built at the University of Iowa this year.

Mechanical details are always tiresome but, if you will draw on your liberal supply of patience, we will consider the engine which has enabled us to make plates of, not 230

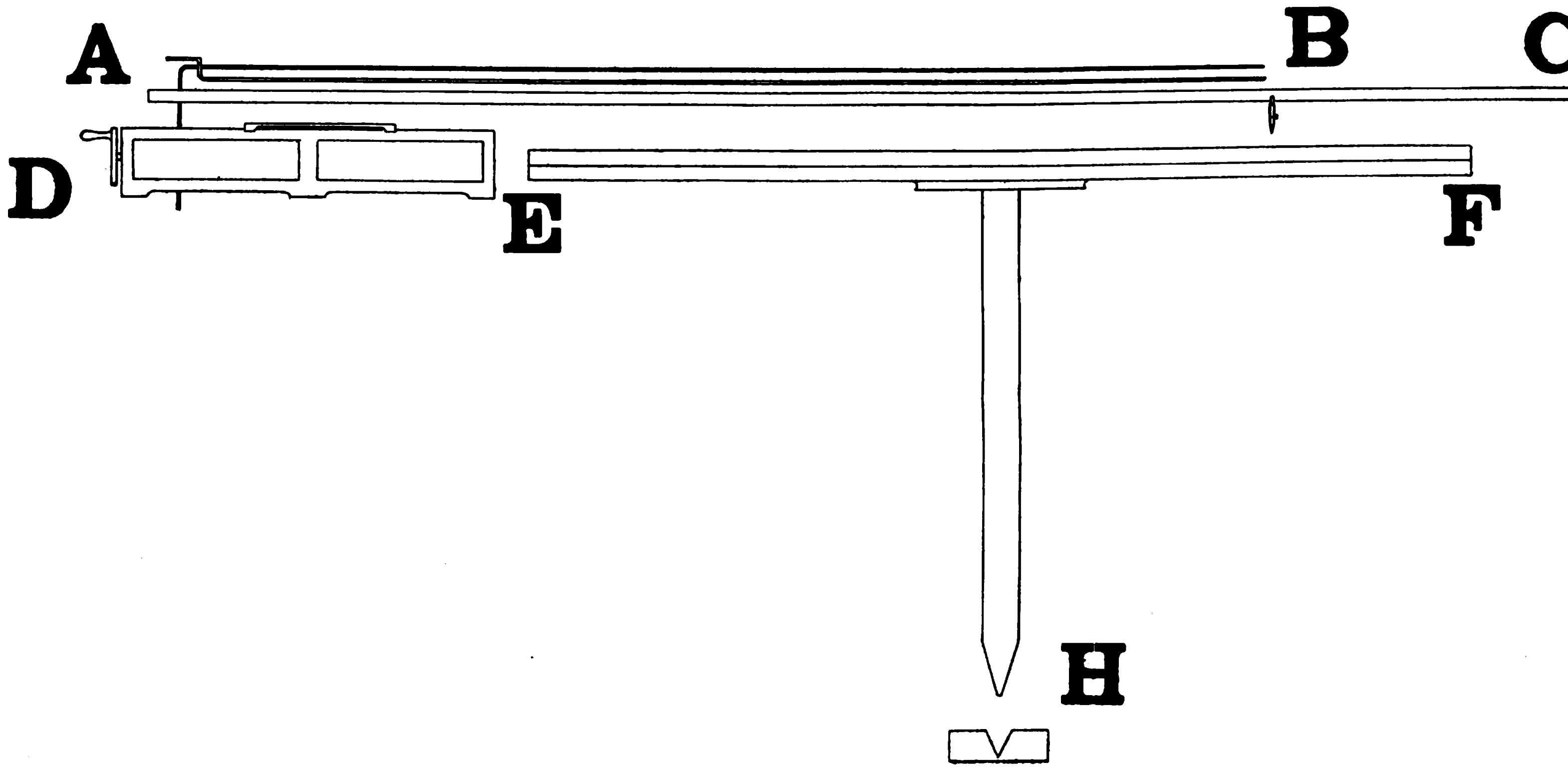

Figure 20.

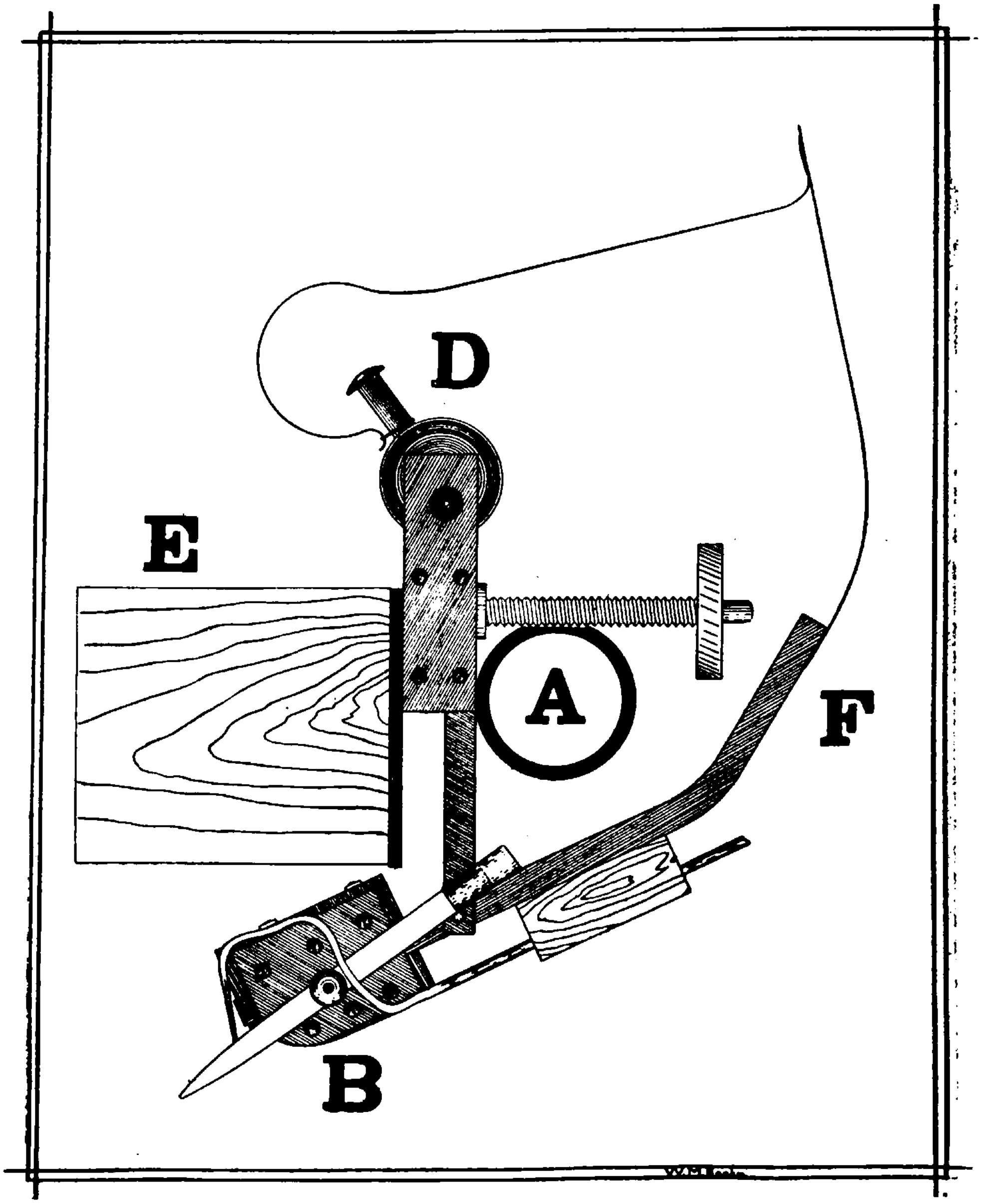

Figure 21.

circles, but of 900 circles, in the short time of eighteen hours.

First of all, the pen was not made to move about a center and describe a circle as in the ordinary process, but the drawing-board was made to revolve and the pen held stationary. In its general outline the machine may be seen in figure 20. A C is a long gas-pipe, selected on account of its smooth surface and cylindrical form. At B the drawing pen is attached. The operator governs it by means of a long brass rod between A and B. This enables him to lift the pen from the paper and lower it at will. Parallel to this rod there runs a long capillary tube through which ink is forced into the pen. The gas-pipe is fastened to the bed of the dividing-engine D E. The drawing-board is supported by a heavy steel shaft which rests in a conical bearing at H.

Figure 21 shows the method of attaching the pen to the gas-pipe, A. Two brass bars, D B and B F, form a hinge. The pen is fastened at B by an arrangement which permits its removal. Here may also be seen the glass capillary tube through which the ink is forced into the pen. This tube is fastened to the hinge in such a manner that the pen can be filled at any position of the hinge. A rubber tube, not shown in the drawing, connects this glass tube with the capillary tube running to the operator's table. At F there is a spring which tends to keep the pen pressed mildly against the surface of the paper. When the operator desires to lower the pen he turns the eccentric at D so as to draw F against the pipe and the pen at B descends. In order to lift the pen he reverses the process and the spring, which is attached to a screw at D, is drawn in the opposite direction. Thus one spring is made to do the work of two. At one time there was a second spring employed to raise the pen but it was found obnoxious and was soon discarded. The screw which you see above the pipe at A is not used when a drawing is made. Its purpose is to hold the point of the pen in a constant position so that depressions in the drawing table may be detected.

While the work is proceeding the pen becomes empty. The operator must have some means of watching the pen and the paper just below it. For this purpose a mirror, E, is attached at an angle of about forty-five degrees to the plane of the drawing-board. This reflects the image of the pen toward the operator's telescope. Occasionally, the pen must be cleaned. This can be done without disturbing its position. The width of the line can also be regulated. The hinge is made to fit closely in order to prevent a motion of the pen from side to side. To provide an additional safeguard against this possibility, a strong wire spring, not shown in the drawing, is attached to F so as to keep the end of the hinge drawn always to one side. The pen can be moved up or down by gentle pressure but not from side to side. It follows any slight elevation or depression in the surface of the drawing-board.

One of the most perplexing of the problems that had to be solved was that concerning the drawing-board. Suppose we had a board seven feet square. In a damp atmosphere it would swell more in one direction than in the other, which is a very undesirable property in this case. Suppose you made your board in two sections, an upper and a lower, having the long fiber at right angles. You would be adopting the method of the man who made the wooden saddle. The surface of the board would not be a plane. After some deliberation the following method was adopted: several pieces of broad pine flooring were taken and a line drawn down the middle of the broad side. Fifteen of these pieces were laid side by side so as to leave about three millimeters between each board and the adjoining one. Over these was placed a second layer of boards with their medial lines also marked. Wherever two of these medial lines intersected a screw was driven. In all about 230 screws. This gives a board which will hold its shape sufficiently for the present purpose. The expansion in the direction of the long fiber is very small. At right angles to this direction let the wood shrink or swell for we have given it sufficient room to do so in the

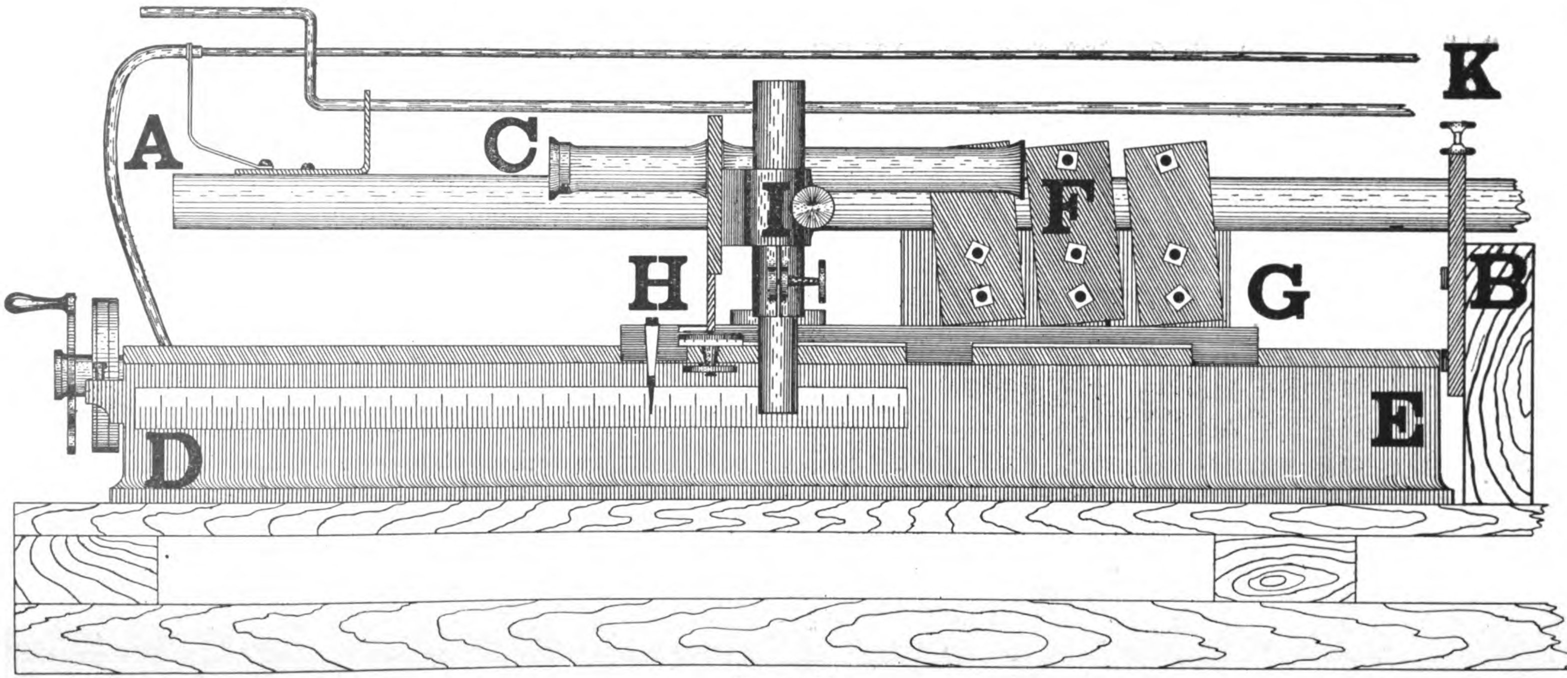

Figure 22.

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interspaces. The board is revolved at the rate of about one revolution in twenty seconds, by means of a small electric motor and a system of pulleys. Both motor and the pulleys have separate structures. The motor is placed on a pier which is free from mechanical contact with the building. The vibrations produced otherwise do not reach the pen or board so that the machine is practically free from all ordinary vibrations.

The diameter of this drawing-board is about 2.10 meters. The sheet of paper used was seventy-two inches wide. [Since drawing-paper is a commercial article, the ancient system is, of course, used.] The dividing-engine DE, figure 22, is only 45 cm. long. Now we should have a screw of more than 100 cm. in length. In order to get around this obstacle the following method was adopted: the gas-pipe, A B, was passed through two supports, KB, one at each end of the drawing-table. They were provided with screws, K, so that the pipe could be firmly fastened and not moved backward or forward. To H G, the movable bed of the engine, a solid iron bar, G, having the same width as the gas-pipe, is fastened. To this, in turn, are fastened three flat brass bars seen at F. A visitor once remarked that they reminded him of the inclined stacks of an ocean steamer, but you may rest assured that the artistic effect was not thought of during the construction of the apparatus. When mechanical perfection is impossible it is well to provide for the imperfections that are detrimental. No attempt was made to drill a hole through which the bolts would exactly fit. When the operator desires to fasten the pipe to the engine he first forces the bars back as far as possible and fastens the two lower bolts. Then the upper bolt is fastened and thus the pipe is firmly clamped to the bed of the engine. In order that the operator may make measurements and watch the actions of the pen there is mounted, at I, a Frauenhofer telescope, CF. It is shown a little higher than the gas-pipe but when in operation it is much nearer the same elevation. From A to K are shown in part, the lever which raises the pen and parallel to it the capillary tube for conveying the

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ink. An injector or, what is more to the point, a force-pump forces ink through the tube and into the pen. It is operated by hand. Along the side of the dividing-engine you may see a scale. A pointer from H shows the number of complete turns of the screw.

Figure 23 shows the engine as seen from the operator's end; the mounting of the telescope between F and I; the attachment of the gas-pipe between A and F; and at D the pointer to the side of the engine. There are two other pointers to be seen here. They are flexible pointers for the divided head which is of a peculiar construction.

Instead of having one divided circle it has three. This was invented after half of the first zone plate was completed and its value is quite apparent from the striking difference in the results obtained. In order to set the engine the figures were taken from a table of square roots, but these could not be used directly since the factor used in this case was thirty. It was simple enough to multiply by ten but to multiply by three involved the manipulation of some thirty thousand figures. It was an immense task but was cheerfully begun. The use of the new scale at the side of the engine, combined with the new form of the divided head, now makes it possible to set the engine directly from the tables without the use of another figure. It may be well to state here that the method of this divided head may be applied in a general manner. The head may be divided into any number of circles, not necessarily three, but the complementary scale, H, figure 24, should be divided into the same number of parts for direct reading. If you will look at this scale, H, you will see that each divisions represents a complete turn of the screw and every third division is numbered in succession. Suppose, for instance, you were to set the engine at 11. 85. You would turn until the pointer on the scale, H, stood at 11. 00. Now you would look at the divided head and use the outer circle, but you would not find .85 on this. It reads from 0 to .33⅓. Turn the screw one complete revolution and your pointer on H would be on the next division which is not marked. Look at the divided head once more and use

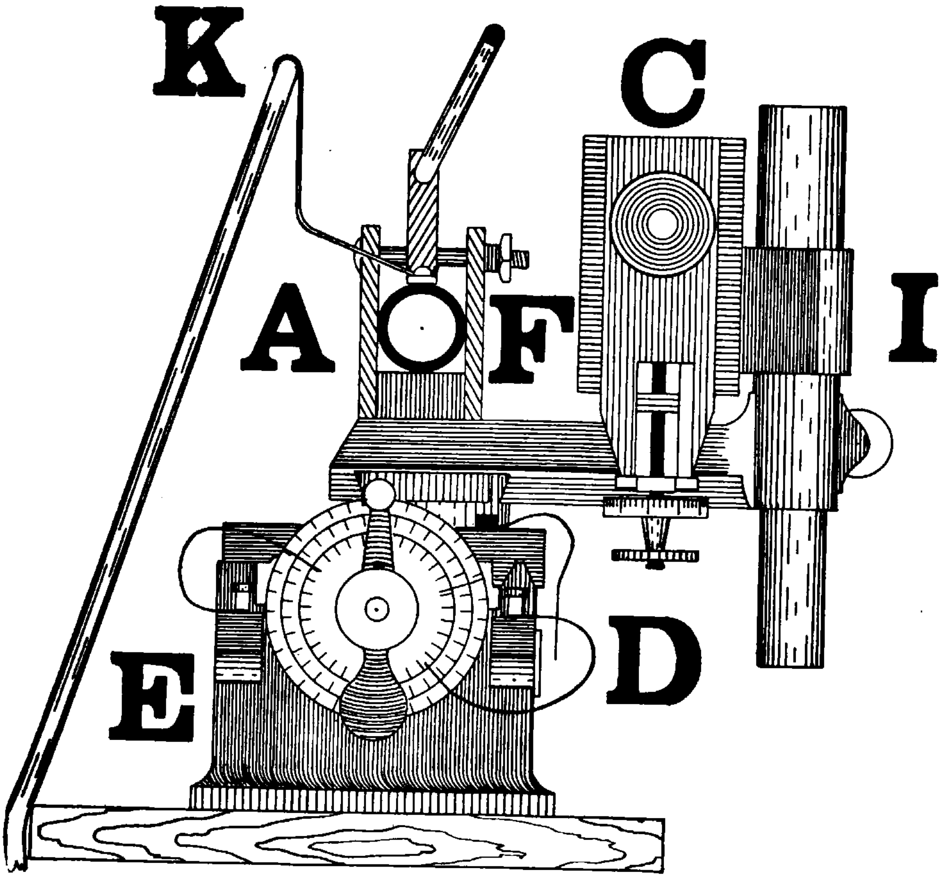

Figure 23.

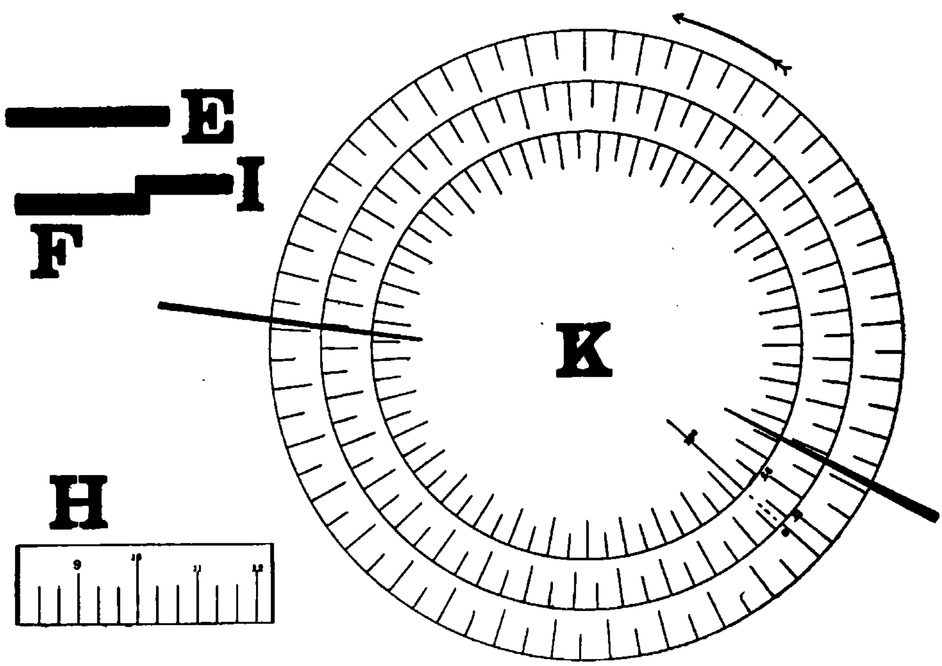

Figure 24.

the middle circle. It reads from .33⅓ to .66⅔, not so far as .85. Turn the screw another complete revolution and look at the divided head; use the inner circle this time It reads from .66⅔ to 1.00. The pointer on H is at the second unmarked scale, but if you turn till the divided head is set at 1.00 you will find the pointer on H at 12.00. Every third division on H is marked in succession. There are three spaces between 11.00 and 12.00. They correspond to three turns of the screw. The two unmarked divisions show which circle, on the divided head, to use.

The two pointers are used to allow for the width of the pen. The one at the right was used for the odd-numbered circles. Suppose the position of one of these circles were the lower margin of E, figure 24. If we had only this one pointer your next line would be at I, say. But, this is too far in a light zone by just the width of the line drawn by the pen. The pointer at the left is set so that, turning the head from the one on the right in the direction indicated, will move the pen forward just the width of the line it draws. The operator then works by the following method: he draws the line E by setting the head on the right pointer. For the next line he again turns until the proper figure appears at this pointer but instead of drawing I he turn and sets by the left pointer. He then draws F. The process is quite simple and the operator becomes mechanical in his actions as the work proceeds.

There is one more point to consider before closing: When the work is done with the beam compass, a small conical hole in a tack serves as the center for all the circles. We cannot do that with the present machine. In order to have the pen pass through the axis of the drawing-table, or through the center of the circle it draws, the table is firmly clamped and the pen moved over the paper. It traces a long straight line. Now the board is revolved through 180 degrees, firmly clamped, and the pen moved over the surface as before. If the two lines coincide, the pen passes through the center; if not, it can be adjusted until it does.

There are other details of more or less importance but they must be omitted. In its present condition the engine leaves room for improvement and improvements are continually being made. If it were to be reconstructed now, it would probably be slightly different from its present form. Many suggestions have been made; some are good, others worthless. In the face of these it is well to remember the words of Mueller:

"Wer jeden Rath berathen will der kommt zu keiner that."

Just what the final results of the investigations with the plates will be only a prophet can tell. This will form the subject-matter for other papers. It has not been the object to consider the plates themselves, but the engine with which we make them. We have been enabled to construct plates of 930 circles, more than four times the number drawn by Prof. Wood, but we can admire the patience with which he applied a beam compass to 230. The investigations with the plates will probably take two years of time at least and then the results may be negative. But what is the spirit of the scientist if not to throw aside years of labor and the most favored opinions, that the truth may be seen more clearly.

The engine was first planned after January 1, 1901. In its present imperfect condition it stands as the interrupted work of the past year. Had it not been for Professor A. A. Veblen, president of this learned body, the work would have come to an abrupt close before this. For his encouragement and many valuable suggestions I desire to express my gratitude.