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A Heath-Robinson Differential Analyser by George Sayell

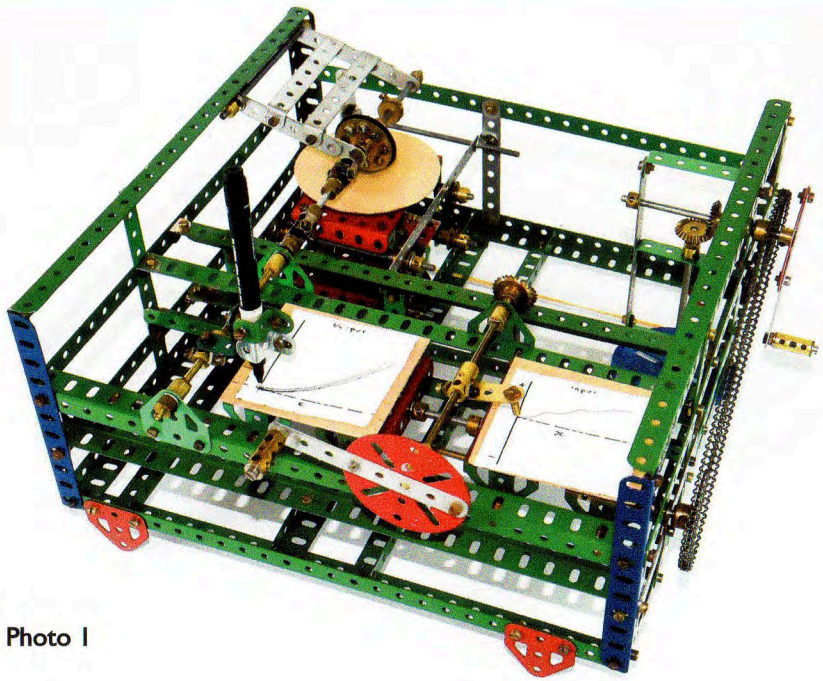


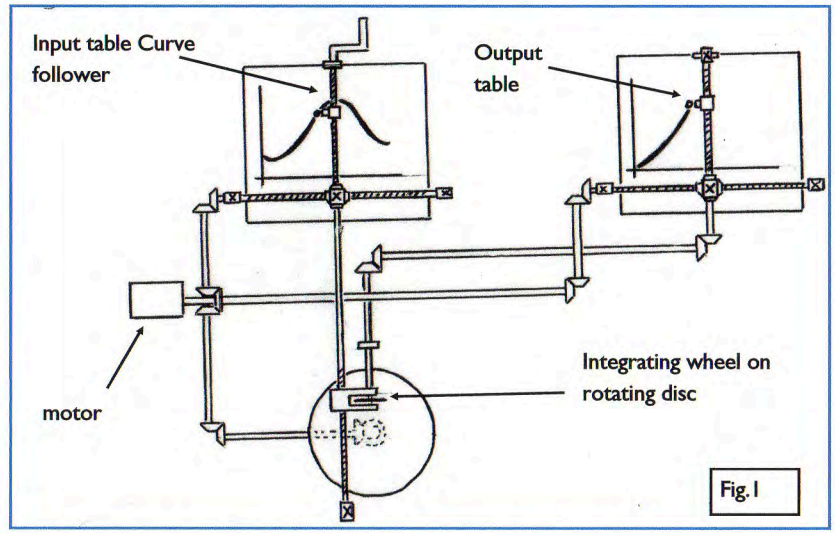
Photo 1

When I was given a collection of Meccano and told that it had been associated with Professor Douglas Hartree who built a Differential Analyser using Meccano in the 1930s and that a model of it was in the Science Museum I was determined to find out more about these machines. I gradually read about Differential Analysers and the important work that they had done and added building one to my long list of future projects. My interest reached fever point when Roger, our Secretary, asked if I would like to take part in a meeting to study and discuss the future of the Hartree model. (reported in MMGB73) Fired with enthusiasm I immediately decided the time had come to get on and build one.

A number of enthusiasts have built Differential Analysers to a high standard capable of performing various tasks to a high degree of accuracy. With my limited experience of Meccano, only a modest collection of parts and time constraints I set my sights lower. I wanted to achieve the simplest model capable of demonstrating the basic working principle and producing recognisable graphical results.

The mathematical purpose of the DA is to solve differential equations, for example such as those describing the motion of a projectile. As non mathematicians this may be interpreted, for simple first order equations, as finding the area under a graph.

The starting point was the simple diagram attributed to Seroka (fig 1). This shows a motor driven single stage unit with an Input Table, Output Table, and an Integrating device. The Integrator comprises a rotating Disc, an Integrating wheel and an Integrating shaft. The components are connected by a number of shafts and bevel gears and utilise screwed rods and threaded couplings to effect travel.

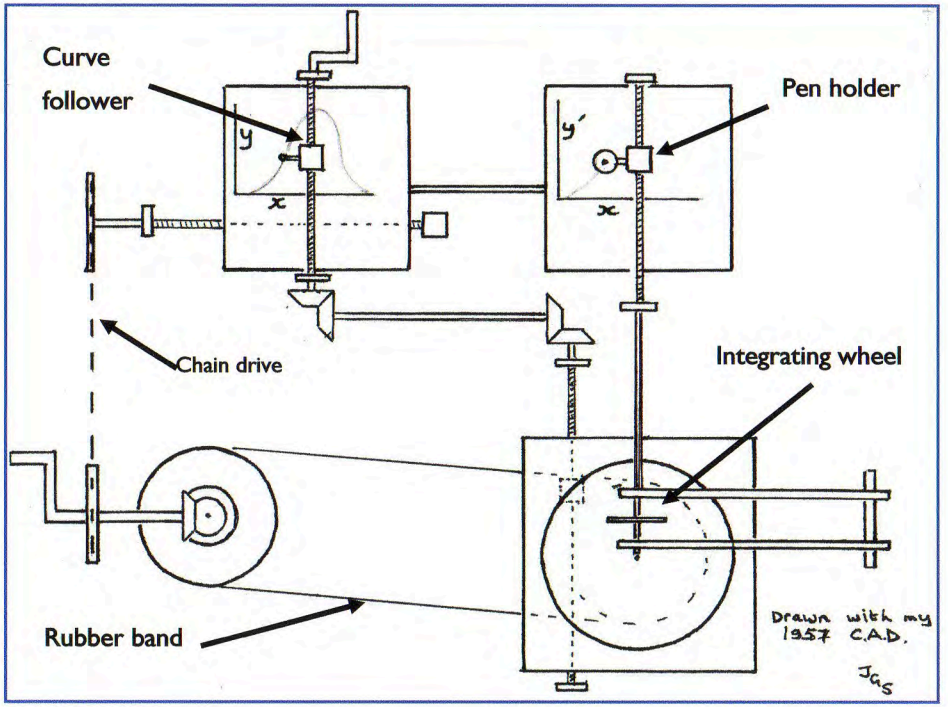


A curve follower is tracked along the 'Y' values of an X-Y graph (Input Table) as the table is moved along the 'X' axis. The tracking moves the Integrating wheel radially across the rotating disc, the wheel thus rotating at a speed determined by the disc speed and the radius of contact. The wheel rotation is used to generate a 'Y' value which is printed on an X-Y graph on the Output Table. The output graph of Y' against X gives the area of the X-Y plot between any values of X.

I studied this diagram and felt it was flawed in several aspects. The Input and Output tables are shown to be separately driven whilst they could be coupled together. It also showed a fixed Disc with the Integrating wheel and Integrating shaft moving over the Disc. The diagram shows the Disc in line with the Input Table and the rotation of the Integrating shaft transmitted to

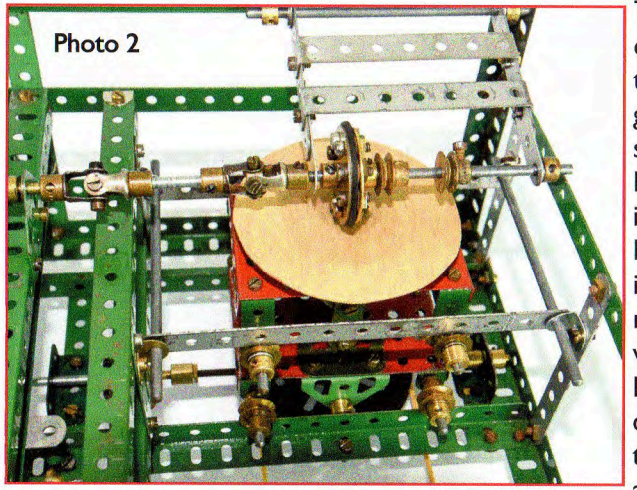
the Y axis of the Output Table using shafts and gears. The output torque of an Integrating Device is weak and is normally amplified in a multi-unit DA.

I decided to couple the Input and Output Tables and to have a manual drive to move them along the X axis and at the same time rotate the Disc. The Integrating Device was arranged to be in line with the Output Table thus minimising transmission losses. The Disc (on a rolling chassis) was moved below the Integrating wheel by the tracked Y position of the input graph using a series of shafts and gears. As the Disc would move during operation a 'rubber band' drive was used. (fig. 2 below).

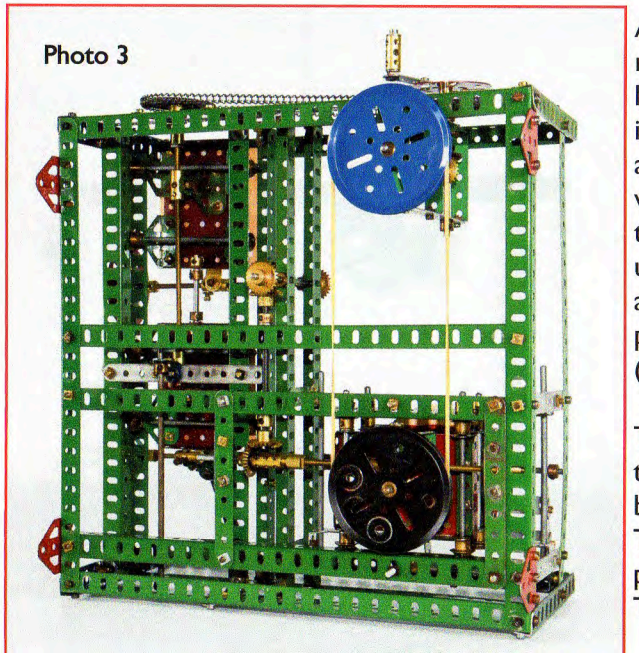


The model (shown in photo 1) is built within a frame comprising 12.1/2" and 5.5" Angle Girders. The carriages for the Input and Output Tables and the Integrating Unit consist of 3.1/2" x 2.1/2" Flanged Plates with ½"Pulleys that run on Angle Girders.

To prevent the Integrating Unit carriage from becoming displaced (a problem identified during the development stages) it is restrained by a second set of Pulley wheels running below Perforated Strips. (see photo 2)



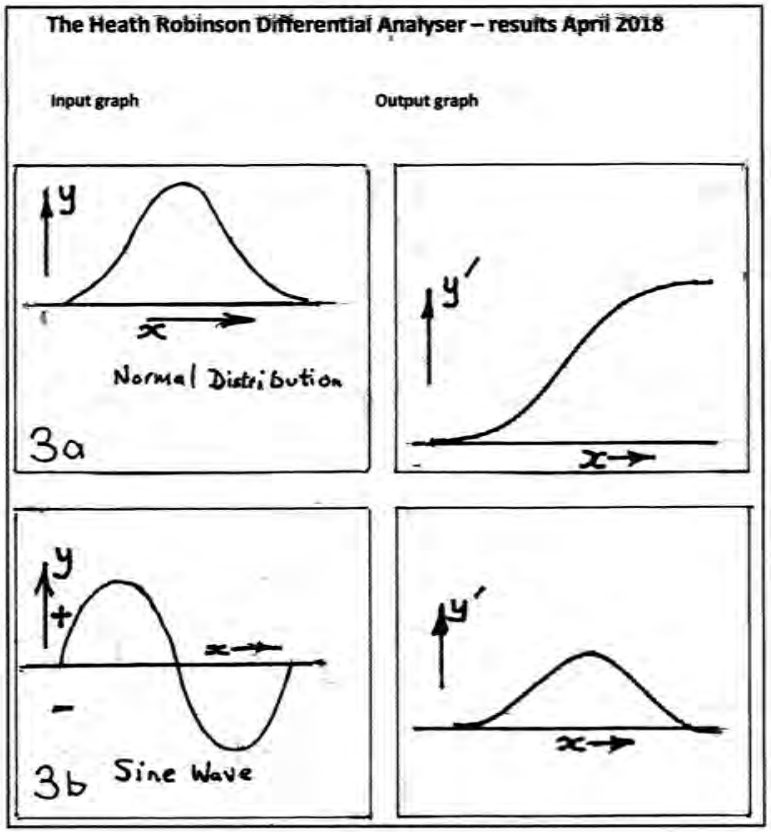
The rotation of the curve follower shaft is transmitted to the Integrating Unit rolling chassis with rods and 7/8" Bevel Gears. The rotating disc is plywood on a Face Plate. The Integrating wheel is trimmed rubber sheet sandwiched between two Bush Wheels. It was considered that the friction between the rubber and the wood would be sufficient to generate sufficient torque to operate the plotter. Two Universal Couplings are used to eliminate errors in alignment between the Integrating shaft and the Output Table. Movement of the carriages, and of the curve follower and pen holder, is by Screwed Rods and Threaded Boss Couplings. (as shown in photo3—the view from underneath the model)



A selected rubber band running between 3" Pulleys drives the Integrating unit rolling chassis and compensates for the variations in centre distance. A chain drive is used between the operating handle and the Input Table drive shaft. (shown in photo 1).

The model is set up with the plotted X-Y graph to be studied on the Input Table with a clean graph paper on the Output Table. While the tables

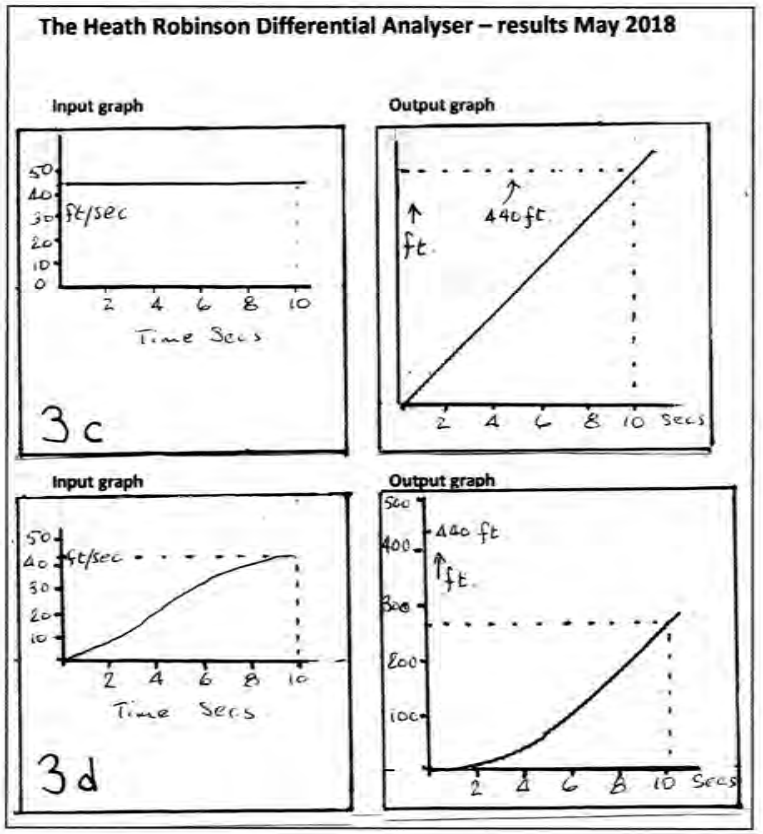
are moved along, the curve follower is tracked along the plot by rotating the Curve follower handle accordingly. Results from the model are shown in figures 3a to 3d. Figs. 3a and 3b show the areas under the curves of mathematical distributions. The input curve in Fig.3a is the 'Normal' distribution (sketched). This is used as a model to describe the frequency of variation (y) of size (x) in both manufacturing processes (e.g. diameter of widgets) and natural situations (e.g. heights of adult males). The output curve showing the area under this distribution is in the form of an ogive. The input curve in fig.3b is a sine wave (sketched). The output curve shows that the area increases as y is positive and then decreases to zero as y is negative.



Figs 3c and 3d illustrates the relationship of speed, distance travelled and time for a moving body. In fig 3c the Input graph shows a body travelling at a constant speed of 44 feet/sec (30 m.p.h.) (y axis) for 10 seconds (x axis). The distance travelled in this time is 44x10 = 440 feet.

The integral is shown in the Output graph where the distance travelled (y axis) against time (x axis) is a constant slope and will be 440 feet at 10 secs. We can use this to determine the scale for the y axis. In fig. 3d the Input graph shows a body now accelerating from rest to 44 feet/sec. in 10 secs. From the Output graph the distance travelled in this time is 270 feet.

The model has met my intended objective. It is basic and simple and I will be offering to show it to local schools where the pupils are learning calculus and to illustrate the early mechanical analogue computer from which the modern computers were developed.



After this first foray into this fascinating subject what do I do next – Could I build a two-stage unit, eliminating the need for torque amplification by building in adequate friction in the first Integrator enabling it to power the second unit, and all within an 18½" square frame .....!

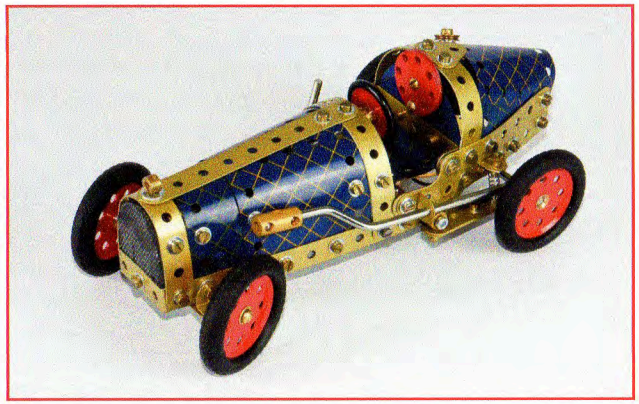
The award for the smallest and most ingenious 'model of the show' goes to **John Evans** for his inspired Binns class submarine which consisted of a seascape with periscope scanning the horizon. Even the wake from the periscope has been included. It was very good to see **John** who travelled from south Wales to be with us.

There were several models that I really didn't have time to look at in any detail – so apologies to the builders. **Sid Beckett** showed a roundabout; **Robin Schoolar** had an interesting Hogle Torque Amplifier and **Roger Marriott** showed his version of Brian Compton's Automatic Coal Loader/Unloader which is being written up as an MMG model plan.

The second part of the report is provided by John Rogers.

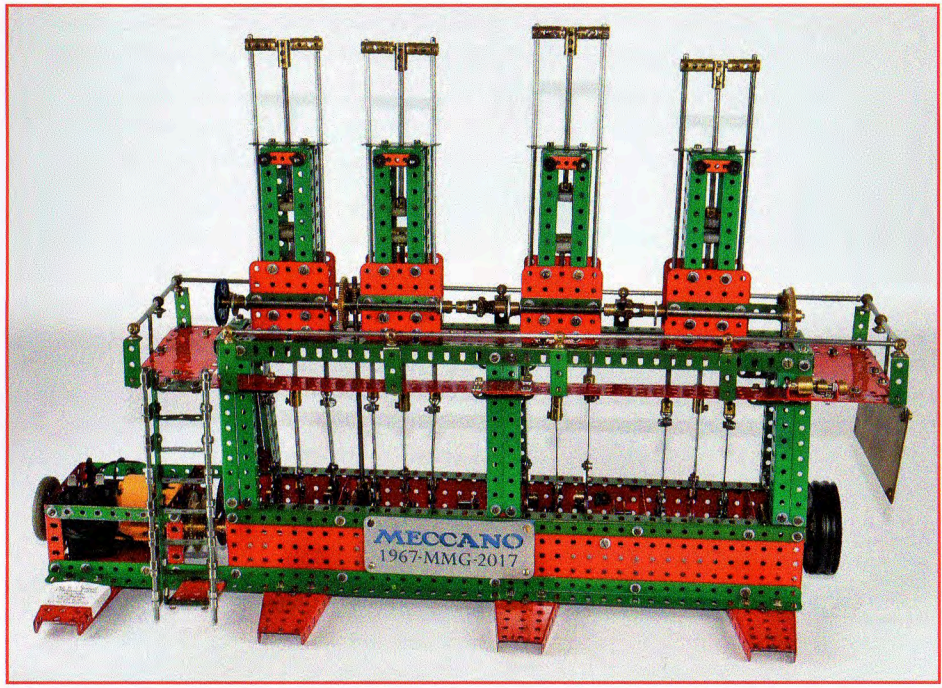
George Sayell displayed his Differential Analyser which he has created for demonstrations. There has been considerable publicity about the Meccano contacts with the Science Museum and research into the Hartree differential analyser. However it can be remembered that in Geoff Wright's Volume 2 published in 1978 on page 31 he selected the June 1934 MM article on this as one of the "finest Meccano model building achievements of all time." George Sayell explains that the original devices included 6 or even more stages. As far as I can understand it, the model provides a mechanical way of calculating the area underneath a graph (which is done analytically (ie using pencil and paper and the human brain) by the mathematical technique of integration) He talked to me with great enthusiasm about using his model for a comparison of speed with time to arrive at a distance v time graph. George Illingworth in his meeting talk commented that "it is the simplest version, built to demonstrate the principles - it works". Also on display was the Differential Analyser built by the late **Ron Fail**. It has two stages (of integration) and is a more complicated model but unfortunately it has to be restored and was not working. This model has been donated to the club and will be restored by John Nuttall. George Illingworth's overall comment - "Wow, what a machine and what a part in history."

Neil Bedford presented the first model he has made in blue/gold loosely based on a pre war Racing Car which he named "Retribution". It has a very smart appearance and is driven with battery power. (right)



Tim Martin had 8 new models exhibiting some ingenious Meccano constructions which were mostly focussed on underlying mathematical relationships. A construction of Mecca-

no Rods functioned as a Corner of a Euler Brick. Tim explains this is Pythagoras's Theorem in 3D with integer dimensions. Wiki tells me this was discovered in 1719 and a Euler brick is a cuboid that possesses integer edges and face diagonals. George Illingworth described the models with considerable accuracy impressing most of us, I suppose, that he actually understood their purpose.



Alan Scargill moved around the hall and the car park with his model of a 4 cylinder diesel engine showing its opposing cylinder movement. He explained that he had developed this from a 2 cylinder Meccano Model Plan. As usual Alan was very amusing company and he attracted some fun with his pre war 6 seater VIP car - which might have carried a very dubious previous owner.

Mark Rolston again displayed his JCB Excavator based on Model Plan 222 from Michael Adler - who spoke to Mark at Skegness and complimented him on a "better job". Mark explains that he has developed a metal tube for the ram and acquired a solid brass 62t gear to resolve weaknesses in the Model Plan.

Colin Reid had loaded his Yorkshire Steam Wagon with no less than 258 ¾" pinions. On Ebay today they are priced around £4 each giving them a gross market value of more than £1,000. Although by now this quantity might exceed total world demand. Colin explains that he acquired his vast quantities of parts at auction, presumably ex dealer. "Who else?" asked George Illingworth.

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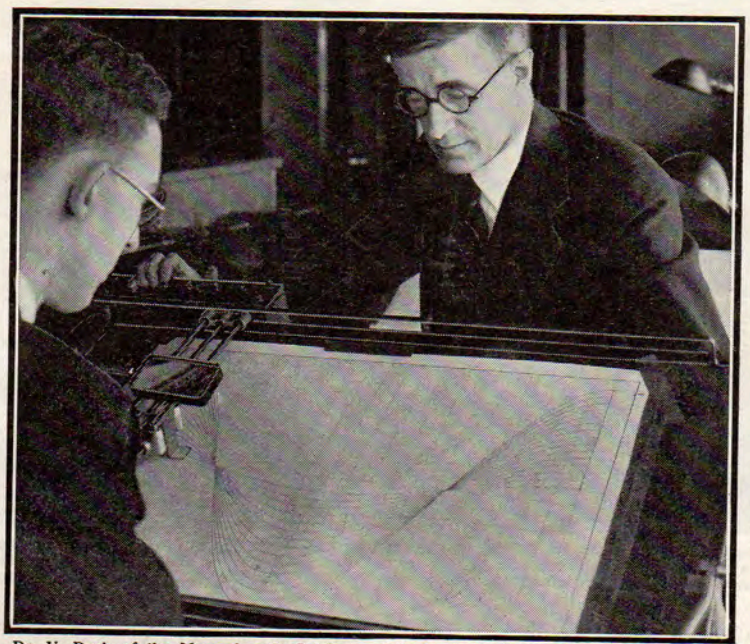
With the Editor

Meccano Aids Scientific Research

All my readers are aware of the many remarkable purposes for which Meccano has been employed by engineers, inventors and scientists. Formerly an engineer or an inventor who wished to try out a new idea in miniature form before launching on full-scale operations was obliged to make, or have made for him, special parts in wood or metal. This was a laborious and costly process, and quite often the completed parts proved in the end to be useless on account of some flaw in the scheme. In such cases these specially-made parts had to be thrown away because they were of no use for any other purpose. Meccano has altered all this by providing ready-made parts with which almost any mechanical movement can be reproduced, and which remain available for further experiments if a scheme turns out to be unsound.

The remarkable Meccano mechanism described on page 442 of this issue is a striking example of the manner in which Meccano can assist the scientist. Some time ago Professor Hartree of Manchester University determined to try to reproduce the movements of the Differential Analyser, a wonderful machine designed by Dr. V. Bush, a well-known American electrical engineer. This machine automatically solves complex mathematical problems with uncanny speed and accuracy, and Professor Hartree's purpose was to investigate its working and to demonstrate its uses. Meccano had provided him with many happy hours when he was a boy, and had been of great assistance to him on many more recent occasions. Naturally, therefore, he used Meccano parts for the building of this new machine, and the result surpassed his expectations, for the mechanism he constructed was capable of carrying out similar work to that done by the original machine.

The Differential Analyser constructed by Professor Hartree illustrates one of the most valuable features of the Meccano system, namely, its infinite elasticity. The original American machine is built up of a number of units, each playing its own part in the intricate process of solving the difficult mathematical problems with which it is designed to cope; and its range can be extended almost indefinitely by the addition of further units. The elasticity of Meccano has made it possible for the model to be built up and extended step by step to adapt it to new problems. The results that Professor Hartree has already achieved with the model in his research work are sufficient in themselves to justify the claim that it represents the most remarkable scientific application of Meccano parts that has yet been made.



Dr. V. Bush of the Massachusetts Institute of Technology, Cambridge, U.S.A., watching the operation of the Differential Analyser, a wonderful machine he has designed for speedily solving intricate mathematical problems. A working reproduction of this machine in Meccano is described in the article on page 442 of this issue.

Are Thinking Machines Possible?

The triumph of the Bush Differential Analyser and of its Meccano counterpart seems to me to mark an important stage in the development of machines. This development originated in attempts to replace muscular effort by mechanical power. During many centuries steady progress was made in this direction by means of power developed by harnessing wind and water, and then came an enormous stride forward with the introduction of the steam engine. More recent developments in the form of electricity and of internal combustion engines have carried the wave of progress still further, and to-day machinery is employed in transport and industry to such an extent that we have begun to look forward to the time when practically all the world's work will be done mechanically.

Machines have even invaded the office, and to-day they play an important part in occupations that until recently were thought to be beyond their range. The first of the invaders was the typewriter, which has been adopted on a world-wide scale and has completely transformed office work. The typewriter was followed by duplicators that produce copies of original documents at high speed, and by tabulating and accounting machines that may be described as super-clerks, for they add, subtract, multiply and divide figures supplied to them, and even sort these out in such a manner as to produce any desired result in the most convenient form. They carry out their complicated tasks in a much shorter time than would be required by human clerks, and are so accurately constructed that they are practically free from error.

I sometimes wonder if there is any limit to the powers of machinery. The machines I have just mentioned are specially adapted for the repeated performance of certain operations. This is true also of the Differential Analyser, but it seems to me that this machine is capable of something that approaches actual "thinking," along the lines laid down for it by its designer. Thinking machines play an important part in fantastic stories of the future, and writers have even imagined contrivances that could interpret the thoughts of their controllers and pass these on to beings of a different type in a form that is intelligible to them. Many of the strangest things of fiction have already become realities, and it would be rash to prophesy the impossibility of producing machines capable of processes equivalent to a mechanical type of thinking. Truly creative thinking of course will always remain beyond the power of any machine.

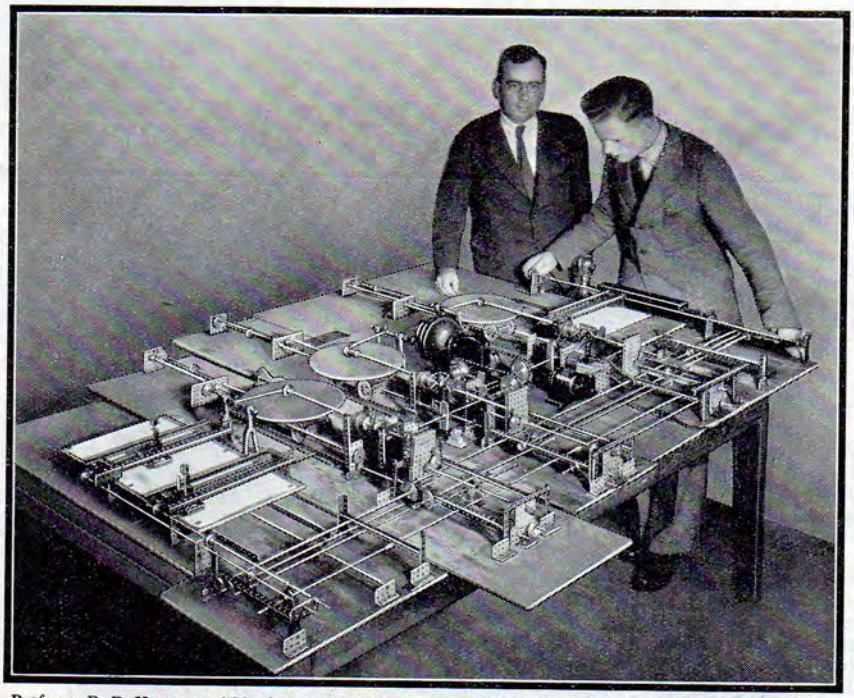
Machine Solves Mathematical Problems

A Wonderful Meccano Mechanism

FROM time to time examples have been given in the "*M.M.*" of the readiness with which the most complicated mechanisms can be reproduced in Meccano. An excellent instance of this is the wonderful astronomical clock described on page 170 of our issue for March, 1933, which automatically gives a wealth of interesting and useful astronomical information. More recently Meccano has been used in the construction of a remarkable machine that solves in a few minutes complicated equations that otherwise could only be dealt with by laborious calculations occupying many hours. The original of this model is a machine known as the Differential Analyser that was developed by Dr. V. Bush, Vice-President of the Massachusetts Institute of Technology, Cambridge, U.S.A. In constructing this machine, which at present is the only one of its kind in the world, Dr. Bush's purpose was to shorten the labour of making calculations from the complicated equations met with in working out problems in electrical and other branches of engineering, and also in physics and astronomy.

The solution of these equations is often difficult, and the kind of arithmetical work involved is not well known, and is prolonged and wearisome. Further, human calculators are liable to error, especially in carrying out long series of similar calculations such as are often necessary in work of this kind. These difficulties are avoided by the use of the machine. In a few hours it can be set to provide solutions for equations of astonishing complexity, and then accurate results can be obtained from it in a convenient form in a few minutes.

A general view of the Differential Analyser is given in the upper illustration on the opposite page. It has been described as one of the most comprehensive pieces of mathematical machinery ever built, but in spite of its formidable appearance it is really simple in construction. It consists of an assembly of units that mechanically add, subtract, and carry out other and more complicated mathematical operations, and by adding more units it can readily be enlarged to deal with problems of increasing complexity. As a matter of fact it grows so continuously that its designer has expressed the opinion that it will never really be complete.



Professor D. R. Hartree and Mr. A. Porter, of the Department of Mathematics, The University, Manchester, with a wonderful Meccano mechanism they have constructed to solve complex mathematical problems. This mechanism is a reproduction on a smaller scale of the Bush Differential Analyser illustrated on the opposite page, and a simpler form of it is illustrated at the top of page 444.

The most important mathematical operation that the machine carries out distinguishes it from other kinds of calculating machine, and makes it unique in the range and complexity of problems to which it can be applied. This operation can best be explained by an example. Suppose that a motor car is starting from rest, and that we have a record of its speed at each moment from the start. This record might be in the form of a graph showing how the speed varied with the time from the start; in handling the problem by the Differential Analyser the information actually would be supplied to it in the form of such a graph. From this information we require to know how far the car goes in, say, two minutes. We can find this approximately by dividing the period of two minutes into smaller intervals, for example into 12 intervals of 10 seconds each; and by imagining that the speed remains constant in each interval, then suddenly changes to another constant value in the next interval, and so on. Thus we can find the distance travelled in each period by multiplying each time interval by the supposed constant speed corresponding to it, and finally add up the distances travelled in successive intervals to find the total distance covered.

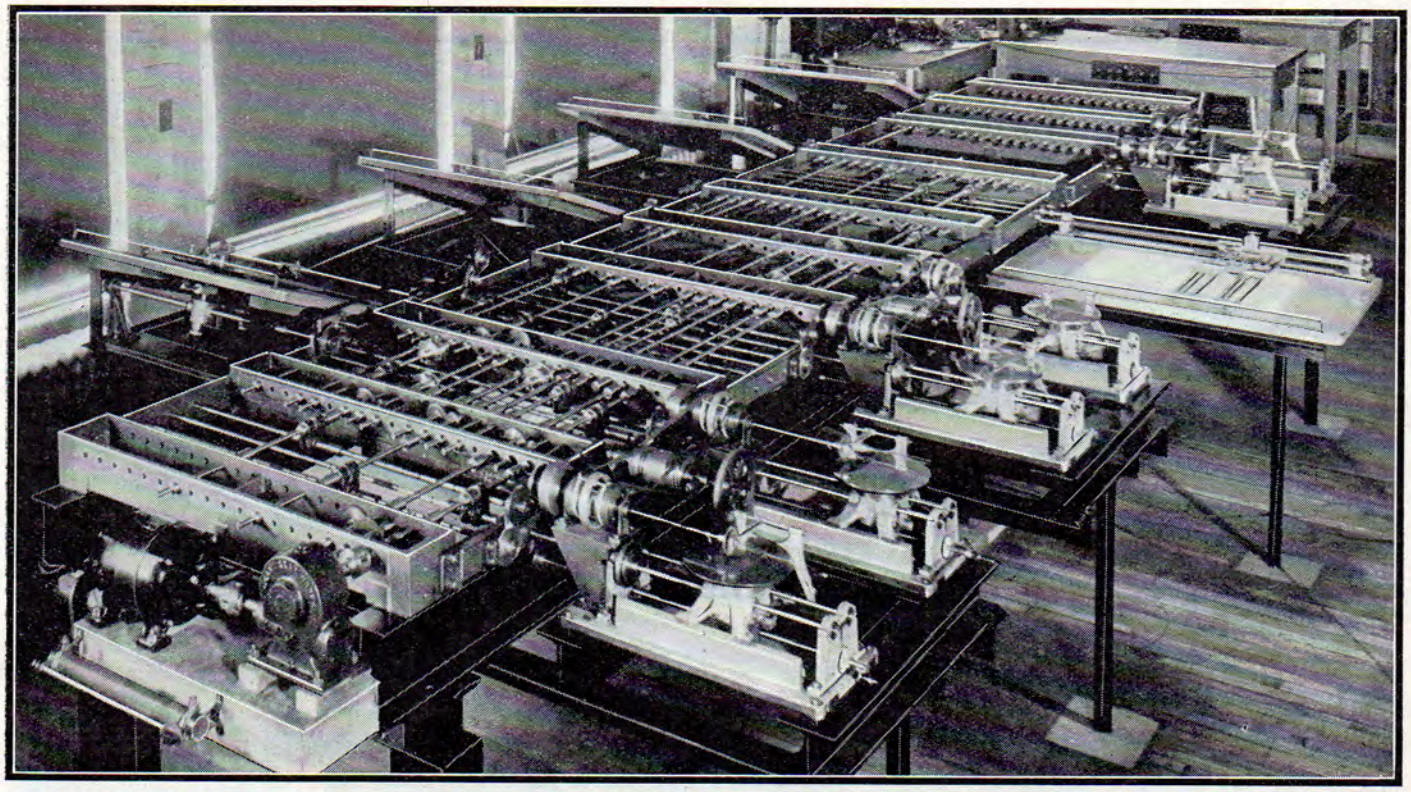
The result will be only approximate, because the speed actually is not constant in each interval, as we have imagined it to be. The error on this account can be decreased, however, by dividing up the period into smaller intervals, say 24 of five seconds each, or 60 of two seconds each, etc., until the variation of speed in each interval becomes too small to matter. By taking small enough intervals an accurate result can be calculated, however rapidly the speed varies during the total period concerned.

The mathematical operation in which the distance traversed is derived from the speed, which is regarded as known, is technically called "integration"; and the essential feature of the machine is that it incorporates devices called "integrators" for carrying out this operation mechanically. How an integrator works will be described later.

This operation of integration arises in the working out of the most varied problems, in astronomy, physics, chemistry, and engineering, and the scope of problems that can be investigated by the machine is correspondingly wide.

In the centre of the machine is a set of longitudinal shafts, which in our illustration can be seen running from the lower left-hand corner towards the right-hand upper corner. These shafts can be geared to each other so as to rotate at various relative speeds, and the rate at which each turns represents a term in the equation for which a solution is required. The manner in which they are geared depends on the relation between the terms. For instance, if any two terms are to be added together, the shafts representing them are connected with a third by means of differential gearing designed to make the third shaft turn at a speed representing the sum of the speeds of the shafts driving it. More complicated relationships are worked out through special devices such as the integrators already mentioned, which can be seen on the right of the longitudinal shafts; and others known as input tables, which are on the left. Both devices are driven by means of cross shafts.

When the necessary connections have been made, one of the shafts is driven by an electric motor, and in turn drives the other shafts, each at its appropriate speed. When this is done, the speed of the shaft representing the term of which the value is to be found then gives the required solution. For the type of equation dealt with on the machine, the kind of result most usually required is not a single number, but a series of related numbers. For example, in the case of the motor car already considered we wished to know the distance the car travelled in two minutes. To complete our information, however, we require to know how far the car goes in three, four, five, or any other number of seconds. The machine

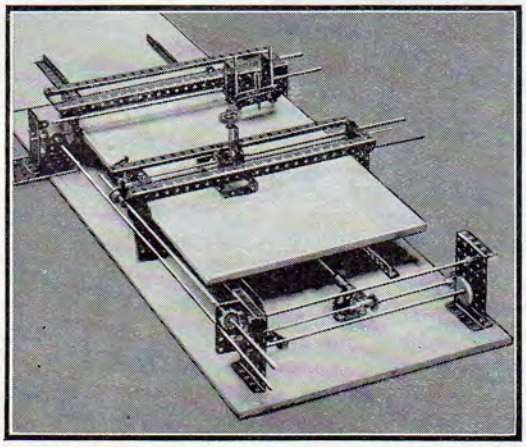


The Bush Differential Analyser at the Massachusetts Institute of Technology, Cambridge, U.S.A. This machine is illustrated also on page 441. We are indebted to the courtesy of Dr. V. Bush for our photographs. Below are the output (left) and input tables of the Meccano reproduction of the machine described in this article.

provides this solution in a very ingenious manner, for the shaft representing distance travelled—the solution of the equation—is made to drive through cross shafts a pencil that moves across a sheet of paper pinned to a board, and this itself is moved at right angles through similar gearing connected to the longitudinal shaft representing time. Thus the pencil draws a curve that shows how the distance travelled increases with the time, and this is the solution to the equation.

The board on which this curve is drawn is called the output table, and in our photograph of the machine is shown on the right of the horizontal shafts. If the pencil were driven from a shaft representing the distance travelled by the car, the curve drawn then would enable the distance at any instant to be found, and the machine can readily be adjusted to give solutions in alternative forms as may be desired. In practice curves for two quantities concerned in the solution can be drawn by using two pencil carriages.

The Meccano model of this ingenious machine was designed and constructed by Professor D. R. Hartree, F.R.S., of the Department of Mathematics, The University, Manchester, and Mr. A. Porter, and is shown in the upper illustration on page 444. It was built for the purpose of demonstrating the principles on which the Bush Differential Analyser works, but it turned out to be more than a demonstration model, and to be capable of solving many equations with a considerable degree of accuracy. It is simpler than the original, but has just the same flexibility, and its range of operations can be increased by the addition of new units. Professor Hartree is finding it of great value in connection with his researches on electrical problems connected with the constitution of the atom, and thus Meccano is playing an important part in an interesting field of scientific work.



As will be seen from the illustration on page 444, the general layout of Professor Hartree's model is similar to that of the Bush machine. The shafts consist of Axle Rods joined where necessary by means of Couplings in order to provide the necessary length. These shafts are journalled in holes in suitable positions in $3\frac{1}{2}'' \times 2\frac{1}{2}''$ Flanged Plates screwed to the table, and drive the cross shafts, also consisting of Axle Rods, by means of $\frac{7}{8}''$ Bevel Gears. A 6-volt Meccano Electric Motor is employed to drive the shafts, and this, together with its transformer, can be seen on the right of the photograph.

The output table of the machine is shown in detail in the left-hand lower corner of this page. The pencil that draws the output curve is supported by a carriage, built of Meccano parts, that moves along two Axle Rods that support it and are fitted in a framework of Girders bolted to $3\frac{1}{2}'' \times 2\frac{1}{2}''$ Flanged Plates screwed down to the table. This is moved by the rotation of a Screwed Rod that passes through a Threaded Crank fixed to the carriage, and is fitted with Collars where it passes through the Flanged Plates so that it cannot move along its length. The Screwed Rod is driven by $\frac{7}{8}''$ Bevel Gears from a cross shaft, which is similarly driven from the main shafts of the machine.

The output table is moved at right angles to the direction followed by the pencil. The drive from the appropriate main shaft is transmitted to it by a Screwed Rod passing under it through a Threaded Crank bolted to an Angle Girder screwed to the under side of the table. A second pencil carriage is provided, as in the original machine. The additional cross shaft can be seen on the left, below the first one.

The input table of the machine is shown in the right-hand lower corner of this page, together with a part of the longitudinal shaft system that has been disconnected from the rest of the machine for convenience in obtaining a photograph. Its purpose is to enable two shafts connected

