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APPENDIX E

DESCRIPTION OF UNITS COMPOSING ANALYZER

In the main body of this report on an electronic difference analyzer, the general features of an electronic computer were outlined. The purpose of this section is to extend the definitions which were given under the technical section (Part II) of this report and to state practical methods by which the operations indicated might be done. While many ways of doing the various operations involved have suggested themselves, we will here limit ourselves to a discussion of the one or two methods which in each case seem to have the most merit. A discussion of suitable tubes and other associated parts will conclude this section and is included to give a better physical picture of the apparatus.

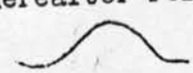
Pulses

Since the entire operation of the device is instigated, controlled and carried out by means of pulses, we will append the previous definition and define several types.

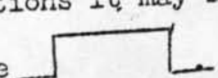
Pulse - General definition as given in Part II of this report:

"An electrical pulse consisting, for example, of a temporary rise or fall in voltage relative to an average voltage level. All pulses are controlled so as to have approximately the same duration and magnitude.

(a) Simple Pulse

For the operation of many of the following circuits the exact shape of the pulse would be relatively unimportant. Under such conditions a "simple pulse" or just a "pulse" or "pip" will be suitable. Such a "pulse" as we will hereafter refer to it, would probably have the appearance of a normal error curve  since it would be the most easily generated and thus the best to use when the application is not critical as to shape. The rate of repetition of such a pulse will be referred to as the "pulse rate", and the duration of such a pulse may be taken as the time for the voltage to go from 5 per cent of its maximum value through the maximum and down to five per cent again.

(b) Square Pulse

For other applications it may be desirable to use a "square pulse" or a pulse of rectangular shape  The same definitions of "pulse rate" and "duration" may be used as were stated for a "simple pulse". Such pulses are needed when it is necessary to define the position of the beginning and/or end of the pulse very accurately, or when the device into which the pulse is applied is rather sensitive to the amplitude of the applied voltage.

(c) Gate Pulse

A "gate pulse" or simply a "gate" is a "square pulse" which is applied to a circuit for the purpose of allowing another pulse, i.e., "simple pulse" or "square pulse" to produce an action on that circuit. As such the "gate" must rise (in voltage) before the advent of the "pulse" it "gates" and fall after the "pulse" has passed. Therefore it will be longer than the "puls which it "gates."

The circuits to be discussed later are made up of the following elementary circuits in special combinations and are operated by the "pulses" described above.

1. <u>Trigger Circuit</u>

Many of the operations involved in the units to follow, especially in the counters, require a circuit to remember that it has received a pulse. For this purpose a trigger circuit is required.

(a) <u>"Gas tubes"</u>

The ability to remember a previous pulse or operation is inherent in the design of a "gas triode" or "thyratron"; however the speed of operation of this device is too slow except for a very minor number of operations involved in the present machine. This device is so generally known as not to warrant further description here, other than to say that it is a tube which will not pass current in one circuit until a second circuit is energized and thereafter will pass current independent of the second circuit until the first circuit is broken. It is similar to a "no-current release" relay (latching relay).

(b) <u>"Vacuum Tube Trigger Circuit"</u>

Three basic ways of obtaining a circuit action similar to that of a thyratron are known.

(1) The first is to employ two vacuum tubes in the circuit shown in Figure 1.

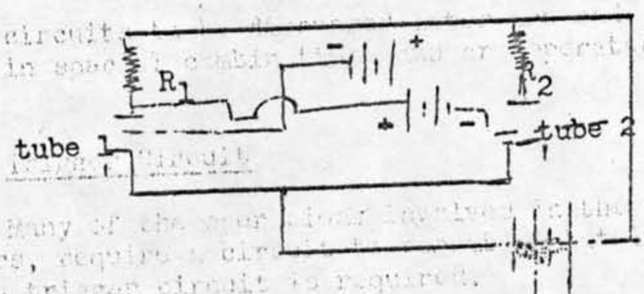


Fig. 1

In the circuit shown in Figure 1 we shall assume the voltage distribution to be such that if the tube (1) is assumed to be conducting the current through resistance R_1 will be such as to cause the grid of tube (2) to be sufficiently negative so as to prevent the passage of any current through R_2. This will result in the grid voltage of tube (1) being sufficiently high to allow the assumed current to flow. It can be seen that this condition is a stable one and the device will remain indefinitely in this condition unless disturbed; also it will be seen that alternately a similar argument would allow tube (2) to be conducting and tube (1) to be non-conducting. Thus it will be seen that two stable states are possible. A transition from one state to the other can be caused by applying pulses of the proper polarity across the resistances R_1 and R. Thus such a trigger can remember by this transition that it has received a pulse. Such a device is the electrical analog of a toggle switch.

(2) The other two vacuum tube trigger circuits are not considered as possibilities for this machine. The first of these two consists of an oscillator circuit which has two stable states, one blocked or non-oscillating, and the other oscillating. The second trigger uses the secondary emission of a pentode vacuum tube to obtain two stable states. Both of these devices are slower in operation, in their present state of development, and not easily coupled to one another.

(c) <u>"Pulse Sharpener"</u>

The previously described trigger circuit can be used as a "pulse sharpener" by appropriate modification of the voltage distribution in the circuit If a square pulse (which, however, not being sufficiently square, needs sharpening) is applied to one of the resistors R_1 or R_2, the circuit will remain dormant until a critical value of voltage is reached, then it will suddenly flip over. If the voltages have been properly arranged it will, however, flip back as soon as the voltage has subsided again to some critical value. It is the electrical analog of the spring bottom found on many oil cans.

(d) <u>"Square Pulse" or "Gate" Formers</u>

Frequently it is necessary to produce a "square pulse" or "gate" from a simple "pulse". This can be accomplished by building a time constant into the trigger circuit in such a way as to make it return at a predetermined time after it has been flipped.

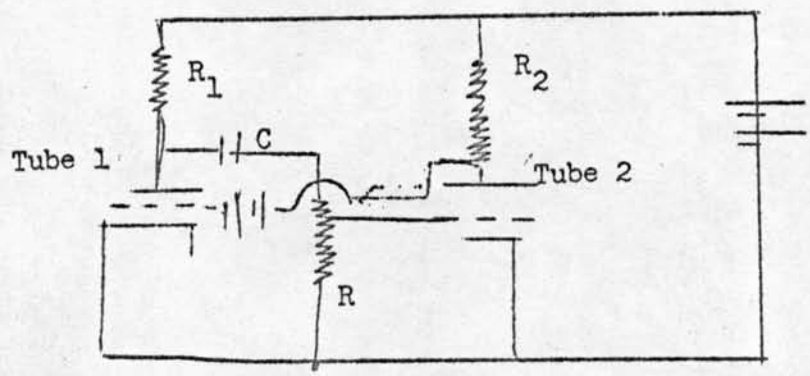


Fig. 2

The trigger circuit of Figure 2 accomplishes this as follows: after a pulse has caused tube (1), which has been non-conducting, to conduct. the condenser C will cause the grid of tube (2) to be held at cutoff, thus maintaining a stable state in the circuit until sufficient electrons have flowed off condenser C through resistance R to allow the trigger to return to its initial state.

An alternate vacuum tube trigger circuit to which it is easier to couple and is somewhat more flexible in application is shown in Figure 3.

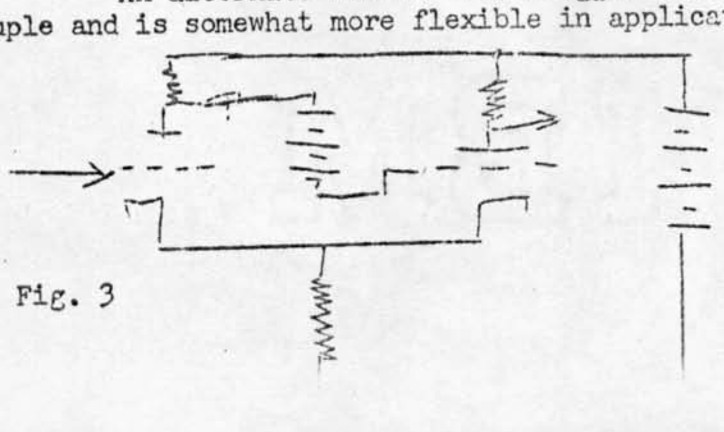


Fig. 3

It can be converted to a "square pulse" or "gate" former as shown in Figure 4.

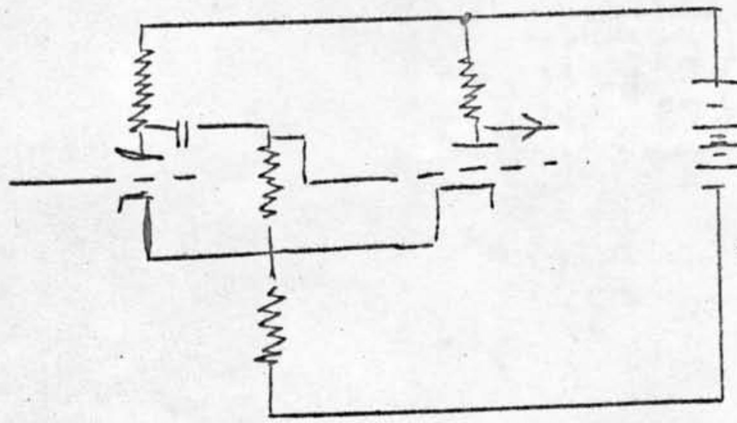


Fig. 4

It should be understood that the batteries shown in the figures are only symbolic, and that by well known rearrangements the circuits would be operated from conventional power supplies.

2. Channel

"Channel" is simply the electric circuit which couples one electrical device to another.

3. Switching Tubes and Coincidence Circuits

At many points in the apparatus it is necessary to connect a device into a given channel only at a certain specified time. This may be done by "switching tubes" used in "coincidence circuits". The switching tube inserted in a channel will only be able to pass the signal pulses when it has been "gated" by a "gate" pulse. Figure 5 shows such a switching tube circuit.

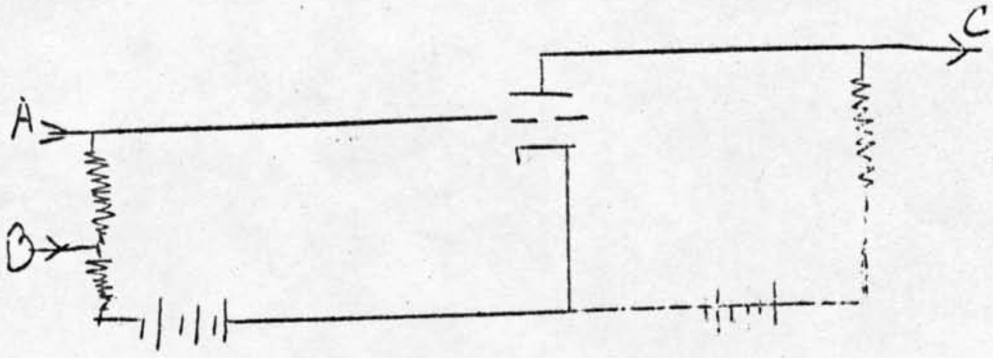


Fig. 5

The vacuum tube is biased beyond cutoff and under these conditions the signal pulses applied at A cannot pass into the output C, even though they are positive, because of the fact that the negative bias is so great that the grid of the tube never reaches a potential which would permit the tube to conduct. If, however, a positive gate is applied to terminal B, the pulses in A cause the grid to reach a potential which permits the tube to conduct and these pulses will appear at C. A number of these switching circuits may have their

A terminals common and thus by proper gating put the signal into any of different channels. Conversely they may have their C terminals common, in which case any number of different signals fed into respective A channels might be introduced into some device.

Figure 6, below, shows an alternate circuit which has the advantage that there is no interchange of energy between the inputs A and B, and that the B input has no series resistance to produce an undesirable time delay in connection with the input capacity of the vacuum tube.

This idea of using the coincidence of two signals to initiate an operation may of course by means of suitable circuits be extended to include the case of the coincidence of three or more simultaneous signals or gates.

4. <u>Clippers and Limiters</u>

Often it is necessary to standardize the amplitude and/or shape of pulses coming through a particular channel. This can be done by inserting tubes in the channel in such a way that they saturate after the signal reaches a specified value and produce a flattening of the voltage wave from then on. Figure 7 is an example of such a device.

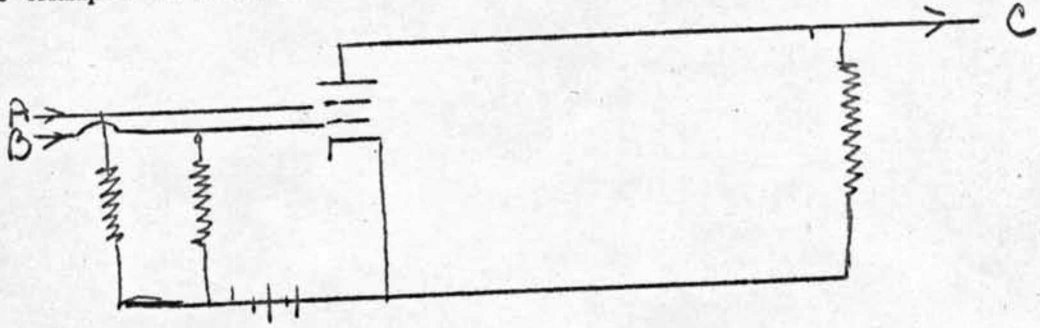


Fig. 6

If the voltage applied at E goes beyond a certain positive value the grid of the tube draws current, and no further increase in grid voltage will accompany an increase in applied voltage, because of the action of the series grid resistor. Under these conditions the output from F will increase only until positive grid voltages are reached and the output wave will be flattened or "limited" beyond this point. The cutoff characteristics of the vacuum tube will likewise "limit" the output in the case of extreme negative input voltages.

If the above circuit is arranged to clip off only in a positive or negative direction, so as to pass only the positive or negative part of the wave, it is known as a "clipper". An alternative form of clipper circuit is shown in Figure 8.

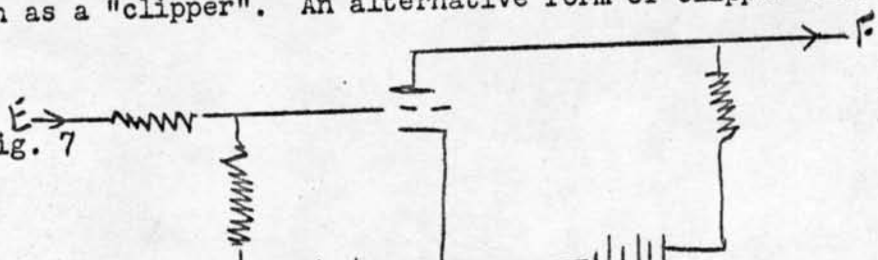


Fig. 7

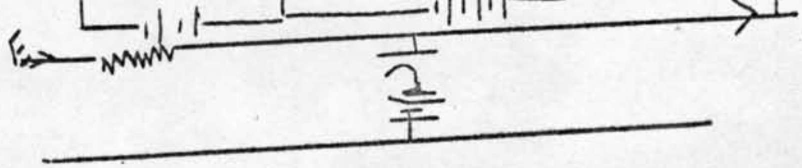


Fig. 8

The diode shunted across the circuit serves to short out signals in one direction, but not the other. Figure 9 shows how two diodes can be combined to act as a limiter.

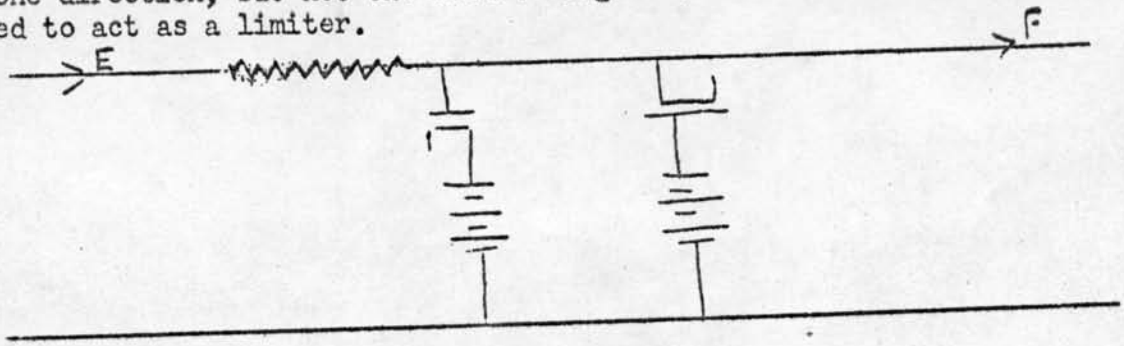


Fig. 9

5. Combination Circuits and Multigrid Tubes

It will be sufficient to state that frequently it will be possible to combine several of these fundamental operations in the same tube or tubes. (This does not refer to the obvious combination of two or more tubes in a single envelope.) This possibility is augmented by the availability of tubes having a multiplicity of control elements. Multi-element tubes may sometimes be used for other reasons, for instance, because of their sharp cutoff characteristics, high transconductance, and ability to effectively shield one circuit from another.

6. Scanning

When it is necessary to transfer a set of pulses from one set of devices to another, it is possible to make this transfer a stepwise process, using only one channel, rather than to do it all at once with a number of channels. This would be achieved by a process known as "scanning", where the various pulses which would otherwise be sent simultaneously through many channels are now sent serially through one channel. The circuits necessary to effect this transmission would then be known as "scanning circuits."

Counter

As previously defined a counter is: "An electrical pulse counter, having a number of stable electrical states. The counter passes from one of these stable states to another, in a regular order, each such transition taking place when a single pulse is fed to its input. A scale-of-n counter has n stable states, and may be arranged to re-cycle again and again as more than n pulses are fed to it. Also, the counter is arranged to deliver one output pulse for every n pulses fed in. This is analogous to the single dial of a mechanical computing machine."

Such a device can be made by combining a number of trigger and coincidence circuits into a ring, as shown in Figure 10.

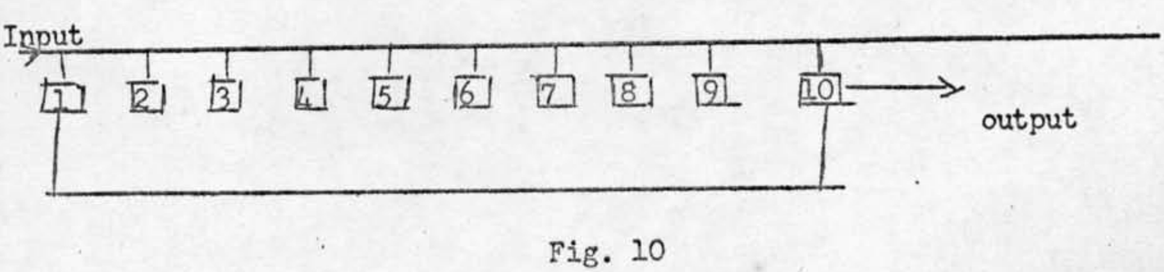


Fig. 10

If we confine ourselves to a scale of ten, which seems desirable at present, we would have ten such trigger circuits in the ring interspersed by ten coincidence circuits. The input pulses are simultaneously fed into all of the coincidence circuits; however, since no gate is also present on any coincidence circuit no action occurs. The outputs of the trigger gates are hooked into the following coincidence circuits. Therefore if a particular trigger has been tripped the following trigger will be in a condition to be tripped by the next pulse by virtue of the gate acting on the interposed coincidence circuit. Thus as pulses are added, more and more trigger circuits in the chain are flipped, corresponding to the number of pulses put in. Some mechanism must be included to reset the trigger in order that the process be a continuous one. This can be done all at once when the tenth trigger has been reached or it can be done one at a time, say after a new trigger is turned on one of the old ones is turned off. When the tenth trigger is reached, and the counter is ready to re-cycle, an output pulse is delivered.

The transition from one trigger to another must not take place too rapidly. since under these conditions the same input pulse might be able to trip several triggers since the gate from a previous trigger just tripped might allow a coincidence of the next stage before the pulse subsided. The required delay in transition can be obtained by a resistor-condenser combination. The circuit of Figure 3 combines the necessary trigger and coincidence action in the triodes.

An alternative arrangement which is somewhat more economical of tubes [illegible] would be to use a scale of two counter feeding into a scale of five counters to obtain a scale of ten. Then since the scale of two requires only two positions (on or off) a single trigger will suffice, thus with five triggers for the scale of five, a total of only 6 triggers would be required, as opposed to ten for the first arrangement.

Accumulators

As previously defined an accumulator is "A group of counters so arranged that (a) the output pulse from one counter is fed to the next, and the output pulse from that is fed to the next, and so on, and (b) input pulses may be fed into any or all of the counters simultaneously. An accumulator is analogous to a set of dials for a mechanical computing machine equipped with carry-over mechanism. It should be particularly noted that, to carry the analogy further all dials usually would operate simultaneously, not serially."

It seemed desirable to connect the counters together in groups of six as far as their mechanical construction goes. This would then register any number up to 999,999. If larger numbers were desired it would simply be necessary to connect two or more together, the output of one feeding into the input of the next.

A problem arises when we connect the counters together to form an accumulator, if a carry-over pulse should arrive from the preceding stage at exactly the same time an external pulse came in from some other device, that counter would record only one pulse, instead of two as it should. This situation can be remedied by making the time required for a carry-over smaller than the time between successive pulses. This, however, might be difficult since the carry-over time might be ten times the flip time of a single trigger in the case where the number 9,999,999,999 changed to 10,000,000,000 upon the addition of a single pulse in the last place. An alternative scheme which would avoid building such high speed trig- [illegible]

[illegible]

gers in the accumulator would be to include an extra trigger circuit for each decade of the accumulator, connected in such a way as to flip from the carry-over pulse and then flip back, transmitting a pulse to the next stage only if notexternal pulse were coming in; if an external pulse were coming in then it would wait until this had occurred and then put its pulse in. However, if the next stage were to have its last trigger conditioned so that it would be caused to re-cycle and give an output by this pulse a connection would put the pulse not only in the next stage, but in the following stages as well. In the example stated (9,999,999,999 to 10,000,000,000) this process would continue down the line so that when the special carry-over trigger for the unit counter finally flipped back, pulses would immediately be put into all the other stages of the accumulator. In other words, a special trigger is connected in to remember any incidental error produced by the coincidence of an input and a carry-over pulse, and to immediately correct this error before the next cycle takes place.

The accumulators will be called upon to transmit the number they contain to other accumulators at certain times during the solution of the problem. Let us consider how a single counter would transmit the number it contains into a channel. Suppose the third trigger was the last one in the ring to have been flipped. This would correspond to that counter registering the number, 2. To transmit this number it must cause a circuit to transmit three pulses into some channel. It must however be in the original condition at the end of the operation. This can be accomplished by putting ten pulses into the external input; after seven pulses have gone into the counter it will be in the 9 position, this is connected to operate a trigger which controls a switching tube allowing the next three pulses to go into the output channel. An additional gate must control a switching tube and prevent the carry-over pulse from going into the next stage. The decade counter will of course be left in its initial condition after receiving ten pulses.

If it is desire to transmit the number from an accumulator as a negative number, this can be accomplished by transmitting the complement, which can be obtained in much the same manner. The only difference is that the switching tube which causes some of the ten pulses to be transmitted into the output channel, is initially on and is turned off by a gate from the special trigger when the counter re-cycles. Thus for the numerical example given above the first seven pulses would be passed into the output before the gate was removed and the remaining three were eliminated.

Additional triggers in an accumulator could remember whether or not the number stored therein were positive or negative as noted from the initial condition or from its passage through zero. In this connection a special pulse would be required to correct the last counter when negative numbers were being handled. The special trigger which remembered whether the number were positive or negative would gate the pulse. The ten pulses and any special controlling pulses for the above operations would be obtained from a channel connected to the "Program Control Unit."

Multiplier

As previously defined a multiplier is "An electronic switching device which, when fed pulses from two sources, will deliver pulses to an accumulator so as to form in that accumulator the product of the two numbers represented by the pulses from the two inputs."

If two numbers, say 879 and 523, are to be multiplied together we could accomplish this by adding 879, 3 times, then moving over a decimal place and adding 879, 2 times, and then moving over another decimal place and adding 879, 5 times. The final sum would be the product of 879 by 523.

Thus

879	Check by conventional multiplication
879	
879	879
879	523
879	2637
879	1758
879	4395
879	459717
879	
879	
459717	

Let us assume that the two numbers to be multiplied together electronically are stored in two accumulators. We shall refer to the accumulator containing the multiplicand as the multiplicand accumulator, for our numerical example 879, and to the accumulator containing the multiplier as the multiplier accumulator, which in the numerical example chosen is 523. We shall call the accumulator into which the multiplier accumulator puts the product, the product accumulator. For our example the multiplicand and the multiplier accumulators need have three decades and the product accumulator must have six decades. The first operation will be for the multiplier to add 879 from the multiplicand accumulator into the last three decades of the product accumulator 3 times. It is enabled to do this by means of connections made by three switching tubes which connect the three decades of the multiplicand accumulator to the last three decades of the product accumulator. Next, it must add 879 from the multiplicand accumulator into the product accumulator 2 times making the connections to the end three decades not counting the last one, using three more switching tubes. Finally it must add 879 from the multiplicand accumulator into the product accumulator 5 times making the connections to the end three decades not counting the last two and using three other switching tubes. The product of 879 and 523 has now been accumulated in the product accumulator. It will be noticed that nine switching tubes were required.

We are now faced by the problem of determining how the machine shall know when to turn on which set of switching tubes and how many times the addition process is to take place when these connections are made. The first set of switching tubes is turned on when the program control unit decides a multiplication shall take place. It first operates the switching tubes and then transmits ten pulses into each channel of the multiplicand accumulator in the manner required for the addition process. Nine of these pulses, one having been deleted by a special counter in the program control unit, are sent into the last decade of the multiplier accumulator. The "carry over" pulses in the multiplier accumulator are prevented during the entire multiplication process. This will leave the last decade of the product accumulator registering the number 2 instead of the number 3.

This process continues until the last decade registers O when by means of a coincidence circuit the first set of switching tubes is turned off and the second set turned on. A similar process follows until the second decade of the product decade reaches O, at which time a coincidence circuit goes into action and the second set of switching tubes is turned off and the last set is turned on. This is followed by the usual addition process resulting in the multiplication being completed and the multiplier accumulator being set to O, which by means of a coincidence circuit allows the program controlling unit to know that the process has been completed. Of course, the value of the multiplier has been lost in this process so that if it is needed for a further process it should have been transferred to another accumulator, by a set of switching tubes, before the multiplication began. Thus a multiplier is seen to consist physically of a set of switching tubes and perhaps an accumulator for remembering the multiplier (523).

To find the number of switching tubes involved let the number of decades in the multiplicand accumulator equal m and the number of decades in the product accumulator equal n, then the number of switching tubes required is (n - m)m.

If the multiplier is to be remembered an additional set of tubes equal in number to the decades in the multiplier accumulator as well as an additional accumulator may be required. If a somewhat slower speed can be tolerated the multiplier may be remembered without the additional accumulator by using an alternative multiplying system.

In order to properly assign the sign of the product as noted by the special trigger inits accumulator a few additional trigger and coincidence circuits are needed in the multiplier. These operate in such a way that if both the multiplier and multiplicand are negative the program control unit is signalled to proceed as if both numbers were positive. If one of the numbers is negative the program control unit is signalled to operate the multiplication in a similar manner to the above except that it should cause complements to be sent to the product register.

Divider

As previously defined a divider is "A unit similar to the multiplier, but with an output which is the ratio of two inputs."

The general principles on which the divider operates are very similar to that of the multiplier. If one subtracts the divisor, which we will assume has three digits, from the first three digits of the dividend as many times as one can without getting a negative result one obtains the first digit of the quotient. If we then shift the decimal point by one unit in the remainder and repeat the process we obtain the second digit of the quotient. This process may be repeated to any degree of accuracy.

This process could be carried out electronically by having the program control unit add the complement of the divisor, which is stored in a suitable accumulator, into the last three decades of the dividend by means of suitable switching tubes (by last three decades we mean the decades corresponding to the first digits of the dividend). This process is continued until the dividend starts to go through zero. At this point a coincidence circuit stops the process. The program control unit connects in another set of switching tubes and the process is continued on the remainder of the quotient. The number of additions in these steps are consecutively fed into the channels of the quotient accumulator, and store there the consecutive digits which form the quotient.

The algebraic sign in this process is taken care of in a manner similar to that done in the multiplication process.

The number of switching tubes required here depend upon the accuracy desired, but for ordinary purposes will be approximately equal to the number of tubes required in a related multiplication.

Recorder

As previously defined, the recorder is "a device for making a permanent record of the results of calculation at any determined stage of the work".

The recorder might use photographic or other means of making a permanent record, but the results will probably be more useful if recorded in punched cards, so that, when desirable, they will be in proper form for IBM machine operations. It is understood that cards may be punched at the rate of three to five per second at the most, using equipment for which designs now exist. When the results of every group of operations must be recorded, this sets a limit upon the overall speed, but since there are no other computing devices able to carry out a train of computations and feed the recorder at this speed, it may be said that the electronic analyzer, used as a computer for a series of similar but discrete arithmetical tasks, is by far the fastest device available.

The limited speed of the recorder is, however, no "bottleneck" in the iterative solution of difference equations. The analyzer will, at any point designated by the program device, transfer to the recorder unit whatever information it is desired to record. The recorder unit will have, in the form of accumulators or other storage devices, the means of receiving and holding this information for the time necessary for the operation of the punch. But once the information has been transmitted to the recorder, the program control unit will resume the step-by-step calculations. Therefore, during the time that the recorder needs for its operation, the calculation of the next value to be recorded will already be under way. For instance, it would suffice to record only every tenth step in the integration process, and if each step requires, say, 30 milliseconds, then at the end of ten steps or 0.3 seconds the recorder will again be ready to receive information. If for any reason it should be desirable to record more often, and higher speed punching mechanism is not available, one may provide two recorders, working alternately.

If it is desired, the recorder need not operate at fixed intervals along the independent variable, but may operate for fixed increments in any variable. This is accomplished by controlling the recorder operation from an accumulator which trips the recorder whenever it passes through zero. Increments in the desired control variable are added into this accumulator at every step, and every time the recorder operates a fixed negative quantity is transferred into the same accumulator, which then trips the recorder again when the accumulated increments in the control variable have brought the accumulator back to zero.

Function Generator

As previously defined, the function generator is "a device for introducing an arbitrary function, the mathematical form of which is either not known or not simple enough to be generated by a simple difference equation." That is, a function generator must be a device which can supply, at times designated by the program control unit, the value of some function, $f(x)$ corresponding to the value of the variable x present in some accumulator. The function generator must, of course, be provided in some manner with information concerning $f(x)$. This information might conveniently be stored in punched cards, and the problem then becomes one of reconciling the high speed with which the function generator must respond with the comparatively low speed at which cards may be passed through a reading machine.

A reasonable solution can be attained by using the same technique as was used for the recorder--that is, the function generator reads from a punched card and stores information permitting it to continue generating the function for a limited range in x while at the same time the mechanical mechanism is substituting one card for another in the reading device. The parameters necessary for building up or interpolating f(x) over the limited x-range might be in the form of a small number of successive differences of f(x). The changing of the cards will not disturb the process of function generation because the reading device is not connected to the function generator except at those times when (a) the cards to be read is in place, and (b) the variable, x, has arrived at the value designated on the card as one for which the function genarator is to be given new information.

Usually the variable, x, will increase at some times and decrease at others. Therefore it will be necessary for several cards for adjacent x-ranges to be in reading positions, or else to use additonal accumulators for storing the information relating to the range just passed.

It will be seen that the function generator in effect interpolates a great number of values of f(x) when provided with f(x) and some of its differences at relatively few points. It is presumed that this interpolation may be carried out by summation of differences rather than by multiplication processes, since additions proceed so rapidly.

Tubes

The practicality of an electronic computer and difference analyzer is enhanced by recent advances in the design of electronic tubes suitable for the circuits to be used. Particular mention should be made of the 6J6, a miniature type twin triode with low input and output capacities and a high transconductance at low operating voltages. Some of the manufacturer's data are given here to illustrate:

For each triode unit of 6J6 twin triode:

Plate voltage	100 volts
Amplification factor	32
Transconductance	5300 micromhos
Plate current	8.5 ma.
Maximum plate dissipation	1.5 watts

Interelectrode capacitances (each triode)

Grid to plate	1.6 μμf
Grid to cathode	2.2 μμf
Plate to cathode	0.4 μμf

Mention should also be made of the existence of special gas tubes designed for use in counter circuits. It is to be expected that vacuum tubes will be preferable for most of the circuits, but that gas tubes may be used for some of the circuits.