lamp 1 goes out. Current flows through output D and through relay X2. Both armatures of X2 are drawn down, and lamp 2 extinguished as the lower armature of X2 is disconnected from C and connected to D. Lamp 3 lights.

The second digit enters at B of unit II, drawing down both armatures of Y2. The lower armature breaks the contact through output C, releasing the armature of X1. This permits current to flow through the C output of unit 3, again lighting lamp 2. The sum is then 110.

The reader may find it easier to follow the problem by drawing Fig. 2 on tracing paper, then drawing and erasing the armatures to indicate the correct positions as each digit is entered.

Techniques of design

Although these circuits are comparitively easy to trace, to verify that they give the correct answer, you may wonder how they are designed. Unfortunately there is no simple answer. Trial and error are useful in many cases and familiarize one with the results of simple combinations. Some authors attempt to systematize these basic circuits as well as some others for common uses[1] while others feel that the technique of Boolean algebra solves many problems.[2] However, some simplifications and original circuits are very difficult to discover by either of these methods, leaving the success of the final circuit to the ingenuity and inspiration of the designer.

The development and modification of the circuit given above to add larger binary numbers are a good example of the evolution of a relay circuit. In its original form, it employs two relays for the first digit and four more for each successive digit. Ultimately we can reduce it to only two relays for each digit. The first simplification is to eliminate the first relay of the second block in each digit (unit III in Fig. 2, for example). But the function of that relay was to keep one circuit closed when there *was* power on the lead A which closes it, and another when there *was not* power. Therefore, if we eliminate the relay, it becomes necessary to have a second lead (A′ in Fig. 3) which has power when and only when A has no power. These two leads will take the place of the wires coming from the contacts of the eliminated relay. The result may be verified by tracing as with Fig. 2.

A second simplification eliminates the second relay of the second block in each digit. However, the carry from the digit before closes this relay. So just as we needed the A′ lead above, we now need a second lead from the preceding digit which will supply power when and only when there is *no* carry. Therefore, we must also add a circuit to provide this so-called no-carry lead for the next digit. When the contacts of the resulting circuit are combined, the result may be seen in Fig. 4, which is best verified by tracing.

Programmed computers

If all large computers had to be designed with this type of direct circuit, giving you the answer with no further instruction from the operator, their power would be strictly limited by the ingenuity of the designer and the number of operations he could build into a circuit. Large computers use a second type of circuit, called "sequential"[3] because they accomplish their result in a series of steps, as opposed to the "combinational" circuits described above. In these circuits, a simple computer of the combinational type is retained to perform each of the steps, which consist of simple operations.

Memories must be added to store intermediate results between operations. A common set of wires called a "bus," connected to each memory and to the input and output of the computing unit within the enlarged calculator, transfers numbers within the whole framework of the computer.

To control this transfer of numbers as well as the operation being performed by the computing unit, a continuous set of instructions called "programming" is fed the computer through the control unit. The actual numbers to be operated with are given to the computer separately, so that this programming will be fixed for a particular sequence of operations—such as involved in solving a quadratic equation, for example.

The 120-relay equipment

It was on this plan that the main computer illustrated in the photograph was designed. Six-digit binary numbers were taken as the base in which all computations were performed: the memories stored six-digit numbers, the bus carried six-digit numbers, the computing unit operated on six-digit numbers. Rather than breaking the working of the machine down into steps of one operation each, it was further broken into cycles. In each cycle, a number may be taken from one section (e.g. memory, input, output, computing unit or instructions) of the computer and put in another. Thus a step would consist of several cycles which would: 1, put the numbers to be operated on in the computing unit; 2, put the code for the correct operation to be performed in the computing unit from the instructions; 3, take the answer from the computing unit to a memory. The actual computation within the unit is performed automatically once the numbers are at hand. A rough block diagram is given in Fig. 5.

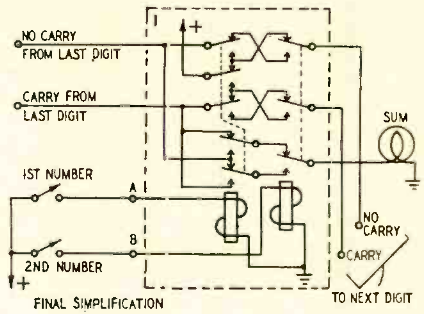

Fig. 4—Another relay is eliminated.

Paper tape was used for the programming, giving the necessary instructions for each cycle in three entries. The first entry determines the section of the computer which is to receive the number. The second determines the section containing the number to be sent and actually connects these through the bus, thus transferring the number. The last entry is provided in case the number to be sent is not in the computer, in which case it will be automatically sent if put on the instructions in this entry. Actually there is another means of putting a new number in the computer: if it is stopped in the middle of the cycle by a special code, a number may be manually connected to the bus with switches as in the simple unit described in Fig. 1.

Memory circuits

The memory (Fig. 6) is the simplest of the individual units within the computer and illustrates the principles for transferring numbers. The actual process of remembering is accomplished by what is called a "holding" circuit. When the relay is temporarily closed by voltage from the bus, a path from the relay

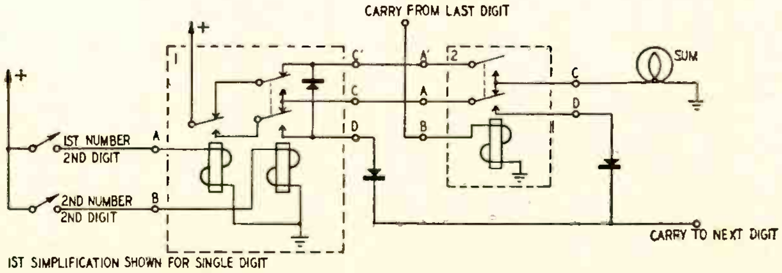

Fig. 3—This simplification eliminates one relay in the second block.

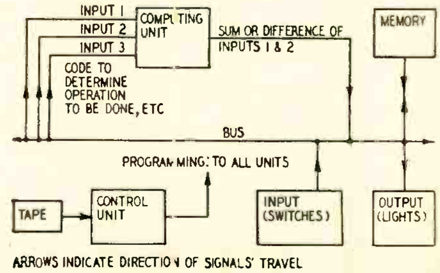

Fig. 5—An elementary block diagram of a programmed type of computor.