Electronic Analog Instruments As Tools of R&D

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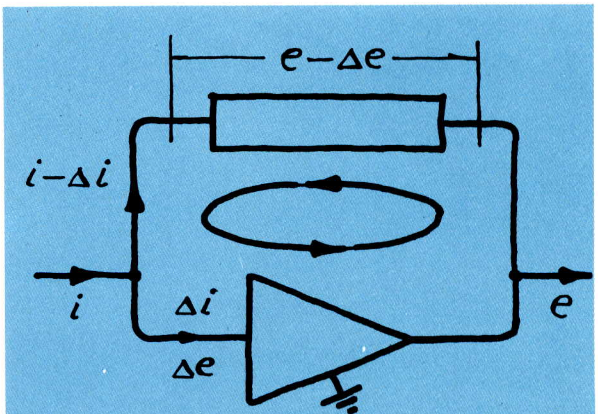
OUT OF CONTROVERSY come truth and progress. Widely held opinions are frequently wrong. On one modern opinion, however, there is little controversy, namely that electronic computing instruments are useful on a very wide scale. Witness the explosive growth of literature on the subject within the past decade. But this leaves room for a number of very real arguments on such issues as the choice of types for any given application. One large debate sets continuous against discrete operations, or if you like analog against digital. If you are a true research person, and it is my privilege and pleasure here to address such persons, then you are not appalled by controversy. It is rather the case that research goes ahead by doubt and iconoclasm, tinged, we all hope, with civility and fairness. So I shall try in what follows to admix some unorthodox attitudes, along with calm common sense, about the application of analog instruments in the laboratory and elsewhere.

This term Analog, although it is fairly well understood in connotation, needs a note of apology owing to certain current illogical usages. Any mechanism which involves continuous variables is nowadays in danger of being called "analog" of course to distinguish it from "digital." This even applies to the most familiar transducers, whether they are input or output transducers, which have no computational or simulative purposes whatever. To make matters still more confounded, the common usage for computing structures, whereby only continuous methods are called analog, is wrong, since it is clear that discrete or digital machines may also embody and constitute analogs of prototype phenomena. But having spoken thus, I shall bow to popular usage myself, except that where a misunderstanding threatens I shall be at some pains to circumvent it.

One more daring step is timely. Note that what are called analog operations need not be *entirely* continuous. Is not the absolute value of a variable a legitimate analog function? How about its first derivative? Such functions are discontinuous, as are many others regularly performed by analog protagonists. The unprejudiced eye will readily see, through considerations of this kind, that discrete functions, quantizing, and logical operations are all in the analog province, as indeed are memory and storage. So we have fetched in some fine fuel for controversy: digital operations are special cases of analog! The reverse, incidentally, is only



Basic Operational Loop: Influences travel cyclically without regard to the directedness of current.

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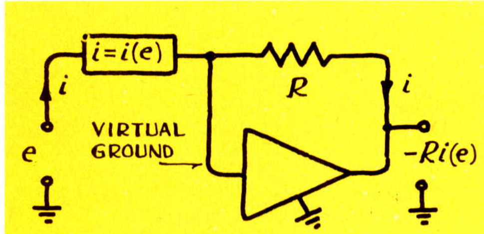
true in the limit, as quantization is carried beyond any thinkable bound. Such radical philosophy, I contend, finds perfect propriety around the laboratory, though I will grant it may be looked on as disruptive in the marketing department.

Research is a fertile and rewarding area for the application of analog computing instruments, including in this large category those which perform the functions of measurement, testing, regulation, data processing and model building. One of the unifying features of these several operations is the benefit they may derive from the technique of *feedback*, which permits influences to act in a cyclically closed path. Though it is now quite broadly known, feedback was unorthodox for many disciplines in the recent past. It imparts to analog devices what quantizing does in the digital field: it affords precision, predictability, and isolation. Perhaps the most succinct application of feedback is found in the null-seeking, or *operational* amplifier. Only the most unromantic engineer can resist the fascination and seemingly paradoxical dynamics of a well-designed feedback circuit with an operational amplifier, wherein a vanishingly small unbalance nevertheless transmits all the information required to maintain this unbalance at a null.

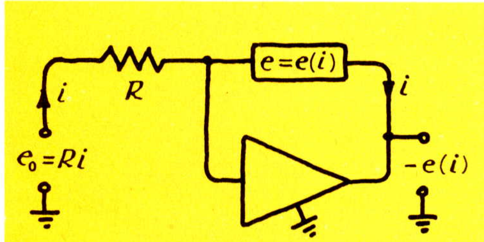
Actually feedback as a laboratory method is very old. Physicists have long made precise measurements, such as that of weight on a beam balance, through nulling operations carried out by manual manipulation. An operator sees the "error," or unbalance, or departure from null, and in consequence alters a corrective "output" quantity to reduce the unbalance and minimize his error. It is evident how this procedure is made automatic, using means and media which are mechanical, hydraulic, pneumatic, electric, electronic, or combinations of these. In the immense family of mechanism which results, one finds the operational amplifier, usually involving a current balance and a voltage null.* This device is my focal point, as you may by now have suspected. Its range of usefulness is alarmingly extensive, as are also the available ranges of power level, speed, resolution, and accuracy. Its applications include computation, simulation, testing, training, controlling, and measurement. Since all these would take a book rather than a paper, let me start with measurement and see how far I can get.

Measurement

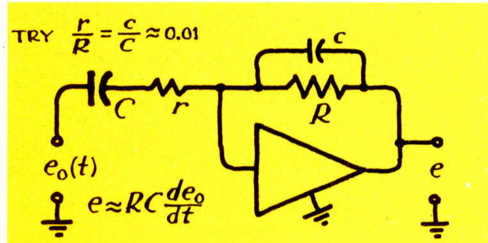
Measurement as a Science, and as contributor to science, is astonishingly rich and varied. The literature of this technical field is the most abundant of all, and has been for over a century. Methods of measurement are often subtle and indirect, that is to say inferential, and have comprised the life work of many a profound and devoted scientist. Yet the scope and power of measurement as an instrumental discipline are not universally appreciated. Naturally I am speaking principally of automatic measurement, which is the order of the day. Consider an electronic data processing operation; it is merely a collection of measurements. It measures primary variables, after these have



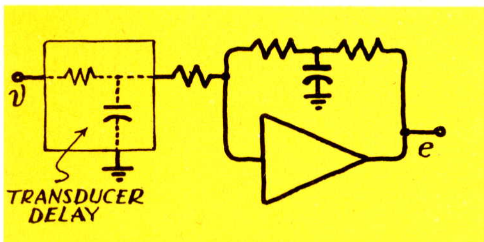
Reading Current as a Function of Voltage



Reading Voltage as a Function of Current



Practical Differentiator

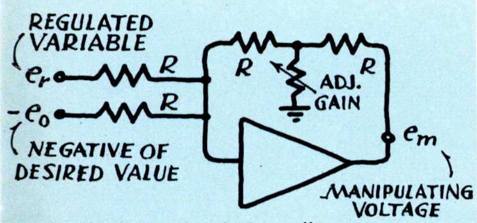


Dynamic Compensator (First order)

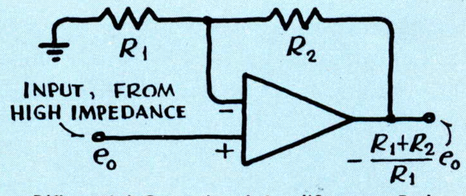
OPERATIONAL AMPLIFIER FUNCTIONS

been "transduced" to proper form, and it measures functions of such variables, defined mathematically or otherwise. More generally, any instrument which performs a mathematical operation is a measuring instrument. One such measures the sum of certain variables; it is called an *adder*. Another measures an integral, or the area under a curve, and gets the name of *integrator*. Since instruments may certainly be permitted to measure one another's outputs and when so interconnected may perform mathematical operations of almost any sort, it is evident that mea-

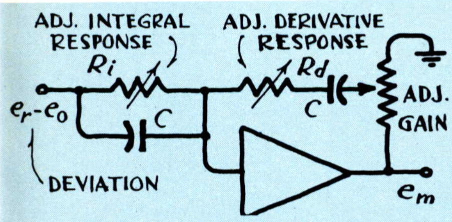
* Rather than giving a detailed account of such amplifiers here, may I refer the reader to the prolific literature which is now available. There was for example the article by Prof. H. M. Paynter and myself, called "The Electronic Analog Computor as a Laboratory Tool," published in the May 1952 issue of Industrial Laboratories: the earlier version of this magazine. A reprint of that article is included in the volume "A Palimpsest on the Electronic Analog Art," which contains other definitive writings, and which is still available at a nominal charge from Philbrick Researches, Inc.



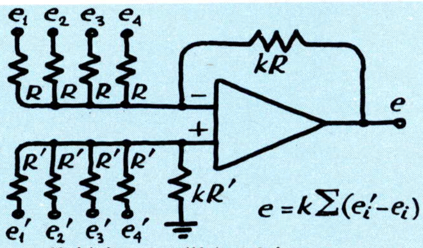
Simple Proportional Controller



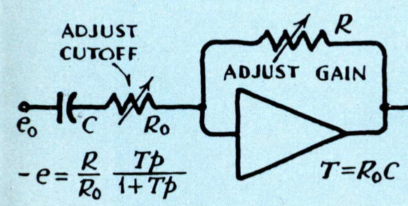
Differential Operational Amplifier as a Probe



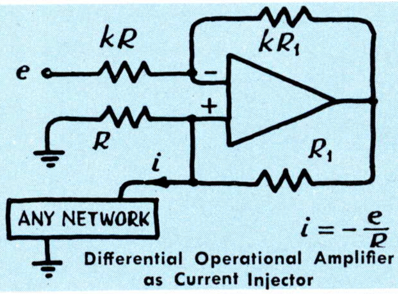
Proportional - plus - Integral - plus - Derivative Controller



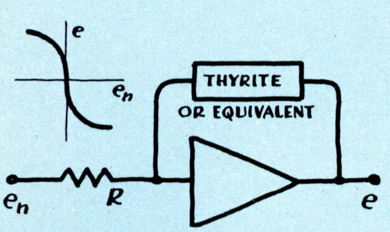
Multiplex Amplifying Subtractor



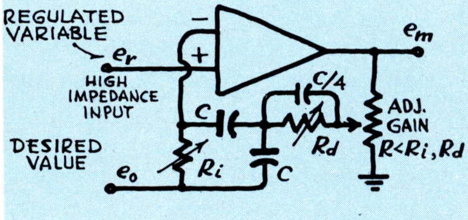
Predictable AC Amplifier



Differential Operational Amplifier as Current Injector



Graduated Null Amplifier



Another Controller

OTHER THAN ADDING, PROPORTIONING, & INTEGRATING

suring operations may be compounded into self-respecting computers. Conversely, it is plausible that any computing machine is nothing but a multiplex measuring device, possibly complicated, frequently introverted, always challenging, and of course preferably analog and full of operational amplifiers. At this point I return abruptly to more modest matters of measurement.

Physical or chemical variables, as implied, are measured in a great variety of ways. Usually, at least in the automatic cases, they are transformed into more convenient variables which may be calibrated in terms of the primary ones. In the overwhelming preponderance of cases, the primary variables involved are continuous in time and excursion. Succeeding operations may quantize these variables in excursion, or sample them in time. The latter is frequently done if some evaluative instrument is to be applied in sequence to a set of many measured variables of the same kind. Both kinds of discontinuity, as you certainly are already aware, are introduced when the variables are submitted to digital computation. More often than not, in my opinion, it is better to retain the continuity of primary or transformed variables through as many stages of computation or compensation as possible, since in this way resolution and dynamic range are preserved, and simplifications are possible without loss of precision.

Transducer Translations

Assume for the moment, then, that the primary variable to be measured, and the secondary variable into which it is transformed, are continuous in excursion and time, and calibratable in terms of some appropriate scale and function. This is not really much of a limitation, but now assume that either the secondary variable or a tertiary variable into which it in turn is transformed is of electrical form, say a voltage, a current, or an impedance. Transducers of this kind form a large class. (See, for example "Instrumentation in Scientific Research — Electrical Input Transducers," by Prof. Kurt S. Lion, McGraw-Hill, 1959). Electricity offers the advantages of speed and simplicity in digesting the results. A complete list of primary variables to which such transducers apply would fill pages. The most familiar are displacement, velocity, acceleration, force, pressure, flow, magnetic field, radiation, and temperature; these are made manifest through such pleasant items as strain gauges, photocells, and thermocouples.

The electrical quantities themselves must not be ignored, of course, since for example one may need to increase or reduce a current or voltage for instrumental convenience, or convert one into the other. For such dealings the operational amplifier is superbly suited. That is to say the operational amplifier is in itself an extremely flexible transducer, of the active variety,

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as applied to electrical variables or variable parameters. Its fidelity as a transducer, say from current to voltage, is often unappreciated in fields of endeavor outside analog computing. Imagine a transducer for example which will translate an input current in the range from plus to minus 100 microamperes dc into an output voltage in the range from minus to plus 100 volts dc, and with the following characteristics: The source impedance may vary from a fraction of a megohm to infinity, as may also the load impedance. Dynamic range, accuracy, and linearity are all on the order of one part per million for a typical amplifier. This same amplifier, simply by a rearrangement of external connections, will carry out a number of other transductions among electrical quantities with similar precision, and will in addition perform a host of mathematical operations.

Time and Space

Among the latter is the well-known analog operation of integrating with respect to time, or of "measuring" precisely the area under a plot of the input current or voltage as it varies with time. By simple switching means, the interval of integration may be chosen at will, as may the initial condition, and the rate of integration may be varied over about a million to one, even during operation, by the alteration of external passive circuit elements. Since in effect the integrand may be arbitrarily forced to zero at any time, by opening the input circuit, this instrument may be used to "hold" or to "store" any significant value of a variable for an extended period. In this way the operational amplifier may serve for time averaging, for sampling, and for remembering. A handy little tool indeed for the experimenter.

But there is much more. For example, it may not be well known that the derivative with respect to time may be measured with an operational amplifier very nearly as aptly and easily as may the integral.

Differentiation

Suppose that whatever primary variable is under scrutiny has been transformed or "transduced" to an electrical quantity which is calibrated in terms of the primary variable, and suppose further in this case that the secondary variable is a voltage. Voltage by the way is the variable of variables to analog instrumenteers, as you know or will have noticed.

Operational outputs are nearly always voltages. Read-outs to recorders or oscilloscopes are generally voltages. Among other excuses for this favoritism is the ease with which voltage may be carried from place to place, typically on a single conductor, and made available with respect to a ubiquitous ground or reference. Furthermore the output voltage of an operational amplifier, traditionally of low impedance, or if you prefer of high stiffness, may be carried simultaneously and without distortion to a number of remote operational inputs.

If you have forgiven this digression I will return to the first-mentioned voltage, which has been varying smoothly with time, but patiently awaiting our attention. Perhaps I should have said continuously rather than smoothly, but anyhow please consider the time rate of change of such a voltage. It is a commom occurrence in the laboratory, among other places, for interest to center on the first derivative of a physical variable. When a derivative is small but steady, a lot of time is wasted in waiting for enough excursion, on a meter or recorder, to permit an accurate evaluation. A good differentiator will save time in many such cases. Granted that a digital voltmeter with many decimal places will also afford a fast evaluation of slow rates by timing its jumps in the low registers, but the operational equipment is less expensive. In addition, a continuous output voltage as a measure of rate is vastly more appropriate for recording or controlling.

It is a standard reaction in a laboratory, when one wishes to measure the rate of change of a voltage, to confront the source of the voltage with a resistor and a capacitor in series, so that under constant conditions the capacitor charges to the input voltage. Under many circumstances the voltage across the resistor gives an adequate measure of the desired rate of change, and the need to know is then assuaged by this very simple structure. Frustration may follow however, when the rate is quite slow and a reasonably up-to-date reading is wanted. The key to this dilemma is that the resistor drop measures not the rate of change of the input voltage but that of the capacitor voltage, which is delayed relatively to the former in proportion to the resistance-capacitance product. A solution lies in creating a *virtual ground* between the two circuit elements, with the capacitor connected between the input voltage and this virtual ground terminal, and in so manipulating the voltage at the far end of the resistor as to enforce the virtual ground or voltage null at the intermediate terminal.

As you may have guessed, the operational amplifier leaps to the rescue in performing this operation. Connect the capacitor as input element and the resistor as feedback element. Since now the capacitor voltage *is* the input voltage, the resistor may be made almost as large as one may wish without increasing the delay. Thus a large rate reading is afforded, as well as a prompt response, together with traditionally low output impedance of the operational amplifier.

The prejudice against operational derivatives arose out of a preference for integrals in classical analog computation. There one has the choice, and it was made long ago in favor of integrators to obtain quiet and well-behaved computing loops. These considerations are greatly modified in the case of measurement.

Filtering Desirable

Granted that noise in the driving voltage of an operational differentiator will come through, possibly in a great crescendo, if there are relatively fast fluctuations superimposed on those input variations which are of primary interest. This is largely the differentiator doing its job. For this reason some filtering of a judicious sort is generally wanted, and is in fact recommended as somewhat relieving the task of the amplifier. A relatively small resistor in series with the input capacitor, and a relatively small capacitor in parallel with the feedback resistor, will almost always suffice. Both may be adjusted to taste, based on stability of the local operational loop, on fast but not too furious differentiation, and on whatever suppression of transmitted noise is required, whether this originates from the source voltage or from the amplifier input itself. May I leave it to intrepid research persons to press on to higher derivatives? It can be done.

The voltage into which a primary variable is translated by a transducer may fall short of final satisfaction as a substitute for a number of reasons. Even when a perfect representation is given the experimenter may have preferred, for example, a linear combination of several primary variables, as when he is seeking to compensate for secondary effects. This sort of compensation is readily attainable with one or more operational amplifiers and purely resistive networks. Again, when functional or curvilinear distortions are required or must be eliminated, nonlinear networks of well-known active types are applicable. I should like to speak here of dynamic distortions, whereby the voltage representing a primary variable may be, in a transient sense, an imperfect image of that variable. There are, of course, the familiar processes of filtering and smoothing which may remove unwanted parts of the spectrum, as for instance a parasitic frequency; operational methods amounting to active filtering are certainly useful in this business. I must not forget the challenging and pioneering area in which such techniques are applied to the elimination of random interference. But largely unappreciated are the quite practical processes by which a tardigrade or "lagged" response may be rejuvenated by operational means. This kind of compensation may be important, not only for the prompt measurement of primary variables, but for fast and stable automatic control as well.

Dynamic degradation in the measurement or transducing of a primary variable usually occurs ahead of the stage at which it is transformed to an electric quantity. The causes are usually practical rather than fundamental. A temperature sensor, for example, may be exposed to a portion of the primary medium which is removed from the region of vital interest, or the sensor itself may have thermal mass and thermal resistance, so that the dynamic relationship between the temperature of prime interest and its ultimate voltage representation is of the sort embodied in a "low pass" filter of aperiodic type. The general principle of compensation in such cases is that of interposing, in the feedback path of an operational loop which receives the measuring voltage, a network which imitates or "models" the dynamic forward path already described.

Admittedly there are limits beyond which this technique fails, notably in the instance of direct time delay, but it is effective for a remarkable gamut of typical dynamic retardations. My chief effort is to show the philosophy of a procedure which amounts to a dynamic proportioning, somewhat analogous to a bridge network, in which a reverse acting model of the obstructing forward path compensates for the dynamic distortion attributable to that path. Inherent in this process is an inversion of cause-and-effect which, contrary to intuition, may be successful to a degree principally subject to the proviso of stability in the operational loop. This technique is akin to prediction, and prediction subject to certain qualifications is indeed possible no matter what you may have heard.

Some Risk Involved

Of course it is not surprising that these processes are accompanied by some risks and alarms. Stabilization of the amplifier loop may take more diligence than in the case of the commoner mathematical operators, but every operational expert is ready with a repertory of tricks. Some may pretend to an aura of black magic in such trickery, and there is no harm in this, but

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actually the art of stabilizing feedback amplifiers is founded on a firm body of technical doctrine, ranging from elementary to advanced. Although the procedures of stabilization, in the more aggravated cases, may involve concessions which mean somewhat less than perfect dynamic compensation, what remains is of great potential value for reaching inside surrounding tardigrade bulwarks to measure immediate happenings.

The easiest to handle, and the most readily successful examples of such dynamic compensation are those in which the tardigrade response to the measured response is of first order, or nearly so. This corresponds roughly to a single energy-storage element at the primary or input end of the transducer. In the case of a thermometric transducer having a necessary mechanical and consequently thermal mass, this may imply a favorable effect stemming from concentration of the thermal resistance on the surface. When an active operational mechanism is permitted to follow such a transducer, with an imitative first-order lag in the feedback path, it should in typical instances be able to speed up the response by more than one order of magnitude.

Regulation

In the laboratory, the automatic control or regulation of primary variables is increasingly popular as a means of reducing the number of dimensions or parameters with which the experimenter must simultaneously contend. Even when all variables but one in a study are held by regulation at a set of constant values, the remaining one may be varied while under control simply by programming the desired value at its controller to follow whatever function of time is appropriate. It is obvious as an extension, where all variables are under automatic control, that a larger program may be carried out by sequential scanning of the variables in a planned or designedly random order, so that the phenomenon under study may be recorded throughout the multidimensional space of all the independent primary influences. The experimenter is thus relieved of much tedious vigilance, and may either run a number of studies in tandem or sit about planning the next experiment, or both. He must be assured, of course, that all his regulatory operations are in good order, with small errors or nulls; in any case he will do well to monitor or record, independently of the regulators, all the primary variables along with the crucial quality measures of the experimental results.

For regulatory operations of this sort the operational amplifier is a perfect instrument. Any automatic control man, or any analog computing expert, will be quick to show how to connect up one or more operational amplifiers as a control mechanism. In general there are two inputs to each controller. One is the primary variable to be regulated itself, converted for example to a derived voltage as above, and the other is the desired value of that variable, represented in one of the simplest cases by a properly scaled and reverse polarized dc voltage. The sum of these two, or in general some linear combination of them, embodies the error or unbalance or "deviation" of the regulated variable in relation to its desired value.

At the downstream end of the operational amplifier, or amplifiers, an output voltage serves to drive whatever "manipulated variable" is chosen to affect the regulated variable through the "plant" and so to enable control of the regulated quantity. The manipulating means may be a motor, a vane, a heater, or any one of a large assortment of such apparatus. In some cases this first manipulating voltage may set the desired value of a subsequent, subordinate regulator. Switching means are easy to include for switching back and forth from automatic to manual operation of the regulating means, as during start-up.

"Proportional-Plus-Integral"

The basic control mechanism, from error to manipulating output, may resemble a completely typical operational computing network. An amplifier with purely resistive input and feedback elements gives a proportional control law, the local gain of course being the resistance ratio. What is called the "proportional band" in control parlance is simply the spread of input voltage corresponding to full excursion of the output voltage. Both these voltages, and consequently the gain and other properties, may be scaled in terms of the physical variables which they correspond to and serve. To get a purely integrating control law, the input resistor is retained but the feedback resistor is replaced by a capacitor, usually not electrolytic. The integrating speed is determined by the resistance-capacitance product, or rather by its inverse. Naturally attenuation anywhere in the control loop reduces this speed, as far as regulatory effectiveness is concerned.

This form of control mechanism is generalised most easily to "proportional-plus-integral" by including a resistor in series with the capacitor in the feedback path. The "repeats per minute" rating for this controller mechanism is simply the inverse of the resistance-capacitance product for the two feedback elements. Gain may be adjusted by the input resistor or elsewhere. The proportional band is determined fractionally by the ratio of the input resistor to the feed-

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back resistor. And so on. A derivative feature may be included by adding a second capacitor in parallel with the input resistor, and its effect made less harsh by a relatively small resistor directly in series with this latter capacitor, or by adding a relatively small capacitor directly in parallel with the resistor in the feedback path.

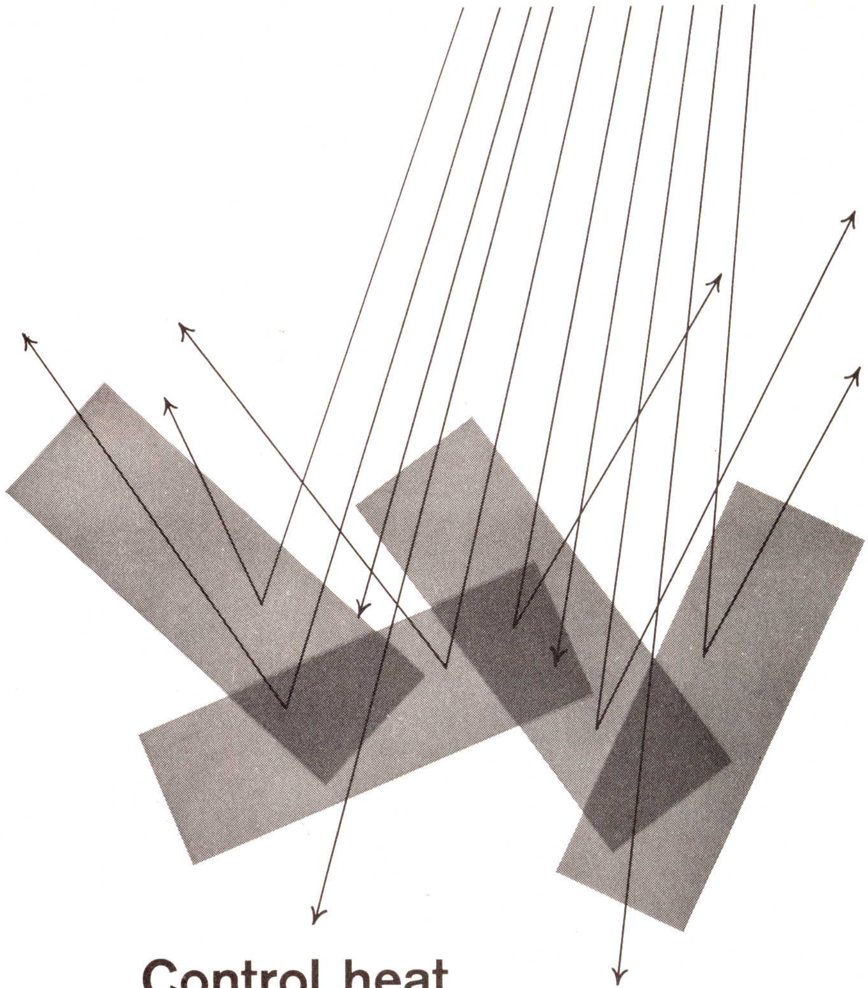
This is only one of a number of workable and satisfactory control mechanisms, having great flexibility and reproducibility, which may be assembled from a single operational amplifier. A second operational amplifier, with its own special network, may be included ahead of the first if desired, for sense-reversal, for simpler isolation of the several functions of gain or integral and derivative dynamics, or for higher order such dynamics.

In cases where small scale laboratory experiments have their conterparts—developmentally — in larger scale industrial operations, there may be virtue in the transformability between the concepts of instrumentation given above and those of industrial control equipment. In certain instances the smaller scale equipment, under control by operational means, serves as training ground for operating and engineering personnel in the larger plant. But I have wandered out of the Research Department, and am in some danger of being mistaken for a pilot plant engineer. My concern in the preceding paragraphs has been more with the application over a broader experimental range than with scaled down or embryonic production processes. None the less it is evident that the operational techniques I have been discussing apply at every level, from the theoretical and experimental environment of the laboratory right up to that of the largest engineering structures. I am neglecting incidentally, among other things, the potential contribution in all these areas of full-fledged general purpose computing devices, but as I hope you know these are treated at length elsewhere.

So-Called AC Amplifiers

Operational amplifiers are traditionally dc devices, though many of them respond to frequencies through the sonic range and far beyond. AC amplifiers, old and familiar in the communications field, ordinarily employ ac coupling between stages as well as at the input or the output. For laboratory purposes, this feature often leads to some awkward properties. First, the low frequency response is rather complex, as reflected for example in the later temporal portions of the transient response to an isolated step input. Second, the behavior under load is difficult to predict, since the point in the chain of stages at which overload may first occur depends on the nature as well as on the strength of the driving signal, and since recovery from overload is similarly complex and generally protracted. I will grant that certain types, such as pulse amplifiers, have provisions to prevent overload, usually amounting to concatenated interstage diode networks, but these are special purpose instruments and so outside my subject.

One ac amplifier which may be formed from an operational amplifier is the differentiator already discussed. At zero frequency it has zero output, and the amplitude response rises with frequency in direct proportion up to the limit. The phase shift is 90 degrees leading. A more generally useful ac amplifier results when the input element comprises a resistor and a capacitor in series, the feedback element being a resistor alone. Gain in the flat portion is determined, and adjusted, by the resistance ratio. The low frequency response is simple and predictable as a first order subsidence



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determined entirely by the resistance-capacitance product for the input element. Within the bandwidth of the amplifier, overload occurs first at the output; recovery is simple and prompt. This often surprises dyed-in-the-wool amplifier experts who have not known the delights of high-gain dc feedback instruments.

With combinations of operational amplifiers, it has been found possible to go far beyond the ordinary range of ac amplifier performance for special purposes, for example in the case of accurately differential and very high impedance input properties, and also where one must extend the response spectrum predictably and reproducibly to quite low frequencies.

Many ac purposes are well served by operational amplifiers with purely resistive computing networks, and operating just as though they were dc amplifiers. Typical are cases in which only periodic steady-state signals are involved, and the important signal properties are relative amplitude and relative phase. Since dc levels are not relevant in such cases, operational amplifiers with extreme low-level precision are not required. The signals involved may be single-frequency sinusoids, complex waves, triangular waves, square waves, etc. The inputs are calibrated resistances or conductances (or ratios thereof) inserted manually or automatically, while the outputs are similar except that they are manipulated to satisfy an ac null.

Structures of this kind will solve algebraic equations, either explicit or implicit, of almost any complexity, since the basic operations of addition, subtraction, multiplication and division are all possible. Nonlinear elements are not required, except possibly in detection of the null. The accuracy is higher than that of classical a n a l o g computation, since circuit elements of one type only need be included. This technique is relatively old but has not been at all widely applied. It has very interesting possibilities for development, combined perhaps with other existing methods. There is nothing wrong, incidentally, with inductance ratios, or even capacitance ratios, substituting for resistance ratios.

An Operational Null Amplifier

In observing a null balance in the laboratory, either where a manual manipulation is performed which is to bring about such a null, or where an automatic response to the null inspires a continuing operation intended to maintain the null at a minimum, there is more interest in the quantitative and detailed behavior of the nulled variable near zero than farther away. On the other hand a large departure from null, owing to the sensitive scaling of the null-carrying variable, saturates or limits that variable so that the observer or subsequent machinery knows only which way the null has gone and almost nothing about how much. Experimenters who have dealt with a linear scale null meter for a precise bridge balance, even when a multiplier switch was available, will understand this circumstance. Certain meters have overcome this defect by increasing the sensitivity near zero indication, through appropriate shaping of the pole pieces. Sometimes, however, other indicators such as oscilloscopes are on the scene, and frequently of course the observer is inanimate.

When an operational amplifier is applied to magnify the variation about a null, there is another reason to avoid saturation, for when it occurs there is almost always a period during which the amplifier seeks inert revenge for such violence even when the null is promptly restored. A common practice is to insert a diode network in the

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feedback, so that the output is maintained within specified bounds, and a local condition of activeness is preserved. Good analog computing instruments employ this feature for similar reasons. In a null amplifier, however, except with a rather complex network, the necessarily high central sensitivity is maintained out to a considerable excursion. A valuable alternative is that of including a readily available and inexpensive nonlinear resistive element known as *Thyrite* (a General Electric trade name) in the feedback path of the amplifier, along with a pure resistance in the input.

For typical moderate-impedance Thyrite elements, the current varies nearly as the cube of the applied voltage, so that the operational function is substantially a cube root version of the null voltage to be amplified. In spite of the relatively large resistor which may be used as input element, very nearly the full gain of the amplifier is allowed to operate near zero, but a smooth decay of sensitivity down to a small value takes place as the excursion from zero proceeds. Even for large departures there is continually supplied intelligence available on the state of emergency. One may choose the input resistor along with the Thyrite element so that maximum input and output voltages occur together.

Differential Operational Amplifiers

When you say operational amplifier today, your listener assumes that you mean a dc amplifier with a single input and a single output, both with respect to a reference or ground. Let me review briefly the operation of this amplifier. When in service, the voltage at the input terminal is held near ground potential, forming thus a virtual ground at this terminal. Further, since the amplifier input impedance is high, at least during feedback operation, and since also the source or sink current is very low, substantially zero current flows from the input terminal either into the amplifier or to the actual ground. As a result the sum of all currents flowing through input and feedback paths is zero.

Another, and equally legitimate form of operational amplifier has two direct inputs rather than one, and responds to the difference in the voltages at these inputs just as the standard form responds to its single input voltage with respect to ground. This form is called a differential operational amplifier. What is called "common mode response" in differential amplifiers is, as the name implies, the response to changes in the common input voltage when the difference between them is maintained constant or at zero, expressed as a fraction of the response to a change in either input alone. Common mode rejection, so-called, is the inverse of the fractional common mode response; in a good amplifier it is quite high.

It is vital to point out that a differential operational amplifier immediately *becomes* a standard or single-ended type if the positive input terminal is grounded. Thus the applications of this generalized form include all those of the standard type.

For many applications in which two standard operational amplifiers are normally employed, one of the differential variety will suffice, and may actually perform better. There is one class of applications which is particularly simple and natural for the differential operational amplifier, impossible with a single standard unit, and fussy with more than one of the latter. These applications arise when one wishes to measure, or reproduce, or amplify the voltage at a point in a passive network without interfering with

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the normal behavior of that network.

A trivial instance is in tapping a potentiometer, to avoid distortions which result from loading. For unity gain through the amplifier one connects the tap to the positive input, and the amplifier output to the negative input. This is the so-called follower connection, and is useful whenever a drastic impedance reduction, without attenuation, is in order. The term "unloading amplifier" is sometimes used for such instruments, having an obvious justification. Voltage gains are possible, without sign inversion, if the negative input is not connected directly to the output but at the junction between a series pair of resistors running from the output to ground. Numerically the gain is the total series resistance divided by the resistance from the junction to ground.

Among other valuable capabilities of the differential operational amplifier is that of injecting a precise and specifiable variable current into any network through a single conductor, with respect to ground. To avoid confusion I want to distinguish between this sort of current injection (or withdrawal) and that which may be had in the feedback path of a conventional operational amplifier. In the latter case, which is in particular very useful for testing static properties of nonlinear impedance elements (which are typically but not always two-terminal devices), the device to which current is to be applied is inserted between the amplifier output and the virtual ground provided by the amplifier input itself. The current may be accurately established and varied by the driving voltage applied to the free end of the known input resistor. Owing to the current balance at the virtual ground, the input current is automatically enforced in the device under test by the feedback action of the amplifier. Notice that the output voltage of the amplifier reads out the voltage across the device corresponding to each current, so that a set of voltage readings are enabled as a dependent function of current for the device.

The characteristic may if desired be displayed as a cross plot on an oscilloscope, if a varying signal is applied to the amplifier and to the horizontal input of the oscilloscope. (Large oscilloscope displays are available, incidentally, in which such displays may be read accurately and easily through a scheme of coordinates superimposed concurrently and automatically along with the characteristic curves under study. In fact these instruments permit simultaneous calibrated display of a number of functions plotted on the same coordinates.)

Arrangement for Testing

The inverse function, or current dependent on voltage, follows if the positions of resistor and two-terminal device are interchanged. This simple arrangement is useful for testing and calibrating, and for introduction of certain nonlinear characteristic in a simulator or computing system, but should not be confused with the quite different and more demanding operation whereby a current is to be driven into, or withdrawn from, a "high" point in a generalized network.

The latter operation may be performed with a pair of conventional operational amplifiers, but it is simpler and more compact with one differential unit. A circuit for this purpose, developed in the Lincoln Laboratory at Massachusetts Institute of Technology, is shown in the accompanying composite figure. An interesting inherent feature of an accurate such current

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source is that it has a high output impedance, in contrast with the usual operational amplifier output, which is a voltage source having very low output impedance.

Automated Research

Throughout the various sections above, and particularly under Measurement and Regulation, I have tried to emphasize ways in which laboratory tasks that are either tedious or frustrating may be entrusted to operational mechanisms. In the hierarchy of automatic tools, these techniques stand in an intermediate position. Further down the line, on an intellectual scale, one must insert safety valves or even automated production machinery, admirable though such apparatus may be. Just above, and overlapping, come the general purpose computing devices which do not fear theoretical problems. It is possible, nay probable, that the upward press of automatism will lay claim to the taking over of large experimental programs as standard developmental procedure.

Before my final and mildly conjectural opinion on this topic, I should like once again to call attention to the pivotal part played by feedback in all this. Feedback occurs, and serves useful ends, within operational amplifiers themselves, but I have not troubled you with such minutiae. It happens around individual amplifiers, to achieve precision and predictability. It is embodied in larger computing and controlling assemblages comprising many feedback amplifiers, to solve equations and to extend our willpower into the future. But feedback is also evident in the mentally guided studies and processes which determine what to compute, what to regulate, and what to experiment upon and to develop.

The largest and most time-consuming development of all has been Natural Evolution itself, of which the end product to date, at least locally, is ourselves. There is still controversy over the question of its control by a superintelligence, plus a meta-controversy on whether or not this controversy itself should be tolerated. In any case it is certain that the process of evolution involves *feedback* on a grand scale, although less unlovely terms are found for it in the biological literature.

The long, detailed cycles of trial, error, and variation, with their concomitant overtones of competition, find obvious parallels in such modern developments as ordinary utensils and motor cars. Perhaps less obvious are the parallels of development in research itself, basic as well as applied, but some reflection will support the analogy: in terms of trial and error, variation, and selection.

Now just as automatic devices can perform measurements, computations, and tests, why can they not also perform the operations involved in research and development? They can and they do, though as yet only in somewhat limited examples. In one example, a combination of conventional analog instruments, plus scanning, selection, decision, and storage features, has been used to "develop" a control system of advanced type, automatically. Other examples could also be cited. All the elements for automating a research project, in this admittedly somewhat restricted sense, are available on the open market, though the brainpower to assemble them is not yet very common.

Automated laboratories will come gradually, but surely, as controversy and conflicting ideologies, logic versus analogy, analysis versus synthesis, theory versus empiricism, first clash and then join hands to get the job done. ■