THE LIGHTNING EMPIRICIST

Advocating electronic models, at least until livelier instrumentalities emerge

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Editorial

We welcome, into the still underpopulated field of analogic periodicals, the shiny new magazine called Simulation. Its first issue has several edifying items, including a solicited article by our founder. Since unfortunately the article had to be cut, as printed in that magazine, *this* magazine contains the original – or unexpurgated – version, beginning on page 3. In any case The Lightning Empiricist has a wider circulation at this reading.

RATE-OF-CHANGE INDICATOR

Long advocated* by Philbrick Researches, Inc. as a practical and useful research tool is the electronic differentiator, and we can report on at least one recent successful application of the versatile P2 amplifier to the indication of the rate of change of voltage.

The problem presented by a customer's instrumentation engineer was one of determining the progress of charge in a battery when under charge or discharge by noting the change of the terminal voltage with time. On the charge cycle, the emphasis is on terminating the cycle when no further increase is evident. When discharging, the "end of life" is shown by a rapid increase in the dropoff of the terminal voltage.

Before the instrumentation engineer discovered the differentiator, he had rejected several standard alternatives — all with good reason. He first tried reading a precision mirrored-scale meter but found that whereas he might barely discern 10 millivolts on the 30-volt scale, a rate reading could only be inferred every 10 minutes: certainly not economical of time or conducive to tight control of the charge-discharge cycles.

Next, he thought that by using a differential input to a recording galvanometer he would have increased sensitivity and time for coffee while the recorder patiently remembered results of his experiment. Unfortunately, this plan was foiled by that most exacting "boss" of all — Nature.

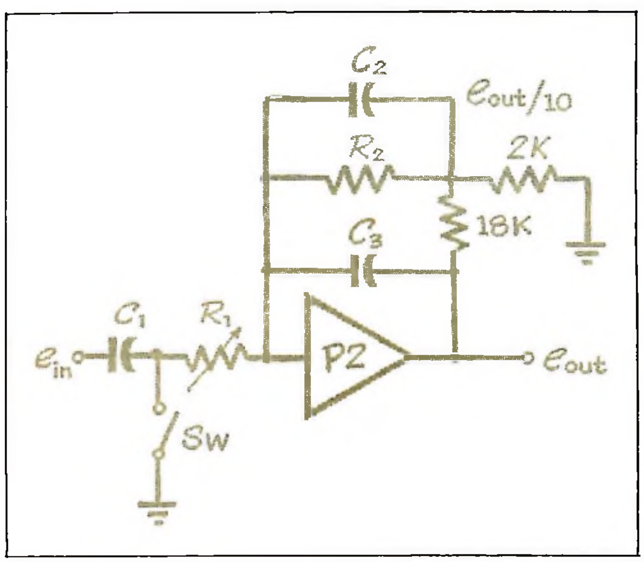
The experiment was to find the slowly varying change of voltage which was indicative of the battery condition. This was obscured by the large voltage changes occurring when the load changed, and the reference input to the differencing amplifier had to be readjusted quite often. Still, the rate of change of voltage was inexactly determined, and then only after minutes had elapsed following the onset of a new status in the operation.

*George A. Philbrick, "Electronic Analog Instruments as Tools of Research and Development" *Research/Development,* October 1961.

Thinking that he had saved the best of techniques to the last, our harried instrumentation engineer borrowed a 5-digit Digital Voltmeter (its cost exceeded any consideration of purchase). Alas, he soon learned that here he must wait a full minute for a 1 millivolt change of his 30-volt battery voltage to register, and patient timing of the intervals between change in voltage was required, since the digital logging accessories were also too expensive for this seemingly-simple task.

Our distressed instrumentation engineer found the Philbrick experts ready to assist with a device in their literature called a Differentiator. In addition to the barrier of computing vs. application-oriented terminology, the fable that "differentiators are noisy" interfered with taking this direct approach at the outset.

Enough for the background. What is the configuration of a working, low-level differentiator? We refer you to the following schematic:



and the equation of performance?

$$e_{out} = \frac{10R_2C_1}{(R_1C_1s + 1)[R_2(10C_3 + C_2)s + 1]} se_{in}$$

with what values?

$R_1 = 22K$ (to 500K) $\quad C_1 = 20$ mf
$R_2 = 120$ megohms $\quad C_2 = 4700$ pf
$C_3 = 1000$ pf

giving as a result:

$$e_{out} = \frac{24{,}000}{(0.44s + 1)\ (1.764s + 1)} se_{in}$$

Scaling is seen to be 4 volts out for a 10 millivolts/minute input rate. Noise and drift from the P2 amplifier contribute less than the 1% error limits.

What of the noise from such sources as the ubiquitous 60 cps pickup? At 60 cps, the gain of the differentiator is 82, and about ½ millivolt of 60 cps noise can be present without being noticed at the output. Then must there be significant delays in reading a rate of change? Not so. Notice that the larger lag is 1.764 seconds, so that useful rate information is available in seconds.

Other features of the actual rate of change indicator are:

- meter indication of the output;
- range switch giving 100 mv/min or 1 volt/min scales;
- variable filter time constant up to 10 seconds (R_1);
- portable and battery powered using PR-30 type of regulator board; and
- overload diode switch with pushbutton at the input.

For readers not in the battery business, may we suggest that the differentiator is adaptable to measure slow rates of change of a variable in the presence of a large steady component.

We wonder, for example, if the differentiator is not well suited to hill-climbing controllers.

This application of Philbrick components was made possible through the system design and special-product fabrication capabilities of PASTORIZA Electronics, Inc., 285 Columbus Avenue, Boston.

THE LIGHTNING EMPIRICIST

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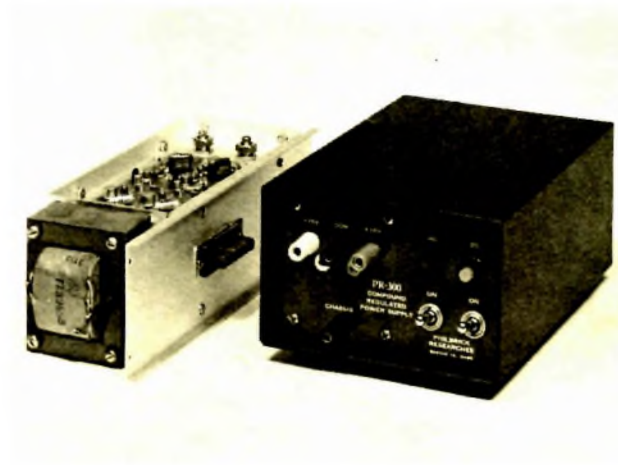
A NEW SOLID STATE POWER SUPPLY



MODEL PR-300 & PR-300C COMPOUND REGULATED POWER SUPPLIES

The latest addition to Philbrick's line of power supplies fulfills the requirements of conservative rating and high quality regulation needed in Computing and Instrumentation. With the PR-300 the output voltages remain at plus and minus fifteen volts from zero load current to beyond 300 milliamperes. The internal resistance is less than one milliohm.

Model PR-300 is a true *tracking* supply with negative and positive voltages always tending to be equal in absolute value, assuring minimal deviations that might affect operational amplifiers and related equipment. Line voltage variations of ±10% cause supply voltage variations typically less than 150μv, or one thousandth of one per cent. The dynamic performance is of a very high order; the unity-gain-crossover frequency of the voltage-regulator is beyond 20 kilocycles per second.

To balance environmental temperature excursions the reference diode incorporated as standard in the PR-300 will typically permit an output variation of plus or minus 15 millivolts or 0.1 per cent over the temperature range minus 25°C to plus 85°C. Interestingly, the electronic amplifiers used in the regulator loop are 10 times better than this in thermometric insensitivity, so that a 0.01 per cent supply is entirely feasible if the market place demands its appearance.

We take paternal pride in a unique feature — the dc pilot light circuit that informs the user that:

1) dc power switch is on
2) both plus and minus supplies are "on line" with the proper voltage
3) neither supply is shorted.

Conventional pilot circuits waste some 10% of the hard won regulated power. In the PR-300 a one transistor switch does logic (in the digital sense) at a very low power level and, when both supply voltages are present, switches on the pilot lamp from a source of unfiltered half-wave rectified a.c. Since the transistor acts as a switch the only power dissipated is that in the lamp filament itself, and this energy can be in a real sense regarded as *signal energy* — a small price to pay for a continuous optical signal to the user that his PR-300 is performing as it was designed to perform.

ANALOGS YESTERDAY, TODAY & TOMORROW
Or: Metaphors of the Continuum

By G. A. Philbrick

Origins

It was naturally pleasurable for me to have been approached by the Simulation Councillors to write an article, substantially under the above super-title, for their new magazine. This euphoria persists even now, when my performance has in fact begun, and is only moderately tempered by the haunting suspicion of what their real reason might have been for so honoring me. It certainly could not be because my views on analog computing and simulation are somewhat eccentric in relation to much of the contemporary doctrine, although I accept and actually relish this characterization. It could conceivably be in recognition of my relatively early start in the field of electronic analog technology; this again is not denied by me, but here we may have found the clue. The fact that I began a long time ago in this sort of activity doesn't mean at all that I am either oracle or authority in it. The truth of the matter is subtler still: it only means that I am getting old. So we have it out at last. They are showing respect for the aged. Here then, steeped in mellow nostalgia, are the musings of a well-meaning and harmless Old Timer.

Since truth will out, I might as well admit immediately that I do not claim to be the original inventor of the operational amplifier. It is true, however, that I did build some of them more than four years before hearing of anyone else's, and that their purpose was truly simulative. These amplifiers were indeed DC feedback units, used to perform mathematical operations in an analog structure, but the very first such amplifier *itself* began as a model of a mechanical control amplifier. Thus my role as model builder, even at that stage, loomed larger than my possible role as inventor, and I have been dealing continually with models and analogs ever since. Hereafter in this context I shall not speak of what I may have invented or originated, and in fact shall not much longer continue in the first person singular. By the same token I shall make no pretense in this article of assigning credit to other individuals or to other institutions. There are far too many of both, hundreds and thousands, stretching from this point back into history, to give any accurate and fair account of the brainpower and perspiration which have made analog computing what it is today, without leaving out many who have put vital links into the chain.

While electronic analog equipment, using this phrase in the modern sense, certainly existed in the thirties, and in the forties became available on the open market in several forms, its roots really went still further back in time. It is doubted that a completely exhaustive chronology of the contributory precursor technologies could ever be produced, let alone by one amateur historian. Nothing even approximating such a feat will be attempted, but it is hoped that an outline of the tools and techniques which were on hand in the previous era will show that the ingredients were already there, and that the modern analog machine was almost inevitable. As is usual in such surges of progress, several fields of science and engineering overlapped to breathe life into this development. Among others were Physics and Scientific Instruments, Communications and Electronics, Controls and Servomechanisms, Mathematics, and Aeronautical plus Electrical plus Mechanical Engineering. It is recognized that these fields are not mutually exclusive, and that each realm constitutes a multidimensional cross-section which has interpenetrated the other realms enumerated.

There is one thread, come to think of it, which appears to run through the whole background of the analog doctrine, and which may be said to belong to it more intrinsically than it does to the other major branch of computation; that thread is *feedback*. It will appear again frequently in what follows.

The clearest anticipation of modern analog machines was in the differential analyzer. This primarily mechanical device could handle total differential equations at least as well as we can now, and in some ways better. One such analyzer afforded automatic establishment of its interconnections and parameters, tape storage of these data, and automatic readout: both numerical and graphical. Although slower than newer electronic equivalents, nonetheless for a 19-integrator problem which was run on it in 1945, a thoroughly nonlinear problem by the way, the analyzer time scale was only twice as slow as the real scale for the remotely controlled glide vehicle which was being simulated. The disc integrators of this machine were things of beauty, with accuracies approaching, and resolution exceeding, 5 decimals. They could integrate with respect to dependent variables, thus enabling multiplication with only two integrators, logarithms without approximation, and so on. Integrators of this same general type were also applied in astronomical and military computing devices, in which less elaborate but still legitimate differential equations were embodied and solved. This sort of equipment inspired many of the electronic analog devices which followed, as well as the digital differential analyzers which have come much later. Although the electronic integrators of analog equipment prefer time as the direct variable of integration, they have shown extreme flexibility of operating speed. One imagines the mechanical discs of the older analyzers running at millions of rpm trying to keep up with their progeny!

The disc integrators of the differential analyzer worked without feedback, as did its other basic parts. Where then did feedback appear in these analyzers? In the differential equations acted out within it. Any equation requiring solution involves at least one causal loop. But for feedback in its more exuberant forms we nominate the next discipline to be considered, namely automatic controls.

Regulatory mechanisms such as those which are found in industrial control systems have been around for a long time. Roughly in historical sequence, they have been mechanical, hydraulic, pneumatic, electric, and electronic. Translating as they do from the unbalance or error in a controlled condition to the manipulation which is intended to reduce that unbalance, they close a feedback loop which includes some sort of plant. In typical cases these mechanisms have embodied mathematical laws with continuous fidelity, and in order to attain fidelity they have resorted to internal feedbacks precisely analogous to those employed in a modern operational amplifier. It may not be widely known, particularly among the younger computing set, that this sort of local feedback was applied in standard controller mechanisms of the twenties and even earlier. These antecedent regulatory devices qualify as DC feedback amplifiers in every sense. So with feedback and even null-seeking at two distinct levels, and with mathematical capabilities, it is not difficult to trace the logical paths of evolution from these devices to analog computing as it is now enjoyed. Furthermore it was not uncommon in the thirties to build simulators embodying convenient models of plants, into which the real regulatory mechanisms could be connected. Both developmental and educational purposes were served by these structures, just as with simulators today. The next stage, in which the real control mechanisms were replaced by models, permitted the whole loop to be electronic and hence vastly more flexible and greatly accelerated. In simulators of this sort, several plants might be interconnected under control, so that the newer stability problems thus encountered could be studied conveniently. Again, plants with multiple inputs and outputs having internally interacting paths were included, and regulatory loops in hierarchies where master controls manipulated the desired conditions of subordinate controls, all could be simulated in an analog. Note the ascending succession of feedback loops, which are most dramatically represented in control systems of this sort: within amplifiers to attain promptness and stability; locally around amplifiers to give the desired mathematical performance for regulatory mechanisms; in control loops to promote the minimum difference between desired and existing conditions; in more comprehensive control loops which include complete but subordinate loops in cascade; in still more comprehensive loops for supervisory or evaluative purposes; and finally in the experimental design and optimizing operations, using models or computational structures to evolve most effective system operation.

Servomechanisms are also part of the lore which preceded and inspired the modern analog machines. Though not as old as the governors, pressure regulators, and controllers of temperature, flow, level, etcetera of the last paragraph, servos as positional followers were functionally similar as regards control philosophy and feedback loops. Further, being more modern, they benefited from the increasingly mathematical technologies of development and design. Perhaps most relevant was the simultaneity and parallelism between servo theory and that of feedback amplifiers in communications. Stability criteria for the latter were seen as applicable to the former, at least in the linear realm. Analysis in the frequency domain, a natural procedure for linear communications equipment, was carried over rather directly to servomechanisms. This debt has since been partially repaid, as servomechanisms have helped to furnish nonlinear analog elements and other items in computing equipment for the study of nonlinear phenomena, generally in the time domain, as they occur in communications and elsewhere. Thus do the various doctrines and practical disciplines feed on each other to mutual benefit, and (if you will forgive the liberty) feed sideways as well as back and forth.

We pick up servomechanisms again, much farther back along the trail, and usually in relatively low-performance embodiments. Though scientific instruments do practically everything today, including computation, synthesis, manipulation, and regulation, on every scale, they were once used principally for measurement, in the laboratory or the observatory. For accurate measurement it was found that feedback methods, when possible, were surpassingly effective. While the underlying philosophical reasons for this circumstance are of vital importance, we shall take them here on faith. Note, however, that the observation of balance in a measurement, and the manipulation which may be made to achieve balance, is still a feedback process even if done by a human agency. The slave can be the experimenter himself. Precise weighing with a beam balance may stand as a clear example of this procedure, but a myriad of others may readily be spread forth. Succinctly, the process is reduced by feedback to dependency on only one or a few reliable elements. Automation of the loop-closing, null-seeking action merely replaces one slave by another. In this light the venerable self-balancing slidewire potentiometer recorder stands with the latest feedback operational amplifier, and so we see yet another plausible path from then to now.

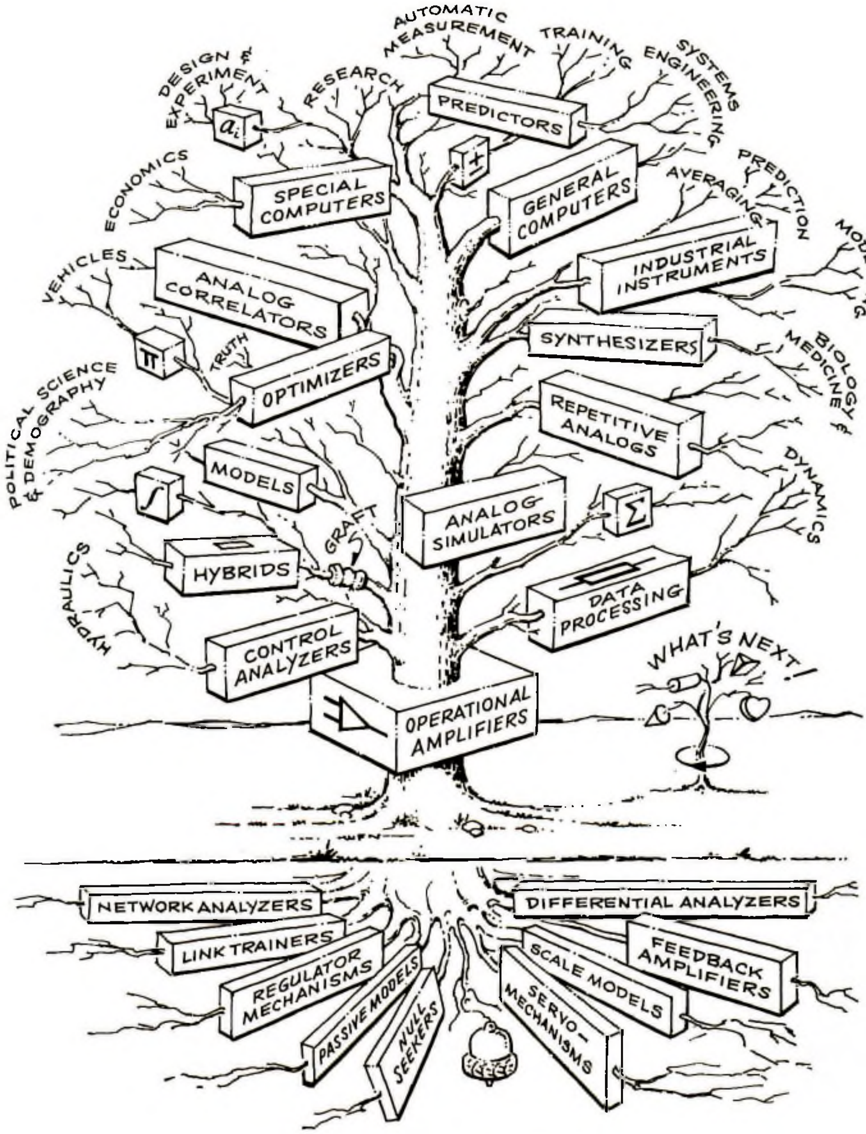
Antedating but partly anticipating the development of active analogs was the use of models which depended much more directly on the analogies between phenomena as they appear in widely differing physical media. Of main concern here are those cases in which the modelling medium has been electric, but quite accurate and articulate models have also been mechanical and hydraulic, and many of these are hoary with age indeed. Ever since accurate and dependable circuit elements have been available, and this has been for many decades, notably for resistors and capacitors, highly successful passive models have been built for the study and solution of such problems as those which occur in heat conduction. Dynamic as well as steady state phenomena may be handled, often in the same model. Again, vibrations have been studied with direct models having all three kinds of circuit element, plus transformers. Furthermore very large and complete simulative structures, called network analyzers and based heavily on passive elements, were used in particular for — though not at all limited to — AC power distribution and communication lines. Even today one finds such continuous conductive models as electrolytic tanks still in use and under development. Many of these tools have specialised capabilities which are hard to match with the more familiar sort of modern apparatus. The similitude conditions and principles which accompanied and abetted the application of such models have been carried over to, and have guided the users of, the newer computing means. It should be added that the very demanding doctrines of "lumping", which must take place when continuous systems are represented by separate but connected analog operations, are substantially unchanged as compared to those in passive models. Here is another branch of knowledge and effort, then, to which we owe recognition as contributing to present day simulation and computing.

From a different direction, in terms of need and application, came another practical model-building technique which is woven into the analog fabric which surrounds us today. This one is straight down the simulation highway; we refer to trainers of the sort used for many years to indoctrinate pilots of aircraft.

These trainers modelled just about everything except non-angular spatial accelerations. They presented, to a human operator, a simulated environment resembling the real one in many important ways, as regards his manipulations and the responses returned to him as a consequence thereof. Of course the later counterparts of the first training aids have become tremendously more refined, and similar structures have been adapted to other man-machine collaborations, but the inspiration to analog enthusiasts on a broader scale seems rather obvious. Here was an operative model, in real time and undelayed, where to the sensory and motor periphery of the trainee the real environment was presented in a safe and pedagogically corrective atmosphere. Now it is true that training devices for physical skills are even more numerous today, and analog simulative equipment finds important applications in these, but a somewhat extended simile might be in order. For system design in its larger implications we are all trainees; analog simulation to teach us how a proposed system might work when at least part of it is new, to guarantee safety if we try out a poor idea, and to offer peripheral communication at the *deliberative level*, projects the trainer concept to an advanced modern setting. The task of simulating the trained pilot and even the learning pilot, or other human operators, provided a challenge which has partly been met, and which is still relevant. Simulating the system designer, as a logical extension, leads as far as you might care to travel.

Overlook

Things are looking up all over for the analog profession. Substantially every branch of engineering now applies analog computing equipment: in theory, experiment, design, manufacture, and test. Applications are even on the increase for scientific research, where in a sense such equipment began. We shall not try to list the many embodiments and applications in this text, but have included some of them in a figure to be found nearby, which has been prepared to bear out the morphology of our burgeoning field.



The Mighty Analog Tree

Analog representation in terms of modern apparatus is a pretty far cry from scale models, but the model concepts still seem incomparably fruitful. In *direct models*, which retain the physical medium of their prototypes, scaling is the biggest part of the game. Similitude conditions must be faithfully adhered to, and an appreciation of these conditions imparts a feeling for models which is never lost. Actually the use of direct scale models has not decreased, and is still a powerful technique in such areas as hydraulics and structures: natural and man-made. Much ingenuity has been lavished on such models; they must by no means be looked down upon by the users and designers of more fashionable modelling items.

In a scale model the transformation of dimensions is typically direct and simple, especially if shape is preserved. Even when the scaling involves distortions of shape, such as relative compression and bending, the transformations generally carry distance into distance, velocity into velocity, and so on, with only numerical scale factors relating them in pairs. Basic parameters, when the scale ratios are properly assigned, turn out also to be numerical, and apply equally to model and to prototype. This doctrine, whereby characteristic system parameters are dimensionless, is applicable to all modelling procedures. The transformation concept, so clear and concise for scale models, carries over with little confusion to modelling in which the physical form is changed, and ultimately to electronic analogs where transformation includes transmogrification. The scale ratios in general, however, are no longer numbers, but the basic parameters may be. This sort of introduction is recommended for physicists and applied mathematicians who may be coming suddenly into modern analog contacts, since it utilizes some of the ideas and precepts, however badly expressed here, of the more classical fields.

Another sort who is momentarily taken aback by the liberties permitted in analog models is typified by an engineer who has been too long away from the time domain. Often brought up, pedagogically, on linear systems and frequency analysis, he (or she) may even be suspicious of a mechanism which gives solutions as functions of time, perhaps not realising that it will provide amplitude and phase spectra as well if one merely applies a different stimulus to the same model structure. It is frequently worthwhile, in these cases, to introduce the analog from the viewpoint of the frequency domain, shifting later from the familiar to the strange and magical. Oddly enough, the most confirmedly practical and the most profoundly theoretical of engineers will both be found to favor the time domain, with or without computing equipment. In the former case this is by virtue of convenience in handling real equipment, and in the latter it is since — among other reasons — he finds it better to approach nonlinear problems in the time domain than in the frequency domain.

Analog engines have not always been as respectable as they are now becoming. Analogy itself we have been warned against, in proverb and in folklore, as being dangerous and requiring proof. Parenthetically, this is good advice. Simulation has had connotations of deceit, empiricism of quackery. It was stylish, even recently, to say that the only good electronics is that which says Yes or No. There is nothing to be gained in disputing these allegations, least of all by excited rejoinder. The continuous active analog is in its infancy, and time is (literally) running in its favor.

Time as an independent variable, given at low cost by Nature, has the advantage of nearly, if not actually, infinite resolution. This continuity, coupled with the continuity of voltage and charge, leads to the ability to close loops at very high frequency, or with short time intervals. As a consequence one may approach the ideals of differentiability which are inherent in the infinitesimal calculus, which postulates the existence of a continuum. While most contemporary analog apparatus does not press these limits, it is comforting to know that there is room left to maneuver in.

In modest applications to on-line measurement and data-processing, it is quite generally conceded that the advantages of continuous analog apparatus make it irresistible. This is partly owing to the simplicity and speed which its continuity makes possible, and partly to the fact that almost every input transducer is also "analog" in character, that is to say continuous in excursion and time. Storage and sampling, for example, are frequently unnecessary in such applications, as in many others. When we turn from simpler to more involved data processing, to ambitious simulation, or when in general we pass from modest to more pretentious computations, there has been some feeling that digital means should automatically be substituted, especially if funds are available. In this connection we should like to quote, on the other side of the argument, no less a figure than Dr. Simon Ramo, writing on Systems Engineering in a collected volume called Parts and Wholes (Daniel Lerner, Ed.; published New York 1963, Macmillan). The following is admittedly taken out of context:

> "Digital computers, however, cannot be used conveniently or efficiently to obtain answers to all of the problems. In some cases, even they cannot solve the equations in any reasonable time, and in other cases the problems are not understood well enough for satisfactory mathematical formulation. Under these circumstances we can often turn to analog, real-time, simulation devices to predict the behaviour of the system. No engineering computing center is well equipped without such devices."

One should certainly be happy to settle for this, even though the text continues in a discussion of other kinds of equipment than analog with which the latter may be associated. Only the most hard-shelled of analog champions would suggest that all simulative and computational equipment be undiluted by numerical or logical adjuncts. Certainly many of the best known individuals and organizations in the analog field are now willing and able to talk about hybrids. This term, by the way, is too broad to have much meaning at this stage of the game. Is an analog apparatus hybridized by adding a digital voltmeter? The possibilities are far too numerous. The present treatment does not even contemplate giving a complete account of analog computing machines themselves, let alone the combination they may form with other machines. A large and growing library of good books cover these areas quite completely. Many of these are written by officials of the Simulation Councils, who typically have the sort of university connections which should give them appropriately unbiased viewpoints: viewpoints which a mere company man can only envy. Perhaps, however, an example or two might be appended here which will amuse and even edify.

At a large Eastern university, under the guidance of a well-known and gifted computationalist, a successful project has been reported on whereby the scaling for an analog installation is done entirely by rote on a digital machine. No guessing or trial runs at all are involved. Straight from the equations, the digital solution dictates the analog settings which will bring the maximum excursion of every variable analog voltage to within 20% of the limiting value. Local wags thus proclaim the discovery at last of a practical contribution by the digital apparatus. Seriously, they enjoy the ability to "get at" the solutions of the analog during operation.

Some analog men, perhaps over-fond and defensive as regards continuous functions, really believe that analog operations are generalisations of digital ones, or that conversely digital operations are special cases of analog ones. What can be done with such people? They deprecate the importance of the fact that discrete measure-scales approach continuity in the limit, alleging that infinite processes are already tacit and available, without passing to the limit, in an analog variable. Pointing for example to analog selector circuits which can pick out and transmit whichever of a set of variables is algebraically the greatest or the least, they cite this capability as broader than the logical sum or the logical product, amounting in fact to infinitely-many-valued logic. Selectors followed, for example, by bounding operations serve directly in the rudimentary case of two-valued logic. On the basis of such reasoning it is surprising, the argument runs, that analog apparatus is not permitted to make decisions for itself. It is hard to answer these arguments, especially when dealing with confirmed analog partisans. When cornered on some point of superior digital accomplishment, they simply claim the whole digital province as part of their analogs.

Predictions are scheduled for the Tomorrow part of this article, but one such properly belongs here. While it is agreed that analog and digital techniques will increasingly cross-fertilize and inter-relate, it is predicted that the controversy between their camps will rage on, good natured but unabated, for years to come in spite of hybrid attachments. The serious issue of reliability has recently arisen as between the two ideologies, referring for example to instruments for interplanetary exploration. It is preferred here to avoid an opinion or judgment on this very important issue, but it is suggested that others similarly withhold judgment. At all costs we must not go down the wrong road. There are quite powerful and rational and experienced brains in which the reliability vote would be cast for analog, or at least against the exclusion of continuous variability. We must cooperate in a dispassionate but devoted study to determine the likeliest facts and fancies in this affair. If one believes that Nature is ahead in reliability, and there would appear to be justification for this belief in recognition of the redundancy, repairability, and adaptability of animal organisms, then conclusions may follow which are based on how one views such organisms. It has been standard practice to view the details of animal nervous systems as evidence that they are digital, but there are major reasons to question this.* The central nervous system itself seems digital to digital men, and analog to analog men. If it is both, then it is a more intimately and profoundly intermingled hybrid than any of the artificial structures which have come to light. One thing is pretty sure, and that is that the brain builds models. We are in good company.

Back on reliability, at least in the sense of predictability, there is a duality to be noted in the relation between analog and digital techniques. If one must predictably manipulate an imperfectly accessible entity, he may proceed by arranging a discrete set of states for that entity, then transmit a prearranged number of command signals to it. Alternatively, with a non-quantitized feedback indicating the state of the entity, one commands changes outwardly by whatever means until the desired state is shown to have been attained. What the one achieves by quantizing, the other does by feedback. This is oversimplified, and does not immediately enable any evaluation of reliability. For the moment, it is only a point in (practical) philosophy, but as with many other continuous/discrete instrumental relations it is reminiscent of the wave-particle dualism.

Auguries

It has been predicted above that the analog-digital struggle will persist, and this will mean some wear and tear as the proponents contend, but on balance such contention will probably be beneficial since it will assure that the maximum potential of each technique will be realized. As to mixtures, all the obvious ones will soon be seen somewhere. More intimate mixtures, which might offer something approaching universal applicability, will depend on the appearance of new instrumental tools. But also note that urgent needs provide as potent a force for development as does the availability of new and startling techniques. Hasty prediction from either angle would be hazardous; certainly anything specific on our part would be irresponsible as well as foolhardy. There do seem to be possibilities, however, in recognition of the ability of continuous analog instruments to operate quickly and smoothly in closing feedback loops, plus the abitrary accuracy and permanency of discrete processes. Graphical computation may give a clue of sorts here, since anyone who deals with geometrical plots is prone to appeal alternately to continuous criteria and to numerical coincidences in calibration. Coordinates in general may have both of these meanings simultaneously. Are they any better than we are?

As to analogs themselves, it is evident that some forms of instrument, though not all, will become progressively smaller and handier in solid state incarnations. It is also evident that optimizing and search operations will be made increasingly automatic, as the deliberative functions of the user are encroached on more and more by deliberately imposed autonomous controls. But one of the principal lessons from the past is that substantially all the earlier techniques will continue to be used, and will grow and improve horizontally. Possibly you have a sliderule in your pocket, though admittedly you may have turned in

*R. W. Jones, *Science* 140, 3566 (1963). See also the companion article by J. S. Gray your abacus for a desk calculator. All the older apparatus of the above section on origins are in current usage, and will continue so. As an example may we consider passive models?

It would be a big surprise if passive electric models do not expand in application and in technical excellence. More adept peripheral instruments, to drive and to measure them, are either in the cards or on the table. Passive circuit elements, adjustable as well as fixed, are gradually but surely improving as to accuracy, bandwidth, and stability. In this category are included not only resistors and capacitors, and less insistently inductors and transformers, but also certain nonlinear elements. A combination of compensation and regulation can cut the parametric effects of temperature down to size, especially with the advent of flexible devices for thermoelectric heat pumping. Relatively little work has been done on passive networks for model building, even for linear systems, compared to that expended for communications. The challenges introduced in the nonlinear cases are considerable, but with newer analytical techniques and instrumental tools it would be unwise to put limits on what might be accomplished. Part of the lure is that many biological structures appear to have been designed along these lines, though not of course without active adjuncts.

Another trend which is evident, and which will probably gain in momentum, is that of the unification of assorted instrumental techniques based on analog feedback operations. When it is considered how fundamental is the function of the operational amplifier, and how its benefits are continually being rediscovered in new fields of technology, it seems likely that multipurpose modular structures will perform the tasks of a number of specialised measuring and manipulative instruments. Beyond its classical and celebrated mathematical operations, comprising addition, algebraic and functional inversion, linear combination, differentiation, integration, etcetera are the abilities to store and to isolate, among a number of others which are less well known. Since it *is* well known, on the other hand, where information of this kind is available, there is no need or propriety to elaborate here on the applicability of this basic tool. However, the philosophy of this sort of amplifier as an electrical null-seeking or balancing agent carries its own impact once it is understood. When basically similar methods and equipment are found to be effective in each, such fields as computing, data processing, testing, regulation, and model building will not be kept separate, but will diffuse and perhaps ultimately fuse with one another. One key to the future appears to lie in the quasi-paradox of special-purpose instrumental assemblages based on general-purpose analog modules.

Systems engineers are coming along now in greater numbers and of higher average caliber, and they are not now so brutally divided into disparate camps of practical and theoretical people. More mutual respect, at least, seems to obtain between these two sides of the track. Analog models will be increasingly resorted to by both groups in studying the formidable problems of system engineering they must attack. It is getting around generally that the modelling approach may best be taken in stages. Not only should subsystems be separately modelled and carefully confirmed, but a given model need not represent all the aspects of a given subsystem or system at once. Linear approximations usually represent only a crude beginning, but may be confirmed by relatively simple analysis. Nonlinear models are harder to build but much harder to analyze, so that frequently the approach to nonlinear structures should begin with drastic approximations to the nonlinear features, which are refined in stages as the project develops. Each step should be simple and well defined, with continual checking of the assumptions, and of those portions which are assumed to be complete, before forging ahead. Of course the parallel development of rudimentary overall models is in order if it is understood that they should be taken with a grain of salt: they may impart some idea of the flavor of the final concoction. Aspects of a system suitable for separate analog study will depend on the nature of the system; this is the age of broadness of system definition, extending even to all of Society. Taking such a case, one might study population density, political stability, wealth and commerce, considering these somewhat independently before they are all joined in one model. Again, the study in each case might be from the viewpoints of transients, or cycles, or statistics (possibly introducing random perturbations from independent sources). Still further, the item of interest might be tolerance to parametric changes, transitions from one regime to another, extrapolations backward and forward in time, and so on. But my prognostications have turned into a ramble.

As an offshoot of specialised training applications, analogs should find growing applications to pedagogy of a more general kind. This is partly owing to the personal experience which the subject may be afforded, but also to the interest which is induced by living analogies. The speed at which dynamic models may be operated is another factor in maintaining interest, and in saving time as well. If fast repetitive operations are employed, an introductory step may involve slower demonstrations, better to enable the mental transformation of time scale. Block diagrams or signal flow graphs become immediately more meaningful if tangible analog apparatus is made available to fulfill them. The innate property of causality, for example, is given memorable and dramatic emphasis. Feedback is of course the big thrill to the innocent in its general framework, along with its embodiment in differential equations, automatic controls including servomechanisms, and vibrations.

Models and analogs, even as concepts, are powerful teaching means in any case. Symbols themselves are rudimentary analogs, striving close to reality in mathematical operators. Words and languages are analogs right down to the ground. Physicists think and talk in models, the very best of them saying that models are their most powerful tools. Similitude conditions apply equally to all physical phenomena, along with dimensional analysis, so called. The unification of a set of properties in one structure, suggestive of an underlying organization and beauty, gives power and appeal to the model concept in the education of students: and students we all should remain, every one. So we close with a student's recollection.

Emerging many years ago from the old Jefferson Physical Laboratory at Harvard, one could read on the Music Building opposite, cut into the stone under the eaves, an inscription which should still be there:

"To charm, to strengthen, and to teach,
These are the three great chords of truth"