THE LIGHTNING EMPIRICIST

Advocating electronic models, at least until livelier instrumentalities emerge

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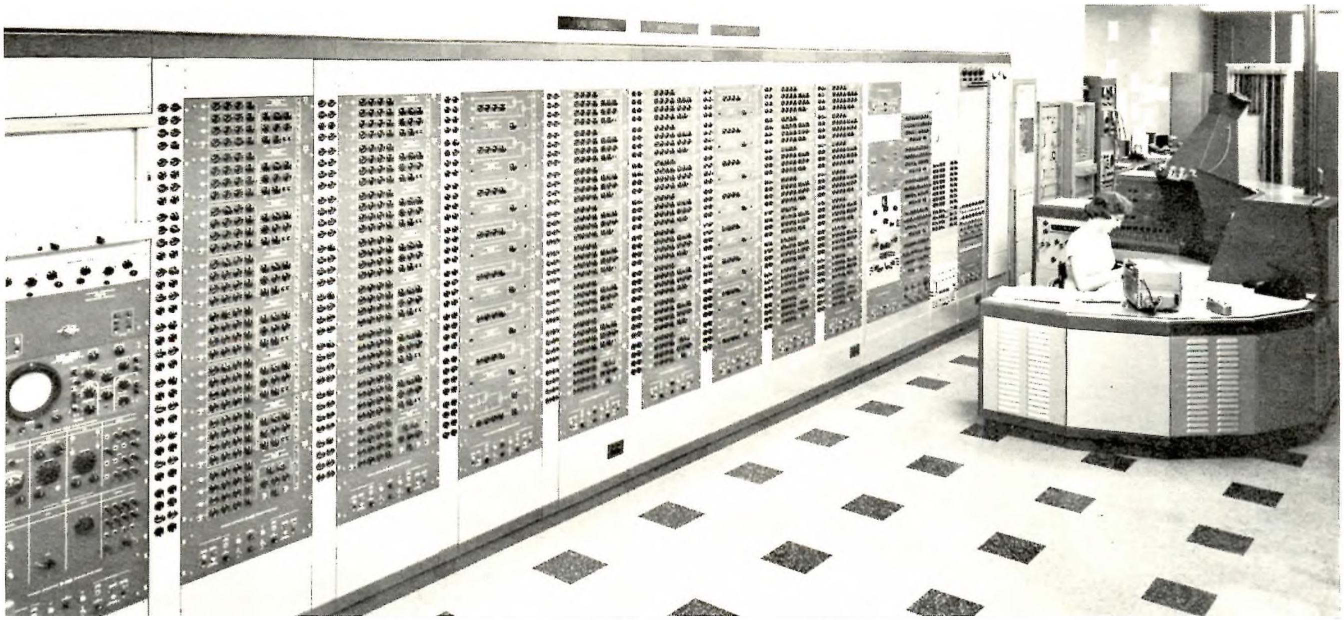


Analog Installation at Hercules Powder Co., Magna, Utah, U.S.A.

INTENTIONALLY UNCONVENTIONAL ANALOGUERY

YOUR orthodox present-day analog computing machine is a thing of pots and patches. That is to say it presents to the viewer a pattern made up of one or more patch bays and a large number of ten-turn potentiometers. Patch cords, generally plugged into boards which occupy the patch bays, establish the sequence of operations comprising the system to be simulated and solved. The settings of the potentiometers are made in accord with parameters which determine the quantitative nature of the system under study.

Perhaps the most striking feature of this Hercules installation is the absence of pots and patches, both being replaced in a uniform way by rotary, manual switches. The switch settings, which may be recorded in a perfectly natural way, embody and define the interconnections as well as the parameters of the system being investigated. A number of advantages follow from this pervasive application of switching throughout the machine, as we shall explain in a moment.

Other features include: a conceptual framework which is mathematical, rather than electronic; provision for *panceleric* performance, whereby the same apparatus operates periodically or aperiodically with a computing time ranging from below 0.05 seconds up to 50 seconds or beyond; and a large-screen electronically calibrated display which permits direct comparison of many variables and convenient photography.

Mathematical Framework

We love operational amplifiers as much as the next analog enthusiast. Many are involved in this installation. The fact is we have probably manufactured most of the operational amplifiers now being used on this planet. But we deprecate the practice of asking the user of computing machines to think in terms of such amplifiers. In this machine, for example, the user deals only with mathematical concepts and operations. His basic such operations comprise: linear combinations of one to four terms; time integrals of such combinations; multiplication and division; bounds; and functions of variables. These, and certain other minor operations, are collected into three principal operational modules, described elsewhere in these pages. Note in particular that the concept of linear combination includes, as special cases, the ideas of adding, subtracting, inverting, and averaging.

The user, in dealing with his differential equations, or functional block diagrams, or signal flow charts, has enough to worry about without electronic folklore. To him such facts as the habitual minus sign involved in one-amplifier transformations must appear as an irrelevant trick of fate. By offering a simple environment for the user's deliberations, his attention may center on the important matters of normalising, scaling, ranges of parameters, etc.

Switched Coefficients

Multi-turn potentiometers belong to our culture. They are available from many makers, with knobs and scales of surpassing cleverness. We like them. We have used them in certain instruments. We do not advocate them, however, for a general purpose machine such as this. Among other reasons are the following:

(a) They are hard to set.
(b) They are hard to read, especially from over two feet away.
(c) They are subject to loading errors.
(d) They waste power.
(e) They do not lend themselves to conveniently calibrated conductance settings.

The usual procedures in which potentiometers are manipulated to establish coefficients do not involve the dial calibration except as an approximate guide or as means whereby one can return to previously held positions. Since the fractional rotation itself is unusable as an accurate coefficient measure, other means are used to measure the fractional transmission of signal through the potentiometer, the latter being manipulated manually or automatically until the desired transmission results. Conversely, an experimental setting must be followed by such a measurement to formalize a coefficient value. This seems too bad, and inferior to a means of coefficient setting wherein the numerical value may be established or read out directly.

The preferred method of handling coefficients in this machine, covering in fact substantially all the computing parameters, involves switch setting by decades for numerical value and switch setting for algebraic sign. The settings as made have validity independently of load. They are easily and quickly made and readable from a distance. They are economical as to electrical power. This is not the place for a detailed account of the means employed to accomplish this end, which is simple if mildly subtle. A three-terminal network is involved, whose transfer conductance progresses arithmetically through as many decades as are required for precision.

Voltages also may be incorporated by the same switching structures, both for sign and for numerical value, as fractions of reference voltages, in decades of conductance switches. Such voltages, indeed, may be looked upon as parameters of the mathematical description.

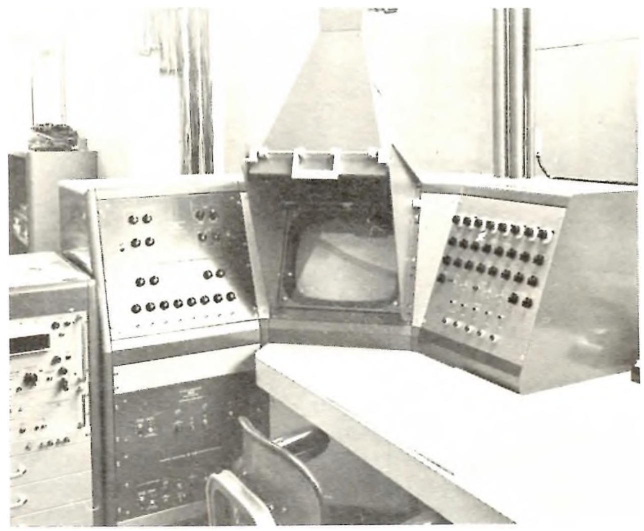
Switched Interconnections

Patch cords are simply replaceable lengths of covered wires which connect the outputs of selected computing sections to the inputs of others, and which thus determine the order of internal operations, or "program." Patch boards are traditionally provided into which these cords can be plugged, and which in turn are bodily inserted — as gigantic multiple plugs — into patch bays which communicate electrically with all relevant elements of the machine.

The idea of the patch board, of course, is to enable *storage* of the program, or pattern of interconnections. While it does this indeed, it fails to store the parameters, which still must be established by setting potentiometers. As all initiates will agree, however, the dominant feature of patch boards is the wild and vermiform tangle of cords which proliferate on them in the case of problems which are more than trivial. These tangles are picturesque but not particularly efficient, and there is evidence that they conduce errors and that such errors are hard to track down.

In the present installation, and in some earlier experimental structures, all wires are removed from the front of the machine. Instead, every interconnection is made by a system of switches very much like that applied for parameters. A pair of decade switches located near each input on each modular panel allows choice, as the variable to be applied to that input, of any output variable in the machine. Each such pair of switches may be said to embody an "inverse address," for evident reasons. Experience has borne out that this technique of switch programming is resistant to errors and easy to operate. It looks like the interconnection method of the future.

Problems for solution are set up on standard tabular sheets, which formally resemble the modular panels of the machine itself. The entries are simply the switch settings and are uniform in style for interconnections and coefficients. These tables naturally serve for storage of problem embodiments for future reference.



Accessories, Including Display

At a central point, thoughtfully arranged about and upon an operator's desk, are instruments attending control of and access to the computing machine proper. Included are: timing apparatus for determining the speed of operation of the machine, relating to the set-run-hold cycle of computation; recorders such as Visicorders and fm tape machines; generators of standard time functions; and, of course, one or more human operators of appropriate sort.

We are pleased that a role of importance was given to our electronically calibrated, large-screen, display system. Hercules put this system into cabinetry of their own choosing. From the central desk, switches select any of the variables on the machine for plotting on the cathode ray display. Advantages of our display include, along with voltage and time calibration to good accuracy, the ability to compare solutions by superimposing them on the same coordinates, monitoring up to eight solutions, and cross-plotting of one such solution against up to seven others.

Appreciation

The Hercules installation is called by them the UNI-VERSE COMPUTER, presumably to reflect its universality of application. It is our policy not to judge the spelling of customers. The fact is we are very proud to have our apparatus chosen for this ambitious and forward-looking installation. While we naturally have heard of some of the computing applications, we cannot describe them here without impropriety. We can say that the machine is in use on a full schedule and that some of the problems being solved are those formerly submitted to the digital facilities at Hercules. For problems of the latter type, the analog equipment permits the user more intimate contact for changes in solution conditions — changes which could not have been foretold before solution was attempted. This points up the superiority in general of analog methods for exploratory studies.

The following individuals among others, at Hercules, have contributed to making successful the installation and its subsequent applications: Messrs. D. J. Cholley, F. M. Wanlass, K. S. Cook, and L. Godfrey. We want especially to thank Mr. David J. Cholley, Analog Analyst at Hercules, with whom we have had the closest contact. His courage and faith supported our efforts in more ways than we like to admit. It is hard to see how the project would have turned out so well without him. This is how he looks when not displeased. He prepared for his present activities at Mount Union College, Alliance, Ohio, taking the degree of Bachelor of Science.

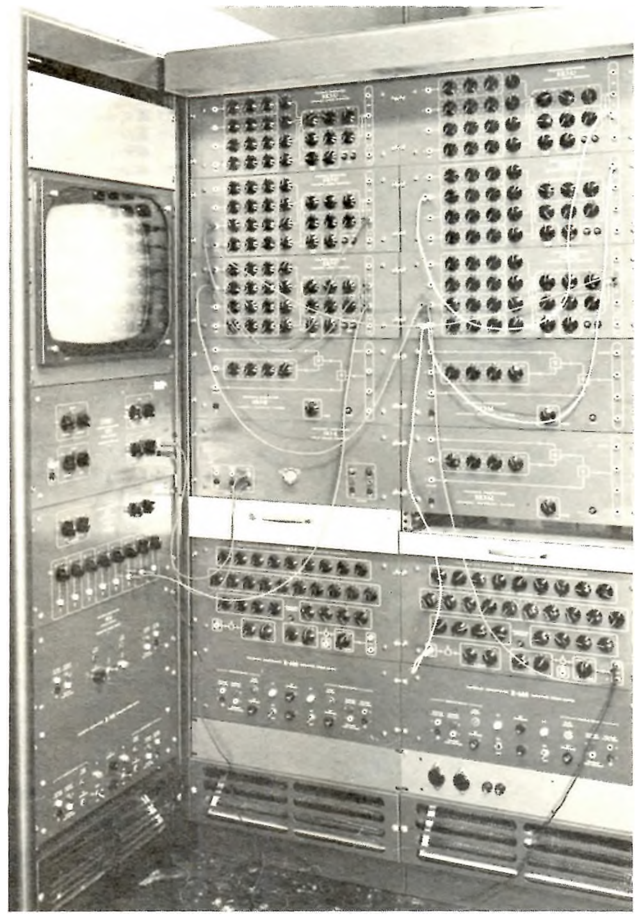
Incidentally, we have reprinted, and have available for interested readers, a pamphlet written by Mr. Cholley in connection with this installation, having the title "A Particular Application of FM Tape Used With An Analog Computor."

Complement of Philbrick Equipment in Hercules Installation as Shown in Photographs

48 Model SK5-U Universal Linear Operators
16 Model SK5-M Multiplier-Dividers
5 Model SK5-F Arbitrary Function Generators
3 Model SK5-R Relay Control Components
1 Model 6009 Operational Manifold
9 Model R-600 Regulated Power Supplies
3 Model R-500 Regulated Power Supplies
1 CS2 Central Signal Component
1 CRM Central Response Component
1 5934 Multi-Channel Calibrated Display System
1 Camera Accessory for Display System

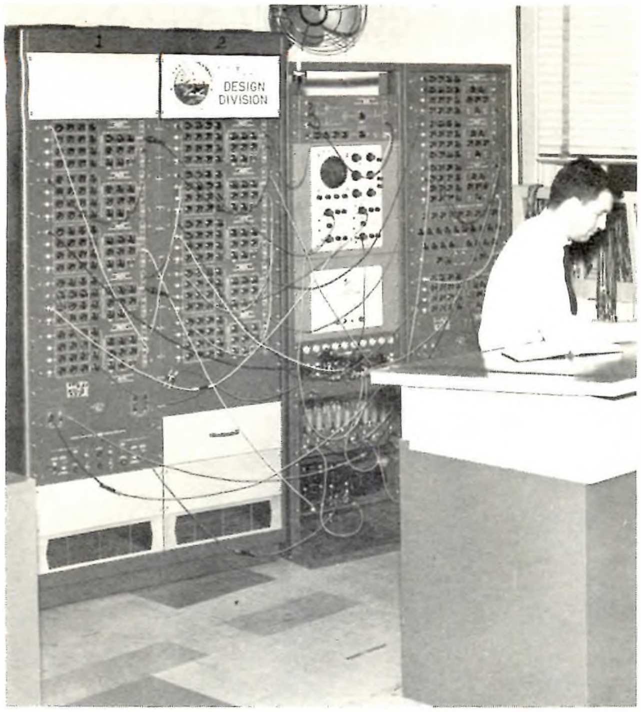
Selected Additional Installations

Since this issue is principally devoted to the nature and applicability of the SK5 modules concept, there is included below a group of photographs and brief descriptions which cover representative computing facilities in which the SK5 devices are given central roles.



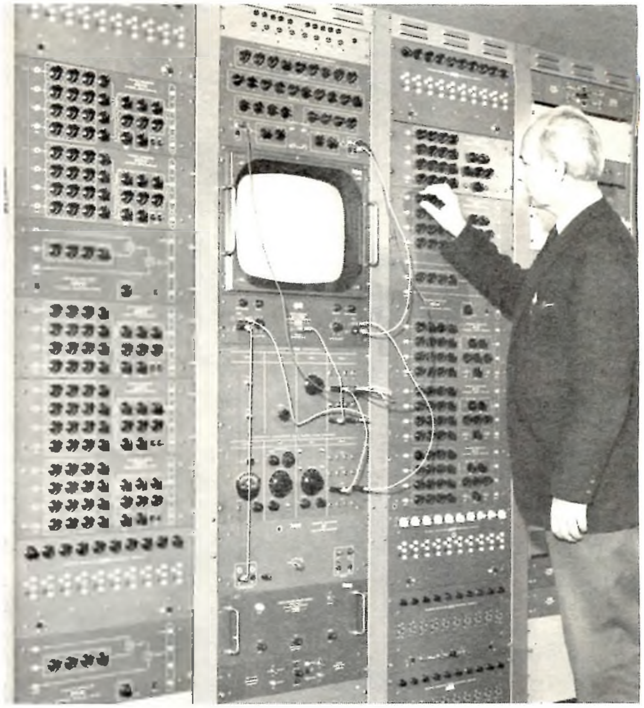
The new installation in the Physiology Department of Western Reserve University Medical School in Cleveland is to be used for various research problems principally in the field of endocrinology. The computor will model transient diffusion, mixing, and reaction kinetic phenomena to help determine the mechanisms involved in the biosynthesis of hormones. In charge of the computor is Dr. Thomas Hoshiko, Assistant Professor, whose research is concerned with ion transport through membranes. Others concerned with the computor include Dr. George Sayers, Head of the Department of Physiology; Dr. Howard Sachs, whose research concerns the biosynthesis of Basopressin; Mr. Gerald Lower, Electronics Technician; and Mr. Barry Lindley, Graduate Student.

The system shown consists of six SK5-U's, three SK5-M's, two SK5-F's, and a 5934 Calibrated Display.



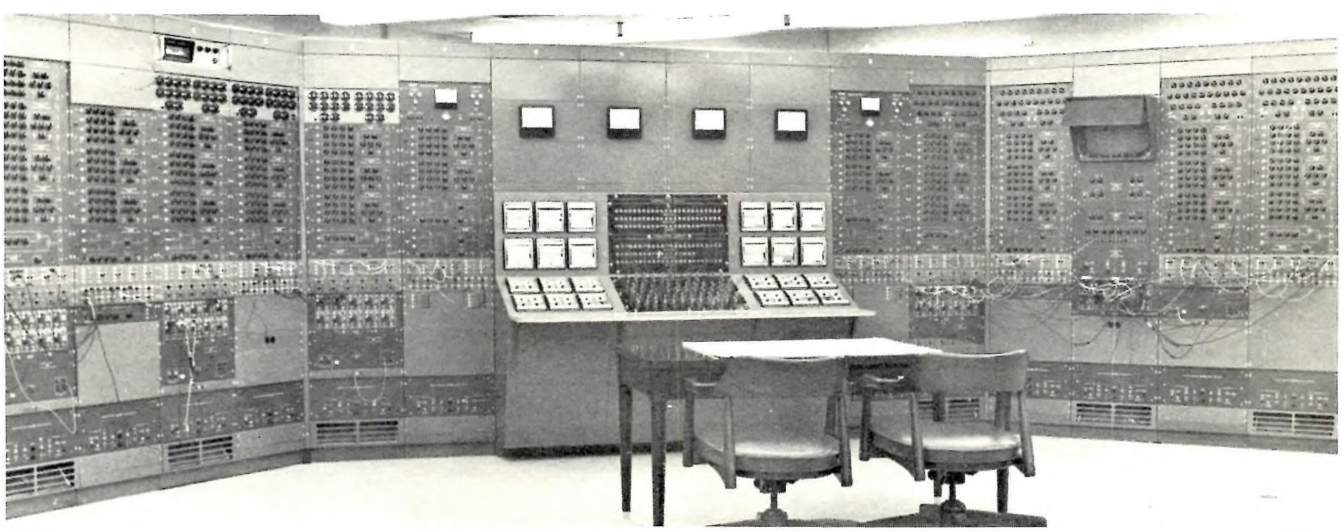
The SK5 Computor at the Portsmouth Naval Shipyard, New Hampshire, is in the Computing Branch of the Design Division which is in the Planning Department under the guidance of Richard Wade, the Supervisory Engineer, and Robert Perkins, the Electronic Engineer.

This facility is made available to all engineers and scientists connected with the yard on an "open shop" basis. Typical problems solved include torpedo firing, mechanical shock, emergency surfacing & emergency flooding of submarines, vibration and design of dash-pots.



Dr. Heinz W. Kasemir, shown in photo above, is the scientist in charge of the U. S. Army Electronics Research and Development Laboratory, Fort Monmouth, New Jersey, Oakhurst Field Station.

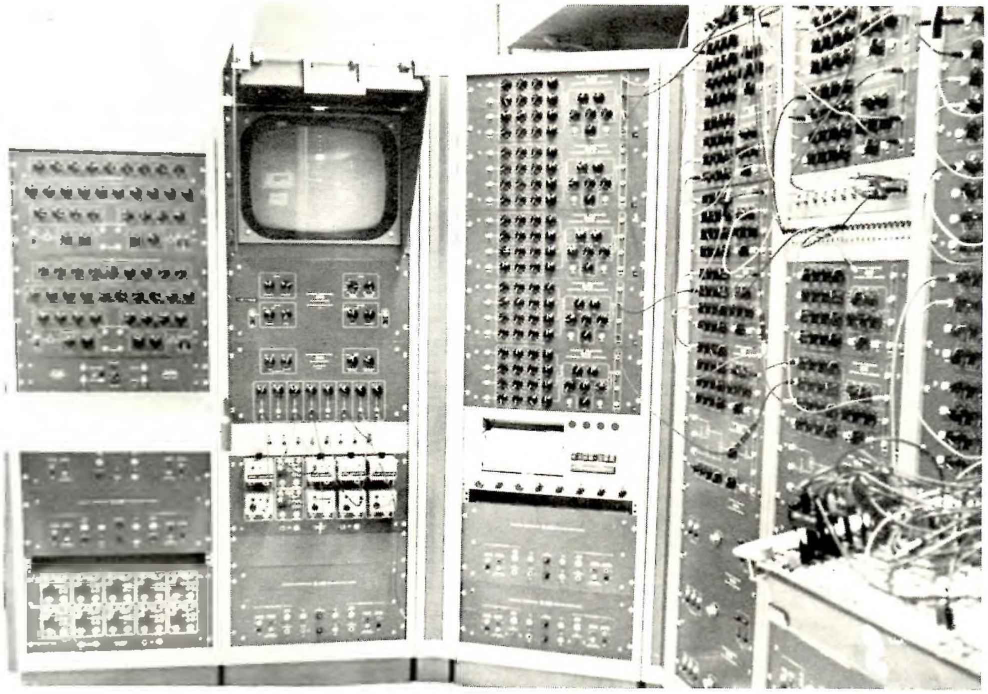
This installation is used for such typical purposes as solving complex differential equations bearing on problems of atmospheric electricity, and in the development of sophisticated electronic systems for making frequency analyses of the speed of lightning strokes and altitudinal variations of air-earth electrical currents.



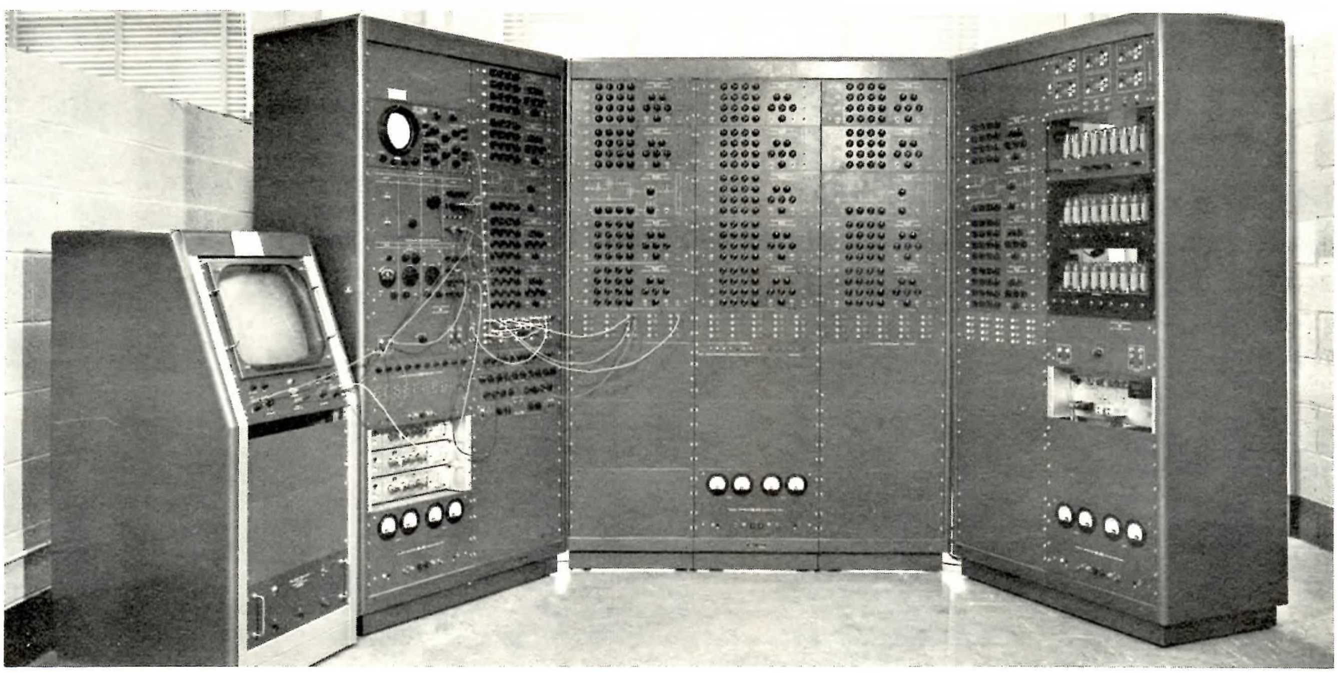
The Dow Chemical Company installation at the Process Control Laboratory, Freeport, Texas, is used for the study of process control systems. Engineered by the Project Engineering Department of The Foxboro Company, it consists of K5-U computing modules and twenty-four Foxboro electronic controllers and pen recorders.

The Texas Division of Dow Chemical Company had spent two years developing analog techniques, and procured this computor built to fill their needs. The processes are modeled with the K5 computor and controlled with hardware similar to that used in actual processes. This enables the engineer or process man to test and evaluate the design of a plant before it is built and to train operating personnel.

This controller/simulator is under the supervision of Porter Hart, Director of the Process Control Laboratories, and Bernard Poettker, Senior Research Physicist. The K5 portion of this installation consists of 32 K5-U's, 13 K5-M's, 5 K7-A10's, 5 RC's, 4 FF's, and a 5934 Display System.

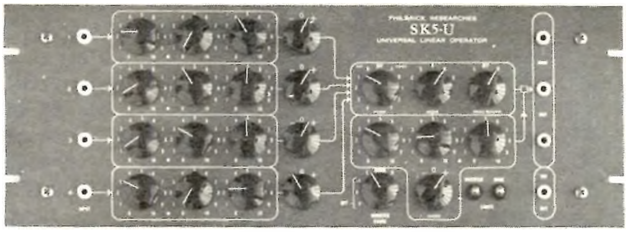


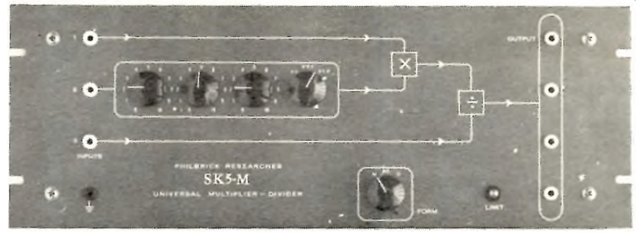
Shown at the left is an installation at the Latter Day Saints Hospital in Salt Lake City which is used for the reduction of biological data and the simulation of biological systems. Dr. Homer Warner, who is in charge of this area has developed many novel techniques for solving physiological problems. His plans for the future include coupling the K5 computor to a digital system in order to perform convolution and correlation. He is ably assisted by Sanford Topham and Wayne Wiscomb. Included are 19 K5-U's, 5 K5-M's, 3 RC's, 2 K7-A10's, 3 FF's, and a 5934 Display System & Camera.



The Analog Computing Facility at the Massachusetts Institute of Technology is located in the Engineering Projects Laboratory. Conceived and promoted into tangible form by Professor Henry M. Paynter of the Mechanical Engineering Department,* it may be used by staff and students of all departments. It is available on an open-shop basis and is in active use on a twenty-four hour, seven-day-a-week schedule. Because it is modular in assembly, the computor has been used successfully during peak load periods, even in the midst of the bi-weekly, three-hour period reserved for maintenance and calibration. Since the computor was installed in 1958, none of the equipment has been out of service for more than a day. The installation includes 20 K5-U's, 4 K5-M's, 2 RC's, and a 5934 Display System (which does not appear in this photo), as well as some earlier manifolds, utility packaged amplifiers, and regulated power supplies.

*A long and fruitful cooperative relationship has existed between this Company and the above-named Department of MIT, particularly through association with Doctor Paynter himself. His inspiration and acknowledged mastery of engineering analysis have supported our convictions on the power of models.





MODEL SK5-U UNIVERSAL LINEAR OPERATOR

The SK5-U is the basic module of an SK5 assemblage, providing capability to compute a linear combination of four input variables, or alternatively the time integral of such a combination. All parametric and internal functional changes are made with multiposition switches which provide both convenience and flexibility. Direct mathematical programming eliminates much of the confusion and drudgery associated with conventional analog computing.

The SK5-U applies an independent arbitrary coefficient (of either sign) to each of four input variables. The coefficients are repeatably and rapidly set with decade switched conductive networks (rather than potentiometers) to three significant figures with less than 0.2% error. Their values range from −10.00 to +10.00 in steps of 0.01.

The output may be the sum of these weighted variables multiplied by ten raised to an arbitrary power (—1, 0, 1, or 2) and added to an adjustable arbitrary three-digit index. Alternatively, the output may be selected to be the time integral of the weighted sum multipled by an arbitrary power of ten (0, 1, 2, 3, or 4) starting from an initial condition determined by the three-digit index. Set, hold, run logic can be manually or automatically controlled independently of or in synchrony with other integrators.

The availability of five integration rates independently selectable for each SK5-U enables systems consisting of both slow and fast sub-systems to be conveniently modelled. Most problems may be solved repetitively at a rapid rate convenient for optimizing parameters with an oscilloscopic display, or singly at a conveniently slow rate for electro-mechanical input or output devices.

The SK5-U output is non-linearly constrained to remain between precisely fixed upper and lower bounds. These bounds, in addition to providing protection against chopper stabilized amplifier saturation, may be used to achieve a variety of elementary non-linear operations such as absolute value, arbitrary bounds, dead zone, hysteresis, and crossing detection.

The SK5-U has two chopper stabilized amplifiers. Normally, one is used as an inverter to achieve the coefficient sign option. However, these amplifiers may also be used independently, thus increasing the computing capability of a single SK5-U with the sacrifice of arbitrary sign for the coefficients. This feature is of arbitrary sign for the coefficients.

MODEL SK5-M UNIVERSAL MULTIPLIER-DIVIDER

The SK5-M is an analog multiplier-divider of superior performance and reliability, designed for use in computing, controlling, and measuring applications. The output is proportional to the product of two input variables divided by a third. The constant of proportionality is switch selected in the ranges 0.100 to 1.000 in steps of 0.001 or 1.00 to 10.00 in steps of 0.01.

A mode switch automatically applies 100 volts to the denominator input, in the Multiply mode, or 100 volts to one of the numerator inputs, in the Divide mode, if one does not require simultaneous multiplication and division. Square rooting of a numerator input is accomplished by feeding back the output into the denominator input using the Divide mode.

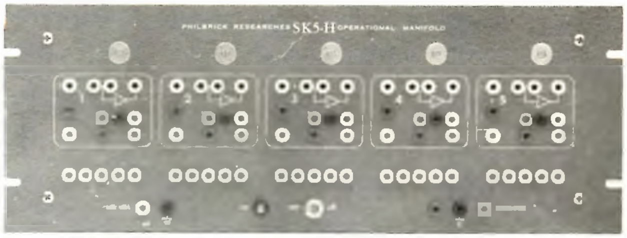
As is the case of all SK5 modules, the SK5-M has nominal output range of ±100 volts. The output is bounded at ±110 volts to prevent saturation of the chopper stabilized amplifiers employed in the circuit, thus assuring virtually instantaneous recovery from any output over-voltage condition such as might result from a small denominator input.

The numerator input variables may be either positive or negative; but should the denominator input be negative, the SK5-M output will bound at ±110 volts.

The SK5-M employs a triangular wave method for multiplication similar to that employed in the K5-M and MU/DV Multipliers. An inherent property of this method is the reduction of error as one or both of the numerator terms approaches zero. The SK5-M static accuracy is comparable with that of a good servo-multiplier (less than 100 millivolts including eight hour drift) yet the SK5-M has a bandwidth comparable to many quarter-square multipliers.

The SK5-M may be used to measure directly the mean square value of a signal having frequency components as high as 3 kcps with no apparent dynamic error. This may be accomplished by inserting a suitable capacitor in parallel with the feedback resistor of the output amplifier using jacks provided on the rear panel.

As in the case of the Model SK5-U module, the inputs and output are available on a rear panel connector as well as on front panel jacks, thus facilitating either direct front panel patching or remote patching or switching.



MODEL SK5-H OPERATIONAL MANIFOLD

The SK5-H Operational Manifold contains five high gain, wide band dc chopper stabilized and boosted operational amplifiers each capable of driving a 10 K load from -100 to $+100$ volts. For each amplifier, there are input and output terminals as well as servicing signals made available on conveniently spaced front panel jacks. As is the case in all SK5 computor modules, these terminals and signals are available on rear panel connectors as well. This arrangement facilitates either direct front panel patching or remote patching and switching.

Individual boxes (Model U2), which plug into these front panel jacks, are available in both committed and uncommitted forms. The committed U2 boxes provide standard analog operations such as:

- Addition
- Multiplication by an Arbitrary Coefficient
- Differentiation
- Function Generation
- Integration
- Selection
- Bounding

These enhance the capabilities of an SK5 computor by providing, at low cost, operations which cannot be performed by an SK5-U, M, or F, or which do not make efficient use of the capabilities of these modules.

The uncommitted U2 boxes enable convenient assembly of special operational networks which involve a single amplifier. The use of these boxes is beneficial in any application where hum and noise must be small because the aluminum case properly grounded provides shielding against ambient electrostatic and electromagnetic fields.

The SK2 amplifiers in SK5-H are particularly well suited for critical applications. The dc open loop gain of these amplifiers is greater than 10^9 while noise, offset, and leakage are typically no more than $100\mu v$, $30\mu v$, and 10^{-10} amps. respectively. Outputs are bounded at about ± 105 volts (passively) to prevent saturation of the chopper stabilized amplifiers, thus assuring virtually instant recovery from any output over voltage. Under usual circumstances, the amplifiers can drive large capacitive loads. For instance, when the load resistance to ground is 100 K or greater, a load capacitance as large as $1000\mu\mu F$ can be driven at the maximum amplifier rate, ± 6 volts/μsec., without special stabilization.

Premium quality components are used throughout to achieve high reliability consistent with many on-line control and critical measurement applications. Furthermore, as with the other SK5 modules, the SK5-H has an individual induced draft fan of capacity adequate to maintain the chassis and panel at almost ambient temperature.

MODEL SK5-F ARBITRARY FUNCTION COMPONENT

The SK5-F performs an arbitrary static non-linear operation on a single input variable. In addition to having non-interacting break-point and slope adjustments, the SK5-F provides adjustable parabolic smoothing at each break point, thus approximating the desired function with a sequence of linear and tangent parabolic segments. Many smooth functions may be approximated using the SK5-F with an error not exceeding 0.2% of full scale at any point along the function.

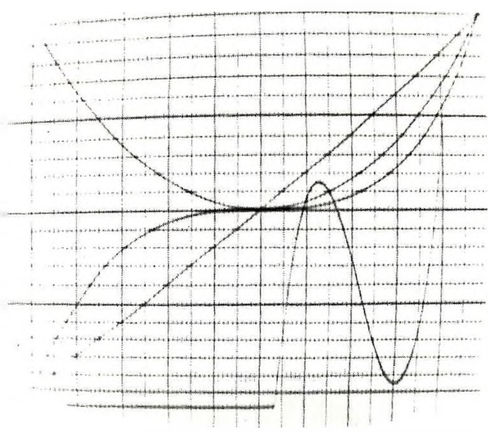
Although the SK5-F resembles its predecessor, the FF, many notable improvements have been made. Slope increments as large as ± 10 may be adjusted accurately without interaction with previous adjustments. The chopper stabilized amplifiers have limit protection so that they cannot saturate during the function programming. Bandwidth is independent of the function programmed (3db at 2 kcps), except that it may be nearly doubled if the maximum slope increment can be limited to ± 5 by feeding back the output to the null input. Also the null input may be used to program functions on the SK5-F which may be available as voltage functions of time.

Premium SK2 series amplifiers and high quality components are used in each critical location to achieve good reliability and repeatability. Furthermore, the module is cooled with an induced draft fan of sufficient capacity to prevent significant temperature gradients.

Inputs and outputs are available on front panel jacks and on a rear panel connector so that either local front panel patching or remote switching or patching may be employed.

Typical of the U2 plug-in components used with the SK5-H Operational Manifold (at left) is the U2-A Adder shown here.

The available operators are enumerated in the SK5-H section; or the user may build his own specials in uncommitted cases of this type, which are available in kit form and require only the simplest mechanical modification. This can be done in any laboratory or model shop.



Candid Shot of our Celebrated Graph Paper

The 5934 Multichannel Calibrated Display System is a convenient monitor for such instrumentalities as an analog computor, providing an accurate readout for repetitive or triggered behaviour. Up to eight variable voltages may be plotted simultaneously in correct phase and voltage relationship against a highly accurate coordinate system. The 5934-0 Display System Camera provides a 4 x 5 photographic record similar to the one reproduced. This reproduction is a negative, the customary photograph having white lines on a black field.

The coordinate grid consists of 21 horizontal lines at 10 volt increments from −100 to +100 volts and 101 vertical lines at 1% intervals of the selected display period. Each coordinate and signal voltage is sampled every 62.5 microseconds. A vertical flying scan system displays these samples on a large cathode ray tube. Periodically, an entire vertical scan is brightened to provide the time calibration lines. Since the grid and signals are displayed simultaneously and by the same electron beam, drift, distortion, phase, and parallax errors are eliminated. The resulting accuracy of the coordinate grid relative to the signals permits voltage and time to be read with an accuracy comparable to that of the best recorders, at speeds useful for instant evaluation of repetitive analog solutions.

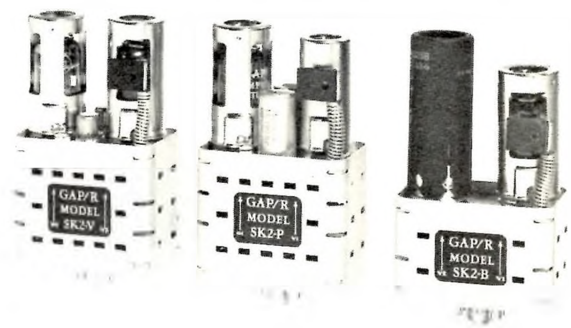
The 5934 produces an output signal which may be used to synchronize the computor to the repetitive display period. Alternatively, the start of the 5934 display period may be triggered periodically or aperiodically with an external signal enabling the display interval to be synchronized with an input device such as a tape recorder.

Although the usual application of the 5934 involves the plotting of computor variables vs. time, the cross plot mode permits up to seven input variables and the voltage calibration to be plotted simultaneously against the eighth. This is useful in making frequency response measurements and in phase plane analyses.

The figure above demonstrates the rather unusual use of the 5934 to present the solution of an algebraic cubic equation. The independent variable is swept from its minimum to maximum value as ramp function of time. The ramp is generated by integrating a constant. Integrating again yields the square of independent variable and a third integration yields the cube. By weighting and summing these functions and adding a constant in an SK5-U, the desired cubic equation is programmed such that when the SK5-U output is zero, the cubic equation is satisfied.

HIGH-PERFORMANCE AMPLIFIERS

The SK2 Series of octal plug-ins used together form an amplifier with outstanding characteristics for commercial applications. Their superior performance led to their utilization in the SK5 computing modules.



Model SK2-V Differential Operational Amplifier is an octal plug-in designed for computing, controlling, and instrumentation. All SK2 amplifiers, have an all-metal case and plug and feature our prize-winning exoskeleton construction. The SK2-V has ±100 volts output at ±3.0 ma, although much higher voltages are possible.

Low drift, low input error, and unusually high gain enable the SK2-V to perform very accurate computing operations. High speed computing is possible too for the open-loop gain, greater than 100,000 at dc, reaches unity at about 1.0 mcps.

Model SK2-B Booster Amplifier, also an octal plug-in, was designed especially for use with Philbrick operational amplifiers (such as SK2-V, K2-XA, and K2-W).

SK2-B follows an SK2-V where output currents greater than 3 ma are required, the SK2-B being used to drive the load, allowing the SK2-V to run essentially unloaded. This combination will drive loads up to ±20 ma at ±100 volts and will maintain the high performance of the SK2-V.

Model SK2-P Stabilizing Amplifier is an octal plug-in chopper amplifier specifically designed to stabilize operational amplifiers such as the SK2-V. The drift rate of the SK2-V, under optimum conditions, is typically about 5 mv per day, but can be many times greater (perhaps 25 or 50 mv) if proper precautions are not observed. When combined with the SK2-P, these drift rates can be reduced to a level usually below 100 microvolts per day. Dependability has been stressed as the major objective in the design of the SK2 series amplifiers. Dissipation has been kept so low that even without any heat sink the case is only reasonably warm.

THE LIGHTNING EMPIRICIST

Beginning with this issue, THE LIGHTNING EMPIRICIST will be published at quarterly intervals by Philbrick Researches, Inc., at 127 Clarendon Street, Boston 16, Massachusetts. This Journal began in June, 1952, and has appeared "aperiodically," in its earlier format, seven times since then. The staff of Philbrick Researches will serve in the various editorial and production capacities as needed. Comments and contributions will be welcome and should be addressed to Editor, LIGHTNING EMPIRICIST.

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