UNIVERSITY OF ILLINOIS
GRADUATE COLLEGE
DIGITAL COMPUTER LABORATORY

TECHNICAL PROGRESS REPORT

Teaching and graduate research are
not, in general, reported herein.

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GENERAL LABORATORY INFORMATION

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PART I

STUDY PROGRAM ON HIGH-SPEED COMPUTER

This work is supported in part through Contract No. AT(11-1)-415 of the Atomic Energy Commission. The contract is supported jointly by the Atomic Energy Commission and the Office of Naval Research. In addition, this work is supported through Contracts N6ori-07130 and Nonr-1834(15), both from the Office of Naval Research.

The University of Toronto is participating in this work through staff members of its Computation Centre.

1. Basic Circuits

Using a slightly modified version of the standard Eccles-Jordan with GF-45011 transistors, a counter was designed which uses steering diodes to go into the collectors. The purpose of this was to obtain an independent estimate of the operation time of such a flipflop, the usual estimate being based on a racing register. It turned out that with speed-up capacitors and series-peaking in the driver preamplifier, frequencies of the order of 40 mc could be processed.

40 Megacycle Counter Stage

The above counter was duplicated to form a scale of four frequency divider to be used in synchronizing an oscilloscope with a low duty-cycle triggering device from racing registers.

A more elaborate synchronizing device for the 517 scope was also designed. The 21-transistor circuit (containing some simple logic and two Schmidt-Trigger flipflops) synchronizes the scope with selected cycles of a high repetition rate signal (from a racing register) whenever a low-frequency control signal comes along. Some dc-level problems were encountered and fixed and the unit provided good practice in assembling the basic circuits. The dc-level problem incidentally led to the re-examination of our last-moving-point design procedures which may have to be modified to take care of input signals which vary very slowly.

The building blocks shown in Chapter IV of Report 80 were modified as announced in the report for October. The new designs have the circuit values given in the following figures. Note that for these circuits

- all transistors are WE GF-45011;
- all diodes in collectors are NU T37D;
- all other diodes are NU T37J;
- all resistor tolerances are $\pm 2\%$;
- all supply voltage tolerances are $\pm 3\%$.

It should be remarked that the National Union diodes may be replaced by Qutronics Q5-250 ($\rightarrow$ T37J) and Q10-600 ($\rightarrow$ T37D).

The circuits shown on page 3 use bumping diodes in the collector to prevent saturation and diodes in the emitter and base leads to limit the reverse bias between emitter and base of the transistors. The nominal swing is $\pm 1.6\text{v}$. The bumping voltages take account of the (average) emitter-base forward drop of 0.4v .

The flow-gating circuit (see October Technical Progress Report) was further analyzed and the general case ($\alpha \neq 1$, variable emitter-base forward drop) was calculated. The set of fundamental circuit inequalities $A > B > C \dots$ etc., where $A(\dots p_i \dots)$, p_i being a general parameter (resistance value, α etc.) was transformed into a linear system by a Taylor Expansion and the linear system was solved by a relaxation method. This method gave the basic solutions to be tested by an analytical program. This analytical program is now in the early stages of preparation.

30 Millimicrosecond Eccles-Jordan Flipflop with Gates
($g = +1.2v \rightarrow$ gate, $g = -2v \rightarrow$ non-gate)

15 Millimicrosecond NOT Circuit

5 Millimicrosecond AND and OR Circuits (Positive Logic)

2. Core Memory

Work was begun on a core memory read amplifier: A prototype was built and tested and appears to be satisfactory if the strobe pulse from the memory is short enough. Changes will be made as more specific memory characteristics become available.

A transistorized pulser capable of driving 50 μ f through 50 volts with a rise-time of less than 100 μ s was designed. Effects of transistor tolerance variations were investigated. The pulser would, when used with one stage of high current vacuum tubes, be suitable for a current driver.

3. Arithmetic Unit

A class of division methods, believed to be new, was devised during the month. For arbitrary radix r , the division methods are such that each quotient digit is one of the integers $-n, -(n-1), \dots, -1, 0, 1, 2, \dots, n$ where n satisfies $\frac{r-1}{2} \leq n \leq r-1$. The method can be contrasted with conventional non-restoring division, for which each quotient digit is one of the integers $-(r-1), \dots, -1, 1, 2, \dots, r-1$, with 0 excluded.

For the new computer, the choice $n = 2, r = 4$, leads to a new base 4 division method which is in some sense the inverse of the multiplication method described in Chapter VIII of Report 80. The base 4 division method shares the conditional complementing-doubling circuits with the multiplication, and does not require the tripling of the divisor to full precision. Circuits to compare on the order of 8 binary digits of partial remainders with $1/2 y$ and $3/2 y$ are required, where y is the standardized divisor.

4. Control Studies

The portion of Monte Crysto I which computes the change in energy of the system when a pair of atoms are interchanged has been recoded for the new computer. This portion of the Monte Crysto I program is the major part of the main loop of the program. Estimating the time to execute other portions of the main loop, assuming that they too were recoded for the new computer, it was found that one pass through a 4000-atom lattice would take about 2.4 seconds on

the new computer[#] compared with 60 seconds for the same calculation on the IBM 704; i.e. the program would run about 25 times faster on the new computer. Estimates were made conservatively so the ratio 25 should represent a lower bound. It was found that the running time of the program was controlled by the memory access time. There was virtually no overlap in the operation of the arithmetic control and memory access. It was also found that there was very little opportunity to effectively use the short loop feature. The loops generally required more than the 8 control groups allowed in the short loop.

In writing this program it would have been convenient to have had available the instructions: $b' = 0$ (short); $b' = b + m$ (long); $a' = a$ and m (long or short). The latter instruction is convenient because it is frequently desired to test the result of an AND instruction for zero.

During this period a fairly simple-minded criterion for answering in an approximate way the question of whether the memory access time or the arithmetic operation time governs the overall operation time of a sequence of instructions was applied to the data presented in File No. 224 "A Study of the Order Types and References to Store in some Illiac and Ferut Library Routines" by J. H. Chung, C. C. Gotlieb and D. E. Muller. We define a unit arithmetic operation as a hypothetical operation requiring for its execution a time equal to an addition time. Thus, in terms of execution time a multiply instruction is equivalent to ten unit arithmetic operations in the new computer; a shift of one place is equivalent to $1/4$ of a unit arithmetic operation time (shift time $\approx .08 \mu s$ in the new computer). We define, for a sequence of instructions,

n_1 = average number of data requests per unit arithmetic operation,

n_2 = average number of data writes per unit arithmetic operation,

n_3 = average number of instructions obeyed per unit arithmetic operation,

p_1 = number of words of data read per memory access,

[#] The number of divide instructions is negligible. For the other operations the following times were assumed: multiply, $3.5 \mu s$; all instructions exclusive of multiply and divide, $.35 \mu s$; memory access time, $1.5 \mu s$.

p_2 = number of words of data written per memory access,

p_3 = number of instructions read per memory access for instructions,

λ = ratio of memory access time to unit operation time,

$$s = \lambda \left(\frac{n_1}{p_1} + \frac{n_2}{p_2} + \frac{n_3}{p_3} \right).$$

If the execution time for the sequence of instructions is to be governed by the arithmetic speed rather than the memory access time then

$$s < 1.$$

This is just a way of expressing the condition that the average memory access time must be less than the average arithmetic operation time. It is assumed in the above that there exists a "very" high-speed auxiliary storage with capacity sufficiently large to hold words read in blocks, as determined by the p's, from the conventional memory.

The quantities n_1 , n_2 , n_3 have been computed from the data of File No. 224 (Table 1a) and are shown in the table below. Using $p_1 = p_2 = 1$, $p_3 = 3$ and $\lambda = 5$, assuming them to be representative for the new computer, the quantity s has been computed and is also shown.

	n_1	n_2	n_3	s
Runge-Kutta (50 steps on J_0)	0.351	0.224	0.660	3.98
Polynomial Root (12 roots)	0.281	0.193	0.692	3.52
DOI	0.384	0.212	0.851	4.40
L-2 (12 equations without input)	0.280	0.175	0.550	3.19
Eigenvalue (without input)	0.283	0.145	0.523	3.01
Circuit Analyzer	0.478	0.261	1.02	5.40

These statistics have also been obtained for an analysis of variance program used by the Agronomy Department.

	n_1	n_2	n_3	s
Analysis of Variance	0.824	0.104	0.380	5.27

In every case $s > 1^{\#}$, thus indicating that the execution time is controlled by the memory access time. This analysis neglects the advantage to be gained from using the two fast access registers in the new computer for temporary storage. Proper account of this would reduce n_1 , probably not by more than $1/2$. However, it is obvious from the above statistics that such a reduction in n_1 will not give $s < 1$ - even with $n_1 = 0$, s is > 1 in every case. This analysis also neglects the advantage to be gained from using short loops with the control groups in O_1 and O_2 . Proper account of this would reduce n_3 . It is unlikely that the reduction would amount to as much as $1/2$ but even assuming this favorable estimate, and reducing n_1 by $1/2$ we still obtain $s > 1$ in every case. It should be recognized that this problem is not obviated by advanced control alone. What is necessary is a decrease in λ or an increase in the values of the p 's, or both in appropriate combination.

Assuming that λ is as small as possible let us see how large the p 's must be to satisfy $s < 1$. Take $p_1 = 6$, $p_2 = 6$, $p_3 = 12$, then we note that in the worst case, the circuit analyzer, this is just sufficient to make $s \approx 1$ taking n_1 , n_2 and n_3 directly as given above. If we reduce n_1 , n_2 and n_3 each by $1/2$, then $p_1 = 3$, $p_2 = 3$, $p_3 = 6$ give $s \approx 1$. These two sets of values represent upper and lower limits on the p 's. If we compromise on $p_1 = 4$, $p_2 = 4$, $p_3 = 8$ we require a 4 word block read and write for data and an 8 word transfer for instructions. This is just the proposal in the appendix to Chapter 3 of Report 80. The above arguments seem to favor strongly such a scheme over the one proposed in the main body of Chapter 3.

[#] Note that the "Data Analysis" programs have the largest s .

PART II

MATHEMATICAL METHODS

1. Iterative Methods for Solving Systems of Linear Equations (Supported in part by the Office of Naval Research under Contract N6ori-07130.)

It has been shown by von Neumann that a class of iterative methods for solving the system of linear equations

$$Ax = y$$

may be described by the equations

$$x_{i+1} = Gx_i + Hy$$

where the matrices G , H and A are related by the equation

$$G + HA = I,$$

and H is a non-singular matrix. It then follows that

$$x_{i+1} - x = G(x_i - x)$$

$$x_{i+1} - x_i = G(x_i - x_{i-1})$$

$$H(y - Ax_{i+1}) = GH(y - Ax_i).$$

The averaging of a collection of iterates has also been considered by von Neumann.

A program has been initiated to study by numerical and analytic means the effect of making various choices for the coefficients of the matrix H given above in terms of the coefficients of the given matrix A . Once H is determined G is known. The criteria for choosing H are (1) that the computing algorithm be simple, and (2) that the convergence, as measured by the behavior of the norm of residuals (the difference of successive iterates or the difference between an iterate and the true solution) be as rapid as possible. In view of the relations given above this implies that the proper values of the matrix G be kept as small as possible in absolute value.

The study includes considering the question as to whether an averaging of a number of iterates leads to closer approximations to the solutions.

2. Minimization of Functions of Several Variables

1. In connection with the problem of reducing interferometer data from earth satellites, a new and very promising method of minimizing a function of n variables has been found. If F is the function, with suitable continuity and differentiability conditions, then the extrema in the interior of the region of definition are those points $\{ \underline{x} \}$ for which $\frac{\partial F}{\partial x_i} = 0$, $i = 1, 2, \dots, n$. Such extrema can be minima, maxima or saddle points. If the point $\underline{a}$ is sufficiently close to a minimum, the system of equations

$$\frac{\partial F}{\partial a_i} + \frac{1}{2!} \sum_j h_j \frac{\partial^2 F}{\partial a_i \partial a_j} = 0$$

can be solved for $\underline{h}$, provided $\left\| \frac{\partial^2 F}{\partial a_i \partial a_j} \right\|$ is not singular, and $\underline{a} + \underline{h}$ is a better approximation to the minimum. This is the Newton-Raphson method in n -dimensions, and requires estimates of the first and second derivatives, obtained, in general, from numerical differentiation.

The method actually used consists of estimating the above partial derivatives by central difference methods, and using the above equations to obtain numbers proportional to $\{ h_i \}$, and then performing a walk in that direction (positive or negative) in which F decreases. When the function fails to decrease, quadratic interpolation is used to obtain the minimum in that direction. Partial derivatives are then re-evaluated and the process repeated.

If all partial derivatives are $O(1)^{\#}$ and the round-off error in calculating F is $O(2^{-39})$, then the step interval for computing first derivatives is $O(2^{-13})$ and the error in estimating first derivatives is $O(2^{-26})$, whereas the optimum step interval for calculating second derivatives is $O(2^{-20})$. By making the process repetitive, the absolute error in the location of the minimum is $O(2^{-26})$.

The effect of introducing the walk is first of all to carry the operating point away from a maximum or saddle point if it happened to be near one; and secondly to make the distance travelled not depend on an extrapolation from local information. As the operating point approaches the minimum, and the second partial derivatives approach their limiting values, the method resembles the iterative

[#]₀ = "of the order of"

solution to a set of linear equations for which an extrapolation factor is calculated in such a way that the next walk will be in a direction orthogonal to this one. Finally, as the operating point gets very near the true minimum, the extrapolation factor tends to 1 (no extrapolation).

The accuracy of the method depends only on how accurately the first derivative can be estimated by finite difference methods. If unknown derivatives are assumed to be $O(1)$ then the following table applies:

Formula for first derivative	Optimum step interval h	Absolute error
2 point	$\approx 2^{-13}$	$\approx 2^{-26}$
4 point	$\approx 2^{-9}$	$\approx 2^{-31}$

For the 4 point formula, points should be chosen at $x_i \pm h$ and $x_i \pm \frac{1}{2}(3 + \sqrt{5})h$. However, numerical differentiation of unknown functions is a very risky business, especially with large step intervals. One advantage of the method described is that it does not depend, for its accuracy, on a very accurate estimate of second derivatives.

2. A method applicable to evaluating determinants, solving linear algebraic equations, inverting matrices, and determining characteristic equations without round-off error, is being tested. The problem is first scaled so every coefficient is an integer. Then integer multiples of one row are subtracted from another in systematic fashion. This will be described for triangularizing the matrix $\|a_{ij}\|$. The elements of the first column $\{a_{i1}\}$ are first ordered in absolute value. Suppose a_{i1} is the largest and a_{j1} is the second largest. If k is the integer for which $k|a_{j1}| \leq |a_{i1}| < (k+1)|a_{j1}|$ then a multiple $+k$ of the j^{th} row is added to the i^{th} row. This decreases the absolute value of the leading coefficient of the i^{th} row to less than $|a_{j1}|$, and it remains an integer. This process is repeated until all but one of the leading coefficients of the rows are zero, the remaining one being the highest common factor of the original leading coefficients. The process is then repeated on the second column of all rows except that which ended with a non-zero leading coefficient in the first row. Continuing in this way, the matrix is eventually triangularized. The calculation requires multiple precision integer arithmetic,

however numbers do not grow as fast as might be expected. The total number of single-length additions required to triangularize an $n \times n$ matrix appears, experimentally, to be less than

$$n^3 \sqrt{n} \frac{d}{2}$$

when d is the average number of decimal digits in the original coefficients.

PART III
GENERAL RESEARCH

Satellite Data Reduction

An attempt is being made to analyze the radio interferometer data taken from the Russian satellites. These programs are also being prepared so that observations on forthcoming U. S. satellites can also be treated. An expected theoretical antenna pattern can be determined as a function of the distance, height, time and orbit inclination of the satellite at closest approach to the observing station. This is then compared to the observed antenna pattern and the weighted discrepancies minimized as a function of the four variables.

It is hoped that information on the refracting properties of the ionosphere can be extracted from these discrepancies. Several working programs have been produced.

The program discussed above exploits the very powerful technique of problem-solving by numerical minimization of an appropriately defined function with respect to its variables. This laboratory has used a series of routines (H-3, H-4, H-5, H-6) for this purpose which predominantly make use of gradient methods. The efficient minimization of a general function is a difficult task which can frustrate practically any method. Experience with the problem substantiate this. It is therefore felt that more efficient methods of function minimization should be investigated. This is especially true in the light of the new computer since more complicated functions of a greater number of variables will certainly need to be treated. (See section 2 under Mathematical Methods of this report.) The function occurring in connection with the satellite problem is sufficiently complicated that it yields an excellent non-trivial test case to which to apply potentially efficient methods. In fact, two methods (in addition to the gradient method) have been tried with some success.

PART IV

ILLIAC USE AND OPERATION - GENERAL LABORATORY INFORMATION

Machine Use

During November specifications were presented for 10 new problems. This list does not indicate how the Illiac was used because large amounts of machine time may have been consumed by problems with numbers less than 1074. Numbers followed by T are for theses.

1074 Computer. DM-Satellite Data Reduction. Given the times at which a satellite crosses the various lobes of two antenna arrays, a distance of closest approach to the observing station and the time of this approach are chosen so as to be most consistent with the given data.

1075 Education. Language Test Revision. The major factors contributing to total variance are to be found in a revised and restandardized language test.

1076 Enrico Fermi Institute for Nuclear Studies. Geomagnetic-Geographic Coordinate Transformation. The transformation of geographic to geomagnetic coordinates is necessary so that a ship bearing a standard University of Chicago - IGY neutron pile may follow constant geomagnetic latitude and longitude courses on a trip to and from Antarctica. The purpose of this trip is twofold: 1) to plot the intensity of cosmic rays as a function of the position on the earth's surface and 2) to observe time variations in cosmic ray intensity in such a manner that the observations obtained on the ship may be easily correlated with those at permanent stations.

1077 Computer. Library Program for Matrix Multiplication Which Uses the Drum. A revised matrix multiplication program is to be prepared for the library.

1078 T Chemical Engineering. Effect of Heat Transfer upon Flow Field at Low Reynolds Numbers. The problem is to predict the temperature and velocity fields in a fluid as it flows at a low Reynolds Number in a vertical tube with

a constant wall temperature. The fluid enters the heated section with a fully developed laminar velocity profile and at a uniform temperature.

Since the non-linear hydrodynamic differential equations cannot be easily solved, an approximate method suggested by Lighthill and modified by this work is being attempted. This method leads to four simultaneous linear first-order differential equations with four parameters to which a numerical solution is sought.

Since it is not known what sort of numbers will be involved, floating decimal routines will be used throughout.

1079 Physics. π^0 Photoproduction from Hydrogen. The problem is to calculate the counter efficiencies for the photoproduction of π^0 mesons from hydrogen. The dynamics of the process, the energy loss of the recoil protons in the target, and the geometry of the counters must be included.

1080 T Mining and Metallurgical Engineering. 3-Dimensional Network Models of Porous Media. The porosity is to be found as a tabulated function of the pore size distribution and a quantity which relates the length of a pore to its radius.

1081 Institute of Communications Research. Emotional Factors in Attitude Change. A statistical study is to be made of the relationships between personality dimensions, mood changes, and attitude changes produced by four different mass communications. Audience responses were obtained for 52 variables, over a period of 8 weeks.

1082 Psychology. Pattern Analysis by Q-Technique. This problem is a preliminary investigation of the application of Q-technique in factor analysis to pattern analysis. The data used would be clinical and psychometric. The programs to be used would be drawn from the Social Sciences Library.

1083 Computer. Floating Precision Linear Equation Solver. Linear algebraic equations can be considered, after appropriate scaling, to have integer coefficients and integer right-hand sides. The matrix is first triangularized

by, in principle, a highest common factor process on the current left-hand column. That is, in general, an integer multiple of the row whose left-hand coefficient is second largest is added/subtracted to/from the equation whose left-hand coefficient is largest. This process is continued until all but one equation have zero coefficients. The resulting system has its order reduced by one and the process is repeated. Back substitution is done in the usual way for rational fractions. The resulting program can, of course, be used for evaluating determinants, inverting matrices, and obtaining characteristic polynomials, exactly.

Table I shows the distribution of machine time for the month of November.

Table I

	Hrs:Min
Regular Maintenance	22:24
Unscheduled Maintenance	1:13
Drum Engineering	36:46
R.A.R.	5:04
Leapfrog	31:43
Wasted	:00

Use by Departments

Computer	39:47
Physics	20:14
Control Systems Lab.	90:06
Structural Research	86:09
Struct. Res. (AF 24994)	35:24
Psychology	24:58
Electrical Engineering	2:51
Chemistry	29:43
Agriculture	16:27
Theor. and Appl. Mech. (ORD 593 IC)	:20
Inst. of Comm. Res.	4:39
State Water Survey	7:40
University of Chicago	1:11
U. S. Navy	:34
Classes	28:24
Demonstrations	3:03
Miscellaneous	10:43
	<hr/>
	499:23

Error Frequency and Analysis

The machine is normally used for "engineering" and maintenance between 7:00 A.M. and 11:00 A.M., and for a check of its performance between 5:30 and 6:00 P.M. of each weekday. Since the periods between 7:00 and 11:00 A.M., together with certain irregular periods like Saturdays and Sundays, are devoted to a heterogeneous group of functions, it is more instructive from an error standpoint to look at the periods between 11:00 A.M. and 7:00 A.M. of the next day in order to make an observation of the error frequency in the machine. This is the actual period when the machine is designated for use. With this in mind, a summary table has been prepared using the period between 11:00 A.M. and 7:00 A.M. of the next day. This table lists the running time when the machine was operating, the amount of time devoted to repairs because of breakdowns, and a number of failures while the machine was listed as running. During the 5:30-6:30 period (when the machine is checked) if no errors are found, the time is given to the "running" column. Each failure was considered to have terminated a running period and was followed by a repair period in preparing this table. Since the leapfrog code is our most significant machine test, the length of time which it has been used on the machine is listed separately together with the number of errors associated with that particular code. This information for the month is presented in Table II.

It is important to notice that any interruption of machine time that was not planned for is considered a failure in this table. In rare cases where the failure is not known until a later time, it is possible that no repair period is associated with the failure. This over-all system has been adopted because it makes it possible for a machine user to estimate directly the probability that the machine will be "running" at any instant of time and the probability of a failure during any given interval of running time.

Table III presents a summary of errors or interruptions for November.

TABLE III

Memory Errors	1
Reader Errors	2
Drum Failures	2
Punch Errors	0
Control Errors	0
Unknown	<u>3</u>
	8

T A B L E II

DATE	RUNNING OK TIME	REPAIR TIME	INTERRUP- TIONS OR FAILURES STOPPING OK TIME	TYPES OF INTERRUPTIONS OR FAILURES CAUSING REPAIR TIME	WASTED	LEAPFROG	FAILURES STOPPING LEAPFROG
11/1/57	20:00	:00	0		:00	:44	0
11/4/57	20:00	:00	0		:00	:41	0
11/5/47	20:00	:00	0		:00	:52	0
11/6/57	20:00	:00	0		:00	:42	0
11/7/57	20:00	:00	0		:00	:51	0
11/8/57	20:00	:00	0		:00	:50	0
11/11/57	19:31	:29	2	(1) Memory Error fuse to address generator blew. Memory pos 2 ⁻²⁰ bad (2) Unknown			
11/12/57	19:47	:13	2	(1) Reader "F" error (2) Reader "F" error	:00	:45	0
11/13/57	20:00	:00	0		:00	:50	0
11/14/57	20:00	:00	0		:00	:40	0
11/15/57	20:00	:00	0		:00	:42	0
11/18/57	20:00	:00	0		:00	:50	0
11/19/57	20:00	:00	0		:00	:40	0
11/20/57	20:00	:00	0		:00	:42	0
11/21/57	19:40	:00	0		:20	:43	0
11/22/57	20:00	:00	0		:00	:39	0
11/25/57	20:00	:00	0		:00	:41	0
11/26/57	19:58	:02	2	(1) Unknown (2) Unknown	:00	:37	0
11/27/57	18:07	1:53	1	(1) Drum failure	:00	:20	0
11/29/57	19:38	:22	1	(1) Drum failure	:00	:43	0
TOTALS	396:41	2:59	8		:20	15:02	0

Reports and Seminars

Seminars

"The Hydrogen Molecule (II)", by Dr. J. N. Snyder, November 5, 1957.

"Some New Techniques in Logical Design", by Dr. D. E. Muller, November 12, 1957.

"A Study of Parallel One's Complement Arithmetic Units with Separate Carry or Borrow Storage", by Gernot Metze, November 26, 1957.

Reports

Digital Computer Laboratory Report No. 81, "Parallel One's Complement Arithmetic Units with Separate Carry or Borrow Storage", November 11, 1957.

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