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NATIONAL BUREAU OF STANDARDS REPORT

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FLEXIBILITY REQUIREMENTS
for
AIR DEFENSE COMPUTERS (U)

By

Franz L. Alt
Applied Mathematics Division

Technical Report
to
U. S. Army Signal Air Defense Engineering Agency
under the terms of MIPR-R-55-2175-SC-91

NBS

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NATIONAL BUREAU OF STANDARDS REPORT

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Flexibility Requirements for Air Defense Computers

Contents

Summary

1. A centralized and mechanized air defense coordination center can be operated either by a special purpose electronic digital computer designed for the purpose, or by a general purpose computer, in particular one manufactured commercially in large numbers.

2. If a special purpose computer is chosen, it must be designed with sufficient flexibility to accommodate varying numbers of batteries and targets, and changing firing doctrines. If this is done, the computer will be able to work with some, though not all, weapons systems other than the one for which it is originally designed.

3. General purpose computers now in production are fully adequate for post-1960 air defense coordination. The use of widely used types of general purpose computers has the advantage that, in case of breakdown in an emergency, the fire coordination computer can quickly be replaced by "drafting" a commercially used computer of the same type.

4. The problem of ballistic missile threat affects computer design in the same way as defense against air breather threat by means of different weapons. It does not introduce additional flexibility requirements of its own, beyond those considered elsewhere in this study.

5. From the standpoint of cost, general purpose and

special purpose systems each have their advantages and drawbacks. The balance of these economic considerations is favorable to the general purpose computer. There are additional advantages in using a computer type which is widely used for business or scientific purposes.

1. Introduction

For some time the National Bureau of Standards, at the request of the Signal Corps of the U. S. Army, has been engaged in studies of air defense tactics. Recently the U. S. Army Signal Air Defense Engineering Agency (USASADEA) asked the Bureau to include, among others, the following topics in these studies:

> 1. Examine the flexibility required of the computer to handle automatic defense functions against the spectrum of post-1960 threats with post-1960 weapons. Consider in particular whether a general purpose computer will suffice; and, if not, what is the degree of specialization required of the special purpose machine.
>
> 2. Effects of inclusion of air breathing threats and ballistic missile threat targets as they influence requirements placed upon the decision function equipments and upon flexibility of the computer.

The present report deals with these questions. In particular, therefore, we are concerned with comparisons between general purpose and special purpose digital computers.

Such comparisons can be made on physical or economic grounds, i.e., on the basis of what a computer can accomplish, or of what a desired accomplishment costs--including the cost of designing, building and operating the computer and of programming a given task in air defense. We are principally concerned with a comparison of physical characteristics of computers; but, inasmuch as physical performance can be traded for monetary savings, we cannot entirely disregard questions of cost. The latter are relegated to the last section of this report.

The distinction between general purpose and special purpose computers is in degree, not in kind. All digital computers are similar in their fundamentals, and many intermediate stages between the extremes are possible. Furthermore, many of the characteristic advantages of general purpose computers depend on the fact that many copies of such computers exist. Thus, machines which are designed for general purposes but of which only a few copies are actually built will occupy a position intermediate between general and special purpose computers. It may also happen that a special purpose computer is built in a large number of copies; it will then enjoy some of the advantages of general purpose computers. Also a computer may have certain special purpose features superimposed on a general purpose basic design; in some cases such features may be optional. All these possibilities tend to blur the distinction between the two classes of machines.

It is therefore not possible to give clear-cut definitions of the words "general purpose computer" and "special purpose computers". Nor are such definitions necessary for the purposes of this report. Vaguely speaking, a general purpose computer is one which is designed to solve many different types of problems, while a special purpose computer incorporates features which facilitate the solution of one type of problem, at the expense of other types. Rather than elaborate on this definition, we shall attempt to clarify it by some examples described in the Appendix to this report.

2. Flexibility Considerations

The need for introducing a measure of flexibility into air defense computers arises from several factors which will be considered here.

(a) Degree of Centralization and Mechanization. In an air defense system containing a number of batteries, selection of targets for batteries may be made locally or centrally, i.e., by each battery for itself or by one fire coordination center. In either case, the process of target assignment may be performed by personnel or by a computer. We thus have four possible systems. At this time a final choice among them has not yet been made though the general thinking is in the direction of centralized automatic systems. For the purposes of the present report the two non-automatic systems present no problems at all, since man is at least equivalent to a highly flexible machine. Automatic target selection, whether local or central, does involve flexibility requirements. These are naturally more stringent for a centralized automatic fire coordination system than for a decentralized one: the centralized system encounters all the variations in tactical situations which are encountered by a decentralized system, and in addition the multiplicity of batteries served by the centralized system will by itself cause some flexibility requirements. For these reasons, the present report deals with the case of a centralized automatic system of fire coordination.

(b) Size of Defense Establishment. The group of studies of which this report forms a part have been concerned with defended areas whose dimension is comparable to the range of the defensive missiles: cities, metropolitan areas or groups of neighboring cities, SAC bases, field armies. They have not been concerned with, say, coordinated defense of the continental United States, or of major subdivisions. It is not realistic to demand that air defense computers be made so flexible that they be adequate to both kinds of tasks. Consequently, we limit our attention to the first group of defended areas, sometimes called "point defense" for short. Even within this group there is wide variation in size of the defense establishment, calling for enough flexibility in computer design to accommodate different sizes. The number of batteries may range from perhaps 50 for the largest and most important defended points to only a few for some military installations. The maximum number of targets which the computer is expected to handle will vary similarly (see (c) below). The number of batteries and targets has an effect on the required computer speed and memory capacity. It is desirable to design a computer in such a way that its memory capacity can be varied, from perhaps a few thousand words for small defense establishments up to the maximum required for the largest defended points. As far as speed is concerned, one can only demand that the speed of the computer be adequate for the largest case; it is probably not useful to design a computer to operate at varying speeds.

(c) Number of Targets. The maximum number of targets that may appear over a defended area is difficult to predict. Fortunately, the purposes of the present report may be achieved without such prediction. It seems proper that design criteria for the fire coordination computer be aimed at the maximum number of targets which the defensive weapons can handle successfully. We may call this the saturation level. If at any time in actual operations the number of targets exceeds this level, then the defense will be unsuccessful no matter how the computer is designed. If the number of targets is below the saturation level, then a computer designed for saturation may not operate at maximum efficiency; but at the same time it is less important for it to be most efficient.

The saturation level depends on the number and kind of defensive weapons employed. For the kind of weapons currently considered, like Nike Hercules, it is roughly of the same order of magnitude as the number of batteries.

(d) Defensive Tactics (Firing Doctrines). The computer should be flexible enough to accommodate several types of firing doctrines, and should be easy to reprogram for new types of doctrines, as yet unforeseen. To date there has not even been complete agreement on what doctrines should be used for present weapons. We know, furthermore, that a change in weapons may call for radically different doctrines. Finally, there is the danger that our doctrines may become known to the attacker, and may therefore have to be discarded and replaced.

Modification of doctrines may also become necessary as a result of further information on countermeasures. To date there is no unanimity on how to behave in the presence of decoys, chaff or radar jamming. The defensive tactics now contemplated may have to be changed from time to time in the light of future studies of countermeasures; a computer chosen today should be flexible enough to allow for such changes.

Different doctrines are called for depending on the nature of the defended area. For instance, in defending a SAC base the object is to delay penetration; in defending a city, to prevent or minimize penetration. The computer must be able to accommodate such different doctrines with ease.

(e) Types of Weapons. A change in defensive weapons may require changing the defensive tactics, as stated above;

it may also call for a change in the speed and memory capacity of the computer. It seems reasonable at this time that the design of a computer should provide sufficient flexibility for changes in doctrines, since this is desirable for other reasons as well, but need not provide for any increase in speed or memory capacity that might be required by future weapons. The introduction of a new weapon is so costly that the design of a new computer is negligible by comparison. Thus, in the present study we limit ourselves to computers adequate for the largest point defense occurring in practice, by means of the weapons currently considered for this purpose. It is plausible that a computer designed for these requirements will also accommodate many other types of weapons, but not necessarily all types that might conceivably be used in post-1960 air defense.

In this connection it is well to distinguish between changing the computer, changing the doctrine, and changing some of the parameters. Quite often a change in weapons will not call for a new doctrine. For example, it appears likely from our present knowledge that for Nike Hercules the same firing doctrine can be used which recommended itself for Nike Ajax; only some of the numbers stored in the computer will have to be changed, e.g. the weights by which different probabilities are combined to obtain a figure of merit. In other cases, where weapons characteristics change more radically, new doctrines may have to be designed, i.e., new instructions programmed for the computer; but we should expect from paragraph (d) above that the fire coordination computer will readily admit such changes in instructions. It is only when the nature of the weapons changes drastically that an entire new computer is required.

(f) Replaceability and Maintenance. In actual operation the computer is in danger of being put out of commission, either by malfunction or by enemy action. It is important to provide for ease of replacing either the entire computer or any of its components. Also, the computer should be designed for easy maintenance. Personnel required for maintenance, operation and programming are subject to attrition; there is a premium on a computer design which facilitates replaceability and/or training of such personnel.

Parenthetically, this requirement constitutes one of the greatest drawbacks of special purpose computers compared with general purpose ones, and especially with those general purpose computers which are in widespread use for business or scientific application. For such computers there is usually an ample pool of repair facilities, spare parts, trained maintenance and operating personnel, experienced coders and even ready-made codes (subroutines) which can be used as building blocks for new computer programs; and there is the possibility of commandeering existing computers for fire coordination use if the original fire coordination machine is incapacitated.

(g) Mobility. In some application (primarily in the defense of field armies) the computer must possess a certain degree of mobility. This is not a stringent requirement, since many of today's electronic computers are at least as mobile as the other installations required for air defense, such as radars and launchers. For other applications, e.g. defense of cities, mobility plays no role.

(h) Capacity and Speed Requirements. A recent report of the G. C. Dewey Company states that a memory capacity of roughly 35,000 words will be adequate for a post-1960 air defense coordination computer. Since computer memories are usually built in sizes which are powers of 2, it is suggested that 32,768, the power of 2 nearest to the G. C. Dewey estimate, be used as a target figure.

The speed necessary for the computer can be determined by the following argument. Suppose that the computer serves B batteries. Suppose further that a battery, after receiving an assignment, remains tied up (i.e., does not require a new assignment) for a period of average length τ. (The actual period of tie-up may vary from assignment to assignment, depending on the time of flight and perhaps other circumstances). Then the average time available to the computer for making an assignment is τ/B. If the batteries worked in exact rhythm, a computer giving out assignments at intervals τ/B would just keep up with the firing. In order to accommodate random variations in tie-up time without risk of letting a battery wait too long for its assignment, a safety factor of 2 or 3 appears in order. For instance, for a safety factor of 2.5, the speed of the computer must be high enough to complete an assignment in time $0.4\ \tau/B$.*)

3. Antiaircraft Capabilities of General Purpose Computers

The studies conducted at the National Bureau of Standards permit the inference that the general purpose computers expected to be in widespread use in 1962 are amply adequate for the severest foreseeable antiaircraft fire coordination tasks.

This statement is based on the past use of an IBM Type 704 computer for simulating antiaircraft defense engagements. Small-scale raids have been simulated at the rate of 4 to 5 per minute. The average computer time, between 12 and 15 seconds per raid, includes not only the assignment of targets

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*) Then, if the intervals between battery requests for assignments are assumed to be Poisson distributed, it can be shown that the probability of two assignments being requested within less than $0.4\ \tau/B$ is $1 - e^{-0.4} \sim .330$, and the probability that this will happen four or five times in succession, so as to cause the computer to fall behind seriously, becomes very small.

to batteries, which is the main object of the simulation, but certain auxiliary operations as well. Among these we mention the "generation" of the raid, i.e., setting up the initial locations of all targets and modifying them as time goes on; "scoring", i.e., deciding by means of random numbers whether an assignment results in killing the target, and collecting various statistics on the progress of the raid; and finally printing out some summary information--a relatively time-consuming process. (If more detailed information is printed, the machine time per raid has to be increased). These auxiliary operations are performed only in simulation. If a computer is used in a real tactical situation, they are omitted; in their place there may be certain other minor operations, such as target identification, and possibly the tracking of friendly aircraft. On the whole it seems plausible that computer time in real tactical employment will be no greater--probably smallor--than in simulation.

The raids to which we referred above have an average of about 36 assignments each, which works out to about 0.4 seconds of machine time per assignment. In these raids there are 6 targets. The computing time is roughly proportional to the number of targets. Thus, in a raid where 60 targets are <u>simultaneously</u> present, within range and eligible for assignment, the computing time would be about 4 seconds per assignment. Generally, for <u>T</u> targets simultaneously under consideration, the computer time per assignment is about .067T. The number of batteries enters into the argument only in the sense that it affects the number of assignments to be made.

These raids use an assignment doctrine which is probably the most sophisticated to date: It is not likely that the assignment process will ultimately use anything much more elaborate, though there is still room for improvement such as taking into account a "value map" of the battlefield, letting the computer watch for limitations imposed on the use of nuclear warheads, or taking account of enemy countermeasures.

Assuming that a battery is tied up, on the average, at least 100 seconds between assignments, and that the computer serves B batteries, assignments must be made at average intervals of 100/B seconds. The time per assignment required by the computer must therefore be smaller than 100/B:

$$.067T < 100/B$$

or

$$BT < 1500$$

This is the limitation*) on the handling capacity of a computer like the IBM 704. For example, if there are 20

*) Strictly speaking this argument is valid only if the computation time per assignment, for given T, does not depend on B. This premise is fulfilled for practically all assignment rules now in use, but it is not true e.g. for matrix-type assignments. In the absence of concrete

batteries in the defense system and 60 targets are simultaneously in range, the computer is not overloaded, since $BT = 20 \times 60 = 1200 < 1500$. One should, however, allow a substantial safety factor and therefore not expect a 704 to handle more than 20 targets against 20 batteries.

The same limits apply to other machines of the same general characteristics, such as the Sperry-Rand 1103. There are machines now in existence which are faster by a factor of 5 to 10. Among these are the IBM 7090, Sperry-Rand 1105 and possibly Transac. Such machines can take on the job of antiaircraft assignments for 50 batteries against 50 simultaneous targets, or similar combinations, even in the face of the greatest imaginable complications and with an ample safety margin in time.

In 1960 two new computer types are expected to be placed into operation: LARC, manufactured by Sperry-Rand, and STRETCH of the IBM Corporation. Their over-all speed will exceed that of the 704 and similar computers by a factor between 50 and 200. The state of the computer art is so advanced that there should be no reasonable doubt about fulfilling the promised design objectives of these machines. Even if the announced completion dates are not

experience it is nevertheless fair to estimate that our final conclusions about the adequacy of general purpose computers remain valid even for matrix-type assignments.

adhered to, it seems safe to assume that such machines will be generally available in the period from 1962 on, which concerns us here. They would be capable of handling configurations such as 50 batteries against 1000 targets, which are larger than anything envisaged as necessary.

So far we have discussed only machine speed. When it comes to memory capacity, we may use the results of a recent study by the G. C. Dewey Company, which indicates that an internal memory of approximately 35,000 words is adequate. This estimate is based on a highly sophisticated system and, in part, on crude extrapolation. It seems to us that it represents an upper limit, and could probably be reduced. (Our own experiments use only 4096 words.) This is true especially if extensive use is made of the device of storing two numbers in one machine storage location, an artifice which is facilitated by the "half-word logic" feature of the IBM 704. Now, most present-day large machines can be equipped with 32,768 words of internal storage as an optional feature. The faster machines of the future will have still larger memories. Additional storage space can be provided with practically all machines by the use of magnetic drums.

In summary, general purpose computers widely available in and after 1962 will be more than adequate for the anti-aircraft defense problem. Most likely even the presently produced computers like the IBM 7090 and Sperry-Rand 1105 will be fully adequate for the most ambitious foreseeable program.

4. Effects of Missile Threat

Defensive measures against attacking missiles have been explored to a far lesser degree than those against air breathing targets. They may possibly require defensive weapons radically different from those now in use or under study; if so, it is plausible that the methods of tactical employment, and therefore the operation of fire coordination computers, if any, would also differ basically from present concepts. In these circumstances there is no point in trying to make a computer so flexible that it could later be adapted to anti-missile defense if desired. The introduction of such new weapons is so costly that the added cost of designing and building new computers for them is not significant.

What we aim to show in the next few paragraphs is that, in some circumstances, a system designed for defense against air breathers will also be effective against missiles. More specifically, we shall show that the change to a different threat can, in a certain sense, be treated as if it were a change to a different defensive weapon operating against the same (original) threat. The effect of such a change has already been discussed in 2(e).

There are two or three characteristics which principally distinguish an enemy missile from a plane. First, it is faster. Second, it is harder to detect, because of its smaller size. We may express this by saying that the distance at which it is first visible to the radar is smaller for the missile than for the plane. And third, possibly, the kill probability of our defensive weapons may be smaller against a missile than against a plane.

Suppose that we have a defense system ("Case I") designed to operate against enemy planes which first become visible when 200 miles away, and which travel at 600 miles per hour. Suppose next that we are faced with an enemy missile ("Case II") which becomes visible at 100 miles, and travels at 900 m.p.h. In order to make the two threats comparable, we choose as our unit of length in the first case the conventional distance of 1 mile, and in the second case a distance of ½ mile; thus the missile becomes visible in both cases when it is 200 "units" away. The speed of the missile in Case II, 900 m.p.h., becomes 1800 "units p.h." We next change the unit of time from 1 hour in Case I to 20 minutes in Case II: now the speed of the missile is expressed as "600 units of length per unit of time" in both cases. Thus, detection range and speed of the two kinds of attackers are expressed by the same numbers (200 and 600, respectively), though in different units of measurement.

The characteristics of the defensive weapons must be expressed in the same units of measurement as those of the attackers. Suppose that we are using a missile with a 50-mile range, an average speed of 750 miles per hour, slewing time of 12 seconds, and a time-of-flight curve given empirically by a set of statements like "the time of flight to an impact point 10 miles away is 54 seconds." If this missile is to be used against the attacker of Case I, its characteristics are represented, in a coordination computer, by the numbers just listed. But if the same defensive missile is used against attacker II, we express its characteristics in the new units: range 100 units, speed 500, slewing time 36 (here we assume that, just as an hour is divided into 3600 seconds, so the new time unit of 20 minutes is divided into 3600 smaller units). Corresponding to the time of flight example above, we have the statement "the time of flight to an impact point 5 units of length away is 18 units of time", and a number of statements of this sort determine the time-of-flight curve.

Since the computer program contains the numbers representing distances, speeds, etc., but does not contain any indication of the units of measurements, the program for Case II with the given defensive missile will look exactly like a program for Case I with a different defensive missile--one with range 100 miles, average speed 500 m.p.h., slewing time 36 seconds.

If the kill probability of the defensive missiles is .8 against the targets of Case I, .6 against the targets of Case II, the latter number remains unaffected by the change in units of measurement.

The numbers used in this example are summarized below.

	(1)	(2)	(3)
	(Case I in conventional units	Case II in conventional units	Case II converted to new units
Attackers:			
Distance when first visible	200 (miles)	100 (miles)	200
Speed	600 (m.p.h.)	900 (m.p.h.)	600
Defenders:			
Range	50 (miles)	50 (miles)	100
Speed	750 (m.p.h.)	750 (m.p.h.)	500
Slewing Time	12 (sec.)	12 (sec.)	36
Kill Prob.	.80	.60	.60

In summary, an engagement between a new type of attacker and an old defender (Case II, column 2) is converted so as to look like an engagement between the old type of attacker and a fictitious new type of defender.

As we have seen in Section 2(e) above, this may or may not be covered by a sufficiently flexible computer design. A computer designed in accordance with the flexibility recommendations of this report will automatically be adequate for a variety of defensive weapons and of attackers. Where larger changes in the characteristics of either defensive weapons or attackers are involved, a different computer may have to be designed. It does not appear reasonable or economical to plan a computer now to take care of all unforeseeable combinations of defensive weapons and attackers. In any case, the problem of computer flexibility in the face of a ballistic missile threat involves no new considerations beyond those already discussed in Section 2(e).

5. Economic Considerations

(a) Production Cost. A special purpose computing machine designed for the air defense coordination problem can work faster than a general purpose machine built from comparable components. It can be so organized that many "housekeeping" instructions--counting and tallying, indexing, discriminations--become superfluous, that the occurrences of one machine component idly waiting for another are avoided or reduced, and that frequently occurring groups of instructions are replaced by single special purpose instructions. Since we are not interested in the greatest possible speed but merely in a speed sufficient for real-time operations, this means that a special purpose machine can get along on slower arithmetic components and on memory devices with greater access time. This in return results in somewhat lower production cost. Also, the size of the memory can be exactly adapted to the problem, and some of the terminal units present in a general purpose computer can be omitted. All of this results in some savings in the cost of building the computer. The extent of the saving will depend greatly on the particular machine design chosen; for a first orientation, we should expect it to lie between 5% and 15%.

This argument in favor of special purpose computers is weakened by the fact that many general purpose computers allow a variety of options in regard to memory size and input-output equipment. One can choose a general purpose combination well adapted to the air defense problem.

(b) Development Cost. The cost of designing a computer, developing and testing new components, and checking the first prototype for design errors is at least comparable to the production cost; occasionally a little smaller, often several times larger. This is true for either special or general purpose computers. For the latter, however, the producer can divide the development cost among several hundred copies built and sold or rented. For a special purpose computer designed for air defense, the question is how many copies are to be built. If only a few, the development cost per copy is considerable and will certainly more than offset the savings in production cost. If between five and twenty copies are built, the two items are comparable. If the air defense computer is to be built in a large number of copies, development costs need not be considered at all.

(c) Programming Cost. The reprogramming of the computer for any changes in doctrines, weapons, targets, etc. which may emerge after its initial installation is likely to be a substantial problem. One should remember the example of the SAGE system, where many man-years (according to some estimates, hundreds of man-years) have been spent writing computer programs for the proposed air defense functions of the SAGE computers. Nothing of this magnitude is expected for the equipment and functions considered here; nevertheless, the cost of programming is not negligible, and the elapsed time in changing programs may well be critical. In this respect a general purpose computer has decisive advantages. While the special purpose computer can be so designed as to facilitate the coding of the initial plan of computation, this bias makes it all the more difficult to code any other plan. More importantly still, for a general purpose computer in widespread use there are available subroutines for frequently occurring functions, subroutines for using the computer itself in many repetitive aspects of coding and subroutines which assist in code checking, in monitoring the operation of the computer and in locating machine failures. It is customary that such systems of subroutines are produced either by the manufacturer of a general purpose machine or cooperatively by an organization of machine users; in either case the cost to the individual user is small. The IBM Corporation has estimated that the production of its FORTRAN coding system required 28 man-years of effort. Other estimates range downward to a few man-years.

(d) Other Factors. A special purpose computer can be designed for great compactness and mobility. Where this is an important consideration and is made explicit in the specifications for the computer, it gives an advantage to the special purpose computer over the general purpose one. Whenever mobility is secondary, it is desirable to lay out the computer in a loose and roomy arrangement which facilitates access to all components for maintenance purposes.

The development time for a special purpose computer, on the order of two years, may be a drawback in some circumstances.

The ready availability of trained and experienced personnel for programming and maintenance as well as of spare parts and components are among the advantages of general purpose machines. So is the ability to replace an entire machine on short notice by "drafting" an existing commercially used machine.

It should be mentioned in this connection that, if a general purpose computer is decided upon, advance mobilization plans should be drawn up for pressing into service in the event of air attack, commercially used machines of the same type. Stand-by lines of communication can be established, operating procedures worked out, personnel informed of location of alternate procedures, and "fire drills" arranged.

Appendix

Special Purpose Features of Digital Computers

A general purpose computer may be thought of as consisting of four kinds of components:

(a) Control units

(b) Arithmetic units

(c) Memory units

(d) Terminal units

Most computers have only one each of (a), (b) and (c) but several terminal (input and output) units of different kinds. Some computers have two or more different memory units (e.g. magnetic cores and drums), a few have two arithmetic units, and some contemplated designs may be interpreted as containing two control units.

(a) The control unit handles the instructions to the computer. As a rule, instructions are coded in the form of numbers, are fed into the computer from an input unit in the same way as other numbers, and are stored in memory with other numbers. For a general purpose computer this system has so many advantages that it is almost universally used. For special purposes various departures from this "stored-program" concept are possible and perhaps advantageous. The greatest advantage of storing instructions in memory--namely, the ability to perform arithmetic operations on instructions and thus let the computer modify its own instructions--is actually used for only a small fraction of all instructions in a program; if the general purpose computer stores <u>all</u> instructions in memory, this is for the sake of greater flexibility and ease of programming. For any special purpose program one might easily store in memory only those few instructions which require automatic modification. All other instructions--the great majority of them--could be stored in a unit which permits rapid reading but not writing, and which can therefore be simpler, faster and/or less costly. Examples of such "fixed storage" are punched paper cards read while stationary, plug boards (or the pin boards used e.g. on the Burroughs E-101 computer), permanently wired magnetic cores or other permanently wired circuits. These arrangements make it difficult to change over to another computer program, increasingly so in the order in which they have been listed. Not only is the physical setting-up of a new program time-consuming, but the process of designing the program is rendered difficult by considerations of the two kinds of instruction storage.

(b) The arithmetic unit, in the usual general purpose computer, performs the arithmetic operations $x + y$, $x - y$, $x \cdot y$, x/y, and participates in most other instructions. Some computers do not provide for division, at least one existing computer has no multiplication instruction. Multiplication can be performed by repeated addition, division by an algorithm involving repeated use of the other three operations. Apart from the arithmetic instructions, the computer must at least provide for some input and output instructions and for a discrimination (branch, conditional transfer of control) instruction. Most computers allow not only these but numerous other instruction types: shifts, different kinds of conditional and unconditional transfers of control, floating-point arithmetic operations, logical operations, isolation of digits or groups of digits in a number, indexing, etc. Nowadays, a typical commercially available computer allows about 100 different instructions. These could be replaced by combinations of simpler instructions, at the cost of complicating the coding process; indeed, the early digital computers got along well on ten or twenty instructions. In today's general purpose computers, the many available instructions represent those operations which have been found, from experience, to be frequently needed in general purpose computing; for instance, floating-point arithmetic operations. For a special purpose machine one might introduce special instructions. For instance, a single instruction

<u>convert from polar to Cartesian coordinates</u>

and another instruction for the opposite conversion, might be useful in handling radar data; such a conversion requires several dozen instructions on a general purpose computer. An instruction

<u>find the smallest of the numbers $x_1, x_2, \ldots, x_n$</u>

would be useful for optimizing. On a general purpose computer this operation requires the execution of several instructions for each of the numbers x_i in sequence.

One might also consider omitting some general purpose instructions which are not needed for the particular tasks of a special purpose computer, thus saving on cost and size of the machine. It is, however, difficult to think of an example of this kind.

(c) Specialization of the memory units consists, apart from the possible provision of "fixed memory" mentioned under (a) above, in the proper choice of capacity and access time. In most cases the general purpose machines also provide some freedom of choice in this respect, by allowing optional memory units. For instance, a typical commercially available general purpose computer might have 4096 words of magnetic core memory as standard equipment, and allow the user to add, at his option, several additional blocks of magnetic core memory of 4096 words each, plus one or more magnetic drums holding 8192 words each. The access time of the core memory is short, say 10 microseconds, that of the drum longer, say 10,000 microseconds on the average. Thus the user can approximate the needs of a special problem within limits. At most a fractional saving in cost can be made by a special purpose design.

In connection with access time one has to consider the order in which stored information is required. Magnetic cores, for instance, are a truly random access memory in which any item is accessible as quickly as any other. Magnetic drums are partly serial, i.e., do not afford a completely random access to stored information. Storage is distributed in parallel among a large number of tracks, access within each track being serial. Magnetic tapes, if used as a storage medium, are entirely serial.

(d) In considering special purpose design of terminal (input and output) equipment, the same arguments apply as under (c) above: the user of general purpose machines has a variety of components to choose from. In addition, some special terminal units may be required which are not generally available. For instance, direct input from a radar to the computer, or direct output signals from the computer to batteries may be needed. This does not mean, however, that the entire computer has to be specially designed. It is usually possible without serious complications to connect specially designed terminal equipment to a general purpose computer.

U. S. DEPARTMENT OF COMMERCE
Lewis L. Strauss, Secretary

NATIONAL BUREAU OF STANDARDS
A. V. Astin, Director

THE NATIONAL BUREAU OF STANDARDS

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Electricity and Electronics. Resistance and Reactance. Electron Devices. Electrical Instruments. Magnetic Measurements. Dielectrics. Engineering Electronics. Electronic Instrumentation. Electrochemistry.

Optics and Metrology. Photometry and Colorimetry. Optical Instruments. Photographic Technology. Length. Engineering Metrology.

Heat. Temperature Physics. Thermodynamics. Cryogenic Physics. Rheology. Engine Fuels. Free Radicals Research.

Atomic and Radiation Physics. Spectroscopy. Radiometry. Mass Spectrometry. Solid State Physics. Electron Physics. Atomic Physics. Neutron Physics. Radiation Theory. Radioactivity. X-rays. High Energy Radiation. Nucleonic Instrumentation. Radiological Equipment.

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Mechanics. Sound. Mechanical Instruments. Fluid Mechanics. Engineering Mechanics. Mass and Scale. Capacity, Density, and Fluid Meters. Combustion Controls.

Organic and Fibrous Materials. Rubber. Textiles. Paper. Leather. Testing and Specifications. Polymer Structure. Plastics. Dental Research.

Metallurgy. Thermal Metallurgy. Chemical Metallurgy. Mechanical Metallurgy. Corrosion. Metal Physics.

Mineral Products. Engineering Ceramics. Glass. Refractories. Enameled Metals. Concreting Materials. Constitution and Microstructure.

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- Office of Basic Instrumentation.
- Office of Weights and Measures.

BOULDER, COLORADO

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Radio Propagation Engineering. Data Reduction Instrumentation. Modulation Systems. Navigation Systems. Radio Noise. Tropospheric Measurements. Tropospheric Analysis. Radio Systems Application Engineering. Radio-Meteorology.

Radio Standards. High Frequency Electrical Standards. Radio Broadcast Service. High Frequency Impedance Standards. Electronic Calibration Center. Microwave Physics. Microwave Circuit Standards.