From Memex to Hypertext: Vannevar Bush and the Mind's Machine

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a world where men increasingly think for themselves. Exhortation needs to be revised, not to weaken its power, but to increase it, for men who are no longer in the third century. As this occurs, and on the essential and central core of faith, science will of necessity be silent.

But its silence will be the silence of humility, not the silence of disdain. A belief may be larger than a fact. A faith that is overdefined is the very faith most likely to prove inadequate to the great moments of life. The late Mr. Justice Holmes said, "... the faith is true and adorable which leads a soldier to throw away his life in obedience to a blindly accepted duty, in a cause he little understands, in a plan of campaign of which he has no notion, under tactics of which he does not see the use." Young men, who will formulate the deep thought of the next generation, should lean on science, for it can teach much and it can inspire. But they should not lean where it does not apply.

Modern philosophy divides, roughly, into two parts. One pores through the ancient record and attempts to recover from it thought that is worth preserving and to present this in modern dress. The other labors to refine our logical processes and our language, that we may reason more assuredly. This is not all that philosophy can do. It can return to its mission in its day of glory. It can dream and it can guide the dreams of men. To do so it will need to present its visions humbly, and in the concepts of the universe that science offers. There are a few who labor to do just this. Their task is difficult, for the universe that science presents as probable is continuously altering, and grasping it depends upon mathematics that requires deep study for many years. Nevertheless, the opportunity is there to present wide-sweeping thought that will sway the minds of men.

And the theologian. He can accept the aid of science, which draws for him a wide universe in all its majesty, with life in all its awe-inspiring complexity. He can accept this, knowing that on the central mysteries science cannot speak. And he can then step beyond to lead men in paths of righteousness and in paths of peace.

And the young man. As always he will build his own concepts, and his own loyalties. He will follow science where it leads, but will not attempt to follow where it cannot lead. And, with a pause, he will admit a faith.

Memex Revisited

Vannevar Bush

While this essay was completed in 1965, it was not published until 1967 as Chapter V of Science Is Not Enough.

An Austrian monk, Gregor Mendel, published a paper in 1865 which stated the essential bases of the modern theory of heredity. Thirty years later the paper was read by men who could understand and extend it. But for thirty years Mendel's work was lost because of the crudity with which information is transmitted between men.

This situation is not improving. The summation of human experience is being expanded at a prodigious rate, and the means we use for threading through the consequent maze to the momentarily important items are almost the same as in the days of square-rigged ships. We are being buried in our own product. Tons of printed material are dumped out every week. In this are thoughts, certainly not often as great as Mendel's, but important to our progress. Many of them become lost; many others are repeated over and over and over.

A revolution must be wrought in the ways in which we make, store, and consult the record of accomplishment. This need holds true in science, in the law, in medicine, in economics, and, for that matter, in the broadest subjects of human relations. It is not just a problem for the libraries, although that is important. Rather, the problem is how creative men think, and what can be done to help them think. It is a problem of how the great mass of material shall be handled so that the individual can draw from it what he needs—instantly, correctly, and with utter freedom. Compact storage of desired material and swift selective access to it are the two basic elements of the problem.

I began worrying over this matter more than a quarter century ago, and some twenty years ago published an essay about it, called "As We May Think." Next in this present discussion I want to present some thoughts from that earlier paper. Then we will have a look at what has happened during the past two decades and try to see if we are any closer to the means of the needed revolution.

In that essay I proposed a machine for personal use rather than the enormous computers which serve whole companies. I suggested that it

Reprinted from Vannevar Bush's Science is Not Enough, *(New York, 1967), pp. 75-101, by permission of William Morrow and Richard Bush, MD.*

serve a man's daily thoughts directly, fitting in with his normal thought processes, rather than just do chores for him.

If it is to fit in with his normal thought processes, the heart of the matter is selection. Our present ineptitude in getting at the record is largely caused by the artificiality of systems of indexing. When data of any sort are placed in storage, they are filed alphabetically or numerically, and information is found (when it is) by being traced down from subclass to subclass. It can be in only one place, unless duplications are used; one has to have rules as to which path will locate it, and the rules are cumbersome. Having found one item, moreover, one has to emerge from the system, like a dog who has dug up a buried bone, and then re-enter the system on a new path. This is a serious handicap, even with the high-speed machinery just now beginning to be applied to the problem of the libraries.

The human mind does not work that way. It operates by association. With one item in its grasp, it snaps instantly to the next that is suggested by the association of ideas, in accordance with some intricate web of trails carried by the cells of the brain. The mind has other characteristics, of course: trails not frequently followed are apt to fade; few items are fully permanent; memory is transitory. Yet the speed of action, the intricacy of trails, the detail of mental pictures, is awe-inspiring beyond all else in nature.

Man cannot hope fully to duplicate this mental process artificially. But he can certainly learn from it; in minor ways he may even improve on it, for his records have relative permanency. But the prime idea to be learned concerns *selection*. Selection by association, rather than by indexing, may yet be mechanized. Although we cannot hope to equal the speed and flexibility with which the mind follows an associative trail, it should be possible to beat the mind decisively in the permanence and clarity of the items resurrected from storage.

To turn directly to that earlier discussion:

> Consider a future device for individual use, which is a sort of mechanized private file and library. It needs a name. To coin one at random, "memex" will do. A memex is a device in which an individual stores all his books, records, and communications, and which is mechanized so that it may be consulted with exceeding speed and flexibility. It is an enlarged intimate supplement to his memory. What does it consist of?

> It consists of a desk. Presumably, it can be operated from a distance, but it is primarily a piece of furniture at which an individual works. On its top are slanting translucent screens, on which material can be projected for convenient reading. There is a keyboard, and sets of buttons and levers. Otherwise, memex looks like an ordinary desk.
>
> In one end is its stored reference material. The matter of bulk can be well taken care of even by present-day miniaturization. Only a small part of the interior of the memex is devoted to storage, the rest to mechanism. Yet if the user inserted 5,000 pages of material a day it would take a hundred years to fill the repository. So he can be profligate, and enter material freely.
>
> Most of the memex contents are purchased on tape ready for insertion. Books of all sorts, pictures, current periodicals, newspapers, are thus obtained and dropped into place. And there is provision for direct entry. On the top of the memex is a transparent platen. On this our user places longhand notes, photographs, memoranda, all sorts of things. When one is in place, the depression of a lever causes it to be recorded on a blank space in a section of the memex memory.
>
> Memex has, of course, provision for consulting the record by the usual scheme of indexing. When the user wishes to consult a certain book, he taps its code on the keyboard, and the title page of the book promptly appears before him, projected onto one of his viewing positions. Frequently-used codes are mnemonic, so that he seldom consults his code book; but when he does, a tap of a key or two projects it for his use. Moreover, he has supplemental levers. By deflecting one of these levers to the right he runs through the book before him, each page in turn being projected at a speed which just allows a recognizing glance at each. If he deflects the lever further to the right he steps through the book 10 pages at a time; still further speeds scanning to 100 pages at a time. Deflection to the left gives him the same control backwards. A special button transfers the user immediately to the first page of the index. Any book of his library can thus be called up and consulted with far greater facility, comfort and convenience than if it were taken from a shelf. And his personal library is voluminous; if he had it present in paper it would fill his house or office solidly.
>
> He has several projection positions; hence he can leave one item in position while he calls up another. He can add marginal notes and comments, for the nature of his stored record is such that he can add or erase, quite as readily as though he were adding notes to the page of a book.
>
> So far, all this is conventional; a mere projection forward of present-day mechanisms and gadgetry. It affords an immediate step, however, to *associative* indexing, the basic idea of which is a provision whereby any

item may be caused at will to select another, immediately and automatically. This is the essential feature of the memex; the process of tying items together to form trails is the heart of the matter.

When the user is building a trail, he names it, inserts the name in his code book, and taps it out on his keyboard. Before him, projected onto adjacent viewing positions, are the items to be joined. At the bottom of each there are a number of blank code spaces; a pointer is set to indicate one of these on each item. The user taps a single key, and the items are permanently joined. In each code space appears the code word. Out of view, but also in the code space, is automatically placed a set of dots as a designation; and on each item these dots by their positions designate the index number of the other.

Thereafter, at any time, when one of these items is in view, the other can be instantly recalled merely by tapping a button adjacent to the code space. Moreover, when numerous items have been thus joined together to form a trail, they can be reviewed in turn, rapidly or slowly, by deflecting a lever like that he used for turning the pages of a book. It is exactly as though the physical items had been gathered together from widely separated sources and bound together to form a new book. But it is more than this; for any item can be joined into numerous trails, the trails can bifurcate, and they can give birth to side trails.

To give you a simple example, the owner of the memex, let us say, is interested in the origin and properties of the bow and arrow. Specifically he is studying why the short Turkish bow was apparently superior to the English long bow in the skirmishes of the Crusades. He has dozens of possibly pertinent books and articles in his memex. First he runs through an encyclopedia, finds an interesting but sketchy article, and leaves it projected. Next, in a history, he finds another pertinent item; he ties the two together. Thus he goes, building a trail of many items. Occasionally he inserts a comment of his own either linking it into the main trail or joining it, by a side trail, to a particular item. When it becomes evident to him that the elastic properties of available materials had a great deal to do with the superiority of the Turkish bow, he branches off on a side trail which takes him through text books on elasticity and tables of physical constants. He inserts a page of longhand analysis of his own. Thus he builds a trail of his interest through the maze of materials available to him.

His trails do not fade. Several years later, his talk with a friend turns to the queer ways in which a people resist innovations, even of vital interest. He has an example in the fact that the Europeans, although outranged, still failed to adopt the Turkish bow. In fact he has a trail on it. A touch brings

up the code book. Tapping a few keys projects the head of the trail. By lever, the user runs through it at will, stopping at interesting items, going off on side excursions. It is an interesting trail, pertinent to the discussion. So he sets a reproducer in action, records the whole trail, and passes the record to his friend for insertion in his own memex, there to be linked to a more general trail.

Now, is this all a dream? It certainly was, two decades ago. It is still a dream, but one that is now attainable. To create an actual memex will be expensive, and will demand initiative, ingenuity, patience, and engineering skill of the highest order. But it can be done.

It can be done, given enough effort, because of the great advances which have been made in mechanization, the instruments which have already been built in great numbers to aid man's computations and his thoughts, the devices already used for storing and consulting masses of data, the ingenious elements of electric and magnetic circuits which have been developed during the last two decades.

New and powerful instrumentalities have come into use to help it on its way toward birth. Highly sensitive photocells capable of seeing things in a physical sense; magnetic tapes that instantly record with utter faithfulness music or vision; advanced photography which can record not only what is seen but also what is not; transistors capable of controlling potent forces under the guidance of less power than a mosquito uses to vibrate his wings; cathode ray tubes rendering visible an occurrence so brief that by comparison a microsecond is a long time; transistor combinations which will carry out involved sequences of operations more reliably than any human operator and thousands of times as fast; miniaturization of solid-state devices which will put the complex circuitry of a radio set into the volume of a pinhead; video tapes which put the moving episodes of a football game onto a little strip of film, and instantly reproduce it—there are plenty of mechanical aids with which now to effect a transformation.

So it *can* be done. Will it be done? Ah, that is another question. The great digital machines of today have had their exciting proliferation because they could vitally aid business, because they could increase profits. The libraries still operate by horse-and-buggy methods, for there is no profit in libraries. Government spends billions on space since it has glamor and hence public appeal. There is no glamor about libraries, and the public do not understand that the welfare of their children depends far more upon effective libraries than it does on the collecting of a bucket of talcum powder from the moon. So it will not be done soon. But eventually it will.

To look forward to memex we will lean on what has already been done. Machines of today fall into two great divisions, first those that supplement man's muscles and his senses, and second those that aid his mind. We do not need to deal with the former, although they have made possible our modern civilization with all its benefits and its dangers. The latter are sometimes included under the general term of thinking machines, but this is an unfortunate expression, for they do not think, they merely aid man to do so. They are of two sorts, analytical machines and data-handling machines, and these are sometimes combined.

The great example of the first sort is the digital machine. It is often called a computer, but this is a misnomer, for the machine does far more than to compute. A single large unit costs several million dollars. Our present business organizations could not operate without it. Properly instructed, it can do about anything a man can do using pencil and paper, and do it a million times as fast. The only things it cannot do are those which distinguish a man from a machine.

It is told what to do by the insertion of a coded tape, and the preparation of this tape is called programming, of which more will be said later. When the computer has completed its job, it delivers its results by rapidly operating a typewriter, or sometimes by drawing them on a screen. It works entirely by using numbers, although these may also represent letters or instructions, and these numbers are in the binary system, that is, to a base two instead of the usual base ten. It gets the numbers it works on from the input tape, or from its own memory, where great masses of data are stored. The tape, and subsidiary instructions stored in the memory, tell it how to manipulate numbers for all its purposes.

Its main element is an elaborate network of electric circuits. These can manipulate numbers by addition, subtraction, multiplication, and division. Thus far it is indeed a computer. But it has, importantly, other circuits which can perform the operations of logic, and it is these which give the digital machine its great power. As a simple example, these can examine a set of numbers and pick out the largest. Or they can follow

one set of instructions or another according to the results of the moment. The machine does all of these things very rapidly indeed, many million operations a second.

Another type of analytical machine is the analogue machine. These are nowhere near so precise as the digital machines, but they are far less expensive and are genuinely useful for exploratory purposes, especially in engineering. The principal form is the differential analyzer which appeared some thirty years ago. To use one of these in examining a problem, say the problem of how a suspension bridge will behave in a gusty wind, one assembles an electric circuit which follows the same physical laws as the bridge, though usually with a different time scale, and which then moves a point of light on a screen in just the way in which the bridge will swing in the wind. One has set up an electrical circuit which obeys the same differential equations as the physical system under study, and which hence behaves in the same way, and then one watches it perform, usually by the pattern it produces on an oscillograph.

There are also special-purpose analytical machines which do not belong to either of these classes. An early one of these is the tide-predicting machine. There are also machines for statistical analysis, evaluating correlation coefficients and the like, and for solving integral equations, or interpreting x-ray diffraction patterns of crystals. Some of these have been crowded out by the great success of the digital machine, but they include ideas which should not be forgotten. Everything that can be done on analogue or special machines can also be done on a digital machine, although often not so neatly or flexibly or inexpensively.

Data-handling machines are also of various sorts, from the extremely simple card catalog up through the numerous ways of manipulating punched cards. The memory component of the digital machine is probably the most remarkable of the data-handling devices. Another should be mentioned as well. This is the rapid selector, which first appeared some twenty years ago. This would take a roll of photographic film containing 100,000 or so items in single frames, and select desired items from these in accordance with a code in the margin. It could do so while viewing the items at the rate of 1000 per second. And it printed out the selected items on a short piece of similar film.

Each item could consist of a page of print, drawings, or photographs. There are now a variety of modern forms of this device. Some of them combine the sorting and ordering facility of the punched-card equipment with rapid selection by code. The same sort of thing can of course be done with magnetic tape.

The evolution of data-handling equipment thus has involved two important features: compression, which allows great masses of data to be stored in a small space, and rapid access, by which a single piece of information can be located and reproduced in a very brief time.

The development of detailed devices or elements did not alone make this whole range of equipment possible. There is another, and very important, general consideration which should be noted:

Over three centuries ago Pascal constructed a calculating machine which embodied many of the essential features of recent keyboard devices, but it could not then come into use. The economics of the situation were against it; the labor involved in constructing it, before the days of mass production, exceeded the labor to be saved by use of it, since all it could accomplish could be duplicated by sufficient use of pencil and paper. Moreover, it would have been subject to frequent breakdown, so that it could not have been depended upon; for at that time and long after, complexity and unreliability were synonymous.

Only a century ago, Babbage, even with remarkably generous support, could not produce his great arithmetical machine. His idea was sound enough, but construction and maintenance costs were then too heavy. Inexpensive construction is a new thing. Had a Pharaoh been given detailed and explicit designs of an automobile, and the tools with which to work metal, and had he understood them completely, it would have taxed the resources of his kingdom to fashion the thousands of parts for a single car, and that car would have broken down on the first trip to Giza.

Machines with interchangeable parts can now be constructed with great economy of effort. In spite of much complexity, they perform reliably. It is this reliable complexity, attained at reasonable cost, produced by hard work and the rigors of competition over many years, together with the advance of basic science, and finally man's ingenuity, which has now made it possible to lighten the burden on man's mind, as earlier developments lifted the load from his muscles.

An excellent example of how the advance goes forward is the history of the thermionic tube and the transistor. The thermionic tube was, at its inception, largely a matter of ingenious tinkering, without much reliance on science. Edison, who was no scientist, noted a current from the filament of one of his electric lamps to a plate he put in, but he did nothing about it. De Forest, who probably knew still less science, added a grid between them, and the thermionic tube was born. For many years it was erratic in operation and likely to fail at any moment. Then engineers learned to make a really good vacuum and it became much better. Finally it became so reliable that it could be installed in an amplifier of a submarine cable at the bottom of the sea and expected to last for forty years. It became so rugged that, in the proximity fuzes of the war, it could be put into a shell, fired out of a gun, and still be expected to work as a sensitive electronic detector.

Then came the transistor, which has superseded the tube for most purposes. This certainly did come out of the application of science. A group of men, working on the theory of electric conduction in solids, soon saw how the phenomena they predicted, and checked in the laboratory, could be put to use. The transistor, which can be as small as the eye of a fly, requiring extreme precision of construction, rugged and long lived when once built, is perhaps the most versatile device man has yet produced. With the use of very little power, and in a small space, it will amplify, modulate, rectify, and do dozens of other things. It is one of a whole family of devices based on the use of semiconductors: photoelectric cells, rectifying valves, etc. When the transistor is combined with other elements, resistors and capacitors, sealed in a resin, an assemblage the size of a thimble will do all that used to be done by a radio receiver as large as a suitcase. More than this: by some very modern methods of depositing very thin layers of material in a vacuum, the whole thing can be reduced to a thin wafer the size of a flyspeck, and a thousand such can be produced identically in a single manufacturing operation.

A very great advance—possibly the greatest so far—as we look toward the future memex, is magnetic tape. We have known it for some time in dictating machines. It hit the market modestly soon after the war, and, around 1958, tapes appeared capable of carrying great detail, so much so that video tapes appeared carrying an entire television broadcast with its 70,000 or so complete pictures on a single reel. The idea is a simple one, and the tape is merely a plastic strip covered with magnetic material in finely powdered form. As it passes over an electromagnet, the voice, picked up by a microphone, causes the strength of that magnet to vary, and these variations become impressed on the tape in the form of its magnetization. A wavy form of air vibrations from the voice becomes an identically wavy form of magnetism on the tape. Then, when the tape is run in front of a coil, the voltages there produced can be amplified and fed into a loudspeaker, and a replica of the original voice appears as sound waves in the air.

All this is now ancient history. But it is relatively new to put on the tape the variation of light impinging on a photocell as an optical system sweeps its view over a scene, and to do this so that all the details of a complex scene are thus recorded in a small fraction of a second. And then to reverse the process and reproduce the scene to a viewer a thousand miles away.

In our living rooms, we watch a football game. A television camera is scanning the scene line by line, twenty-four pictures a second. The response of its photoelectric equipment, transmitted a thousand miles to our living room, controls the intensity of an electron beam which sweeps over our TV screen and reproduces the play as it occurs. But the output of the camera also sweeps over a fairly broad magnetic tape, and magnetizes it. Thus, a few moments after a play occurs, the tape record can be re-scanned, and the result transmitted to our TV set, so that we can see the play over again. To accomplish this, using a reasonable amount of tape, has required a great compression of the magnetic record. But it has been done and is now accepted by television viewers as a commonplace.

Another important feature of magnetic tape, for our future memex, is that it can be erased. Fortunately, this is easy. One merely sweeps a permanent magnet over the tape and the record is gone. When we take a photograph we are stuck with it; to make a change we must take another whole photograph. But with a magnetic tape which presents to us a picture one can cancel half a line, if he will, add a changed line, or put in a marginal note or code. The moving finger writes, but its record is not here irrevocable.

The advent of the laser may bring photography back into competition for memex storage. It can produce such a small spot of light that there is a factor of 100 or more on compactness compared to magnetic storage. The spot can be intense, so much so that it is used to bore small holes in diamonds, and this means a photographic record can be made in a very short interval, and read out equally rapidly for projection. The film used can be of such low sensitivity that daylight will not affect it appreciably, and the usual processes of development can be avoided, which means parts can be obliterated and additions made to the record.

Beyond this the laser renders possible an exciting process called holography, which may render it possible to project the record so that it is three-dimensional. This is an utterly new form of three-dimensional projection, for it is as though the original scene or model were actually present, and one can move about and view it from various angles. There are many tough problems to be solved before the use of the laser for such purposes becomes practicable. But, for a long view ahead, it exhibits a wholly new field of versatility in which ingenuity will certainly produce results.

There is a point here worth pausing to consider for a moment. For the purposes of memex we need a readily alterable record, and we have it. But alteration of records has a sinister connotation. We watch a girl on the screen moving her mouth and someone else is doing the singing. One can put into a man's mouth for all to hear words he never spoke. The ingenuity which special-effects men use on television is often amusing, sometimes powerfully dramatic, sometimes annoying, as when a razor is seen to shave sandpaper. Advancing technology is making it easy to fool people. It would be well if technology also devoted itself to producing forms of records, photographic, printed, sound-recorded, which cannot be altered without detection, at least to the degree of a dollar bill. But it would be still more effective if the code of morals accepted generally rendered it a universally condemned sin to alter a record without notice that it is being done.

It is thus fairly clear that there is no serious problem today in assembling, editing, and correcting the record, or in compressing it into as small a volume as we may need for memex. If we wish it, a whole private library could be reduced to the volume of a matchbox; similarly, a library of a million volumes could be compressed into one end of a desk. If the human race has produced, since the invention of movable type, a total record in the form of magazines, newspapers, books, tracts, advertising blurbs, correspondence, having a volume corresponding to a billion books, the whole affair, assembled and compressed, could be lugged off in a wheelbarrow.

Compression is important not only to keep us from being swamped, but also when it comes to costs. The material for a microfilm private library might cost a nickel, and it could be mailed anywhere for a few cents. What would it cost to print a million copies? To print a sheet of newspaper, in a large edition, costs a small fraction of a cent. The entire material of a private library in reduced film form would go on ten eight-and-one-half-by-eleven-inch sheets. Once that was available, with the reproduction methods now available, duplicates in large quantities could probably be turned out for a few cents apiece beyond the cost of materials.

Mere compression, of course, is not enough; one needs not only to make and store a record, to add to it at will, and to erase, but also to consult it. As things are now, even the modern great library is not generally consulted; it is nibbled at by a few. How to consult the new compressed record is a major question in selective analysis.

The great digital computers of today keep their extensive records in various ways. The records constitute their memory, which they consult as they proceed with computation. They use magnetic tapes or disks. But they also use great arrays of minute toroids of magnetic material, interlaced with fine wires. The reason for these latter is the necessity of rapid access. The fast access, in a computer, is fast indeed, and has to be. Times, for them, should be mentioned in nanoseconds, or billionths of a second. In a nanosecond light will move only about one foot. That is why it is important to keep the components of a computer small; its speed of operation is sometimes limited by the time necessary to get an electric pulse from one part to another. The storage in little toroids can respond in times like these.

No problem of speed of access need bother the future memex. Indeed, for memex we need only relatively slow access, as compared to that which the digital machines demand: a tenth of a second to bring forward any item from a vast storage will do nicely. For memex, the problem is not swift access, but selective access. The indication of a possible beginning here is to be found in the rapid selector mentioned earlier. When items on frames projected for viewing can readily have codes entered in their margins, by which they can automatically select other items, we have a significant step toward memex. But the access problem is by no means solved. The storage of memex will be huge, and all parts of it need to be promptly available.

Clearly, we need to study further how the human brain meets this puzzle. Its memory system consists of a three-dimensional array of cells, each cell very small compared to even the volume of magnetic tape used for a single impulse, and the magnetic tape is two-dimensional. We make three-dimensional storage, for example, by an array of toroids, but the units here are huge compared to a cell. Somehow the brain consults this full array and brings into consciousness, not just the state of one cell, but the related content of thousands, to recall to us a scene of a decade ago. We have very little idea as to how it is done. In fact we do not even know what we mean when we write "consciousness." If there is a roadblock in the path toward a useful memex, it lies in this problem of moderately rapid access to really large memory storage.

The heart of this problem, and of the personal machine we have here considered, is the task of selection. And here, in spite of great progress, we are still lame.

Selection, in the broad sense, is still a stone adze in the hands of a cabinetmaker. Yet, in a narrow sense and in other areas, something has already been done mechanically on selection. The personnel officer of a factory drops a stack of a few thousand employee cards into a selecting machine, sets a code in accordance with an established convention, and produces in a short time a list of all employees who are females, live in Trenton, and know Spanish. Even such devices are much too slow when it comes, for example, to matching a set of fingerprints with one of five million on file. Selection devices of this sort have now been speeded up from their previous rate of reviewing data at a few hundred a minute. The great computer will enter its active memory and select a desired item in a microsecond or less, if it is told just where to go for it, and in an interval which is still very brief if it has to hunt for it.

So much for the methods of storing record and of retrieving items from storage. But what about the making of the record? Is it possible that somewhere during this procedure we may find ways of anticipating the selective needs to be encountered later when one wishes to consult that record? Our record-making system of today should remind us of the covered wagon; we are bound to have to improve it, and in doing so we must have an eye to the possibilities of coding, cross-linking, and all else that will be requisite to selective access.

Today, to make a record, we still push a pencil or tap a typewriter. Then comes the business of digestion and correction, followed by an intricate—and largely cockeyed—process of typesetting, printing, and distribution. To consider the first stage of procedure, will the author of the future cease writing by hand or typewriter and talk directly to the record? He does so (indirectly) even now, of course, by talking to a stenographer or into a dictating machine. And there is also the stenotype, that somewhat disconcerting device encountered in court or at public meetings. The operator strokes its keys languidly and looks about the room and sometimes at the speaker with a disquieting gaze. From the machine emerges a typed strip which records, in a phonetically simplified language, what the speaker is supposed to have said. Later this strip is retyped into ordinary language, for in its nascent form it is intelligible only to the initiated. It would be fairly easy to rig a device to operate a stenotype as one talked. In short, if anyone wishes to have his talk directly produce a typed record, all the elements are here. All he needs to do is to take advantage of existing mechanisms—and alter his language.

Our present languages are not well adapted to mechanization. True, digital machines can be made to translate languages, Russian into English, for example. As with their writing of poetry or composition of music, one wonders, not that they do it badly, but that they do it at all. So far, machine translation has not become really useful. But it is improving, and the study that is being devoted to the problem is showing us much about the nature of languages themselves. It is strange that the inventors of universal languages, none of which have ever caught on, have not seized upon the idea of producing one which better fits the technique for transmitting, recording, and modifying speech.

The business of communication between men and machines thus is a complex affair. Men's language has grown without reference to machine use, and now, if we try to talk directly to a machine, it will not understand us. Even if we write or type our material, we have to be careful to put it in form that the machine can grasp.

We see a simple example of this in the numbers put on bank checks with magnetic ink, so that machines can sort them. They have a faint resemblance to figures as we ordinarily write them, but to the machine their altered form is entirely clear.

A better example occurs with the digital computers. These can do extraordinary things, but only if they are given explicit and detailed instructions on how to do them. The process of instruction, programming, uses a special language, incomprehensible to the layman, learned by a human operator only after careful study and experience, but lucid and unambiguous to the machine. There are several new languages under development for this purpose of telling digital computers what to do and how to do it. They are in terms of binary numbers, when they enter the machine, for that is the natural language of the computer.

We will not expect our personal machine of the future, our memex, to do the job of the great computers. But we can expect it to do clever things for us in the handling of the mass of data we insert into it. We particularly expect it to learn from its own experience and to refine its own trails. So our means of communication with it merits careful consideration. Usually we will tell it what to do by pushing a button or moving a lever. Pushing just one button will often call up a fairly complicated internally stored set of instructions. This will serve for ordinary use. But it would be nice, and easily arranged for, if the machine would respond also to simple remarks. If Fido will respond to "lie down," the machine ought to respond readily to such a remark as "hold it."

This matter of a memex learning from its own experience merits some discussion. A digital machine can now be caused thus to learn. Such machines, for example, can be set up to play checkers with a human opponent. Chess is too much for them, because of its complication, which merely means that it calls for an excessive amount of storage and time, but they do very well at checkers. In fact, they can learn to beat a good player. In the digital machine's memory is stored a large number of positions that may occur in a game, and possible following moves to be used. But positions and moves are rated in accordance with assumed values. Confronted with a position, the machine consults its memory and chooses the best-rated move to use. But now comes the real point. It continually alters the rating of the moves in accordance with its success or failure. If a move results in a more highly valued position, its rating goes up, and if it results in catastrophe, it goes down. In this way the machine learns. Playing at first a very poor game, it finally becomes expert.

A memex can be constructed to do similar things. Let's say its master is a mechanical engineer, and that he has a trail which he uses very frequently on the whole subject of heat transfer. The memex notices (we have to use such terms; there are no others) that nearly every time he pursues the trail there are a series of items on which he hardly pauses. It takes them out of the main trail and appends them as a side trail. It also notices that when he comes to a certain item he usually goes off on a side trail, so it proceeds to incorporate this in the main trail.

It can do more than this; it can build trails for its master. Say he suddenly becomes interested in the diffusion of hydrogen through steel at high temperatures, and he has no trail on it. Memex can work when he is not there. So he gives it instructions to search, furnishing the trail codes likely to have pertinent material. All night memex plods on, at ten or more pages a second. Whenever it finds the words "hydrogen" and "diffusion" in the same item, it links that item into a new trail. In the morning its master reviews the new trail, discarding most of the items, and joining the new trail to a pertinent position.

Does this sort of thing sound bizarre or far-fetched? Machines are doing more surprising things than this today.

Much needs to occur between the collection of data and observations, the extraction of parallel material from the existing record, and the final insertion of new material into the general body of the common record. For mature thought there is no mechanical substitute. But creative thought and essentially repetitive thought are very different things. For the latter there are already powerful mechanical aids. We shall need still more.

In particular we have delved far enough into the chemical processes by which the human body operates to grasp the fact that we shall never come to full understanding in this enormously complex field until our processes of reasoning have been greatly refined, and divested

of all the clutter of repetitive acts which now take up most of the time that we consider we are devoting to thought. For this reason there will come more machines to handle advanced mathematics and manipulation of data for the scientist. Some of them will be sufficiently bizarre to suit the most fastidious connoisseur of the present artifacts of civilization.

The scientist, however, is not the only person who manipulates data and examines the world about him by the use of logical processes, though he sometimes preserves this appearance by adopting into the fold anyone who becomes logical, much in the manner in which a British labor leader is elevated to knighthood. Whenever logical processes of thought are employed—that is, whenever thought for a time runs along an accepted groove—there is an opportunity for the machine. In fact a machine which will manipulate premises in accordance with formal logic has already been constructed. Put a set of premises into such a device and turn the crank; it will readily pass out conclusion after conclusion, all in accordance with logical law, and with no more slips than would be expected of a keyboard adding machine.

Logic can become enormously difficult, and it would undoubtedly be well to produce more assurance in the use of it. The machines for higher analysis have usually been equation *solvers*. But we now have equation *transformers*, which will rearrange the relationship expressed by an equation in accordance with strict and rather advanced logic. Progress here is a bit inhibited by the exceedingly crude way in which mathematicians express their relationships. They employ a symbolism which grew like Topsy and has little consistency; a strange fact in that most logical field.

What might be the consequences of the developments we have been discussing? Assuredly they would *not* be limited to the men of science. It could be hoped that the writing of history and biography, for example, would improve, not just in accuracy, but in art, as the writer is able to turn the drudge part of his task over to a tireless assistant, always willing to work when he is, and never at a loss to divine what he wishes to remember. Wholly new forms of encyclopedias will appear, ready-made with a mesh of associative trails running through them, ready to be dropped into the memex and there amplified. The lawyer will have at his touch the associated opinions and decisions of his whole experience, and of the experience of friends and authorities. The patent attorney will have on call the millions of issued patents, with familiar trails to every point of his client's interest. The physician, puzzled by a patient's reactions, will strike the trail established in studying an earlier similar case, and run rapidly through analogous case histories, with side references to the classics for the pertinent anatomy and histology.

Another area in which new machine accomplishments are needed is organic chemistry. These accomplishments are just beginning to appear. There are millions of organic compounds that have been studied, and an unlimited number of possible ones, many of them no doubt useful. The organic chemist is in a tough spot. His memory is severely taxed, and much of his time is consumed in labor that does not call on his true skills. He ought to be able to turn to a machine with a specification of a compound, in terms of either its form or its properties, and have it immediately before him with all that is known about it. Moreover, if he then proposes a chemical manipulation on such a compound, the machine should tell him, within the limits of knowledge at the time, just what will happen. It would do so by using the known laws of chemistry, and the chemist should turn to experiment in the laboratory only for confirmation, or when entering unexplored territory. We are a long way today from such a situation. But machines can certainly do this, if we build them intelligently and then tell them what to do.

The historian, of whom I have spoken above, with his vast chronological account of a people, can parallel this with a skip-trail which stops only on the salient items; he can follow at any time contemporary trails which lead him all over civilization at a particular epoch. There will be a new profession of trailblazers, those who find delight in the task of establishing useful trails through the enormous mass of the common record. The inheritance from the master will become, not only his additions to the world's record, but for his disciples the entire scaffolding by which they were erected. Each generation will receive from its predecessor, not a conglomerate mass of discrete facts and theories, but an interconnected web which covers all that the race has thus far attained.

When the first article on memex was written, the personal machine, the memex, appeared to be far in the future. It still appears to be in the future, but not so far. Great progress, as we have seen, has been made in the last twenty years on all the elements necessary. Storage has been reduced in size, access has become more rapid. Transistors, video tape, television, high-speed electric circuits, have revolutionized the conditions under which we approach the problem. Except for the one factor of better access to large memories, all we need to do is to put the proper elements together—at reasonable expense—and we will have a memex.

Will we soon have a personal machine for our use? Unfortunately not. First we will no doubt see the mechanization of our libraries, and this itself will take years. Then we will see the group machine, specialized, used by many. This will be especially valuable in medicine, in order that those who minister to our ills may do so in the light of the broad experience of their fellows. Finally, a long time from now, I fear, will come the personal machine. It will be delayed in coming principally by costs, and we know that costs will go down, how much and how rapidly none can tell.

It is worth striving for. Adequately equipped with machines which leave him free to use his primary attribute as a human being—the ability to think creatively and wisely, unencumbered by unworthy tasks—man can face an increasingly complex existence with hope, even with confidence.

Presumably man's spirit should be elevated if he can better review his shady past and analyze more completely and objectively his present problems. He has built a civilization so complex that he needs to mechanize his records more fully if he is to push his experiment in its proper paths and not become bogged down when partway home by having overtaxed his limited memory. His excursions may be more enjoyable if he can reacquire the privilege of forgetting the manifold things he does not need to have immediately at hand, with some assurance that he can find them again if they prove important.

The applications of science have built man a well-supplied house, and are teaching him to live healthily in it. They have also enabled him to throw masses of people against one another with cruel weapons. They may yet allow him truly to encompass the great record and to grow in the wisdom of race experience. He may perish in conflict before he learns to wield that record for his true good. Yet, in the application of science to the needs and desires of man, this would seem to be a singularly unfortunate stage at which to terminate the process, or to lose hope as to the outcome.

From "Of Inventions and Inventors"

Vannevar Bush

This passage is taken from Chapter V, "Of Inventions and Inventors" in Pieces of the Action, *Bush's autobiography.*

As I NOTED EARLIER, there is a story to be told in connection with the differential analyzer, for it illustrates a number of things that I am anxious to clarify. There is no question that my young assistants and I developed the differential analyzer at M.I.T. during the twenties. But who invented it? Ah, that is hard to answer for it depends upon how we define invention.

First, what is a differential analyzer? It is the first of the great family of modern analytical machines to appear—the computers, in ordinary parlance. It is an analogue machine. This means that when one has a problem before him, say the problem of how a bridge that has not yet been built will sway in a gusty wind, he proceeds to make a combination of mechanical or electrical elements which will act in exactly the same manner as the bridge—that is, will obey the same differential equations—and then by noting how this combination acts he will be able to predict the performance of the bridge. The trick, in a really useful device, is so to construct this model that by shifting some mechanical connections, or better by switching some electrical circuits, one can make it possible to handle a wide variety of differential equations, and hence of practical problems. If one does not know what a differential equation is, perhaps I can make it clear by a very simple example. Suppose an apple drops from a tree. One is supposed to have done so, to have hit Isaac Newton on the head and thus cleared his mind, although I doubt it. The thing we know about that apple is, to a first approximation, that its acceleration is constant, that is, that the rate at which it gains speed as it falls does not vary. So we just write this fact down in mathematical symbols. That is a differential equation, one very easy to solve, and thus we are enabled to make a plot of the position of the apple at every instant. But suppose we want to include the resistance that air offers to the fall. This just puts another term in our equation but makes it hard to solve formally. We can still very readily solve it on a machine. We simply connect together elements, electrical

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