Information: The Ultimate Frontier

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Not too long ago I was invited to a conference that was called to look into the future of technology. The organization that invited me, along with such distinguished scientists as Murray Gell-Mann of Caltech and Bernd Matthias of the University of California, was a government agency, and, in keeping with its policy, it did not tell us the purpose of the meeting until we arrived. Once there, however, we could understand why it was kept quiet. This agency wanted to know what big scientific discoveries were in the offing in the next two decades. When it became clear that this discussion was going nowhere, Gell-Mann volunteered the suggestion that the agency had brought in the wrong people.

Summary. Although long-term forecasting is best left to science fiction writers, scientists can illumine basic technological trends, as in the 100-year scenario presented here. Computers will continue the "small is beautiful" trend, but they are not likely to follow the semilog trail because extrapolation from the current base would lead to absurdities such as a computer cost of 3/100 of a cent. To achieve inexpensive high speed and Lilliputian size, new techniques are likely to replace silicon technology. The ultimate computer might be biological and patterned on DNA. Future computers will reacquire information when needed rather than store it, and we will see personalized products at mass production prices. Light wave communication will broaden communications exchange, but software that is more friendly to human users will be needed. By taking over knowledge distribution, electronic information systems will let universities concentrate on new knowledge. More importantly, they will expand everyone's right to information and free expression through the existing media system and to protection from misuse of information by others.

"The people you need here," said Gell-Mann, "are the science fiction writers. They are skilled in telling you what will be discovered in the next 20 years. We scientists are the experts in why these visionary ideas won't work." "I agree," Matthias broke in, "but why call a meeting of science fiction writers? Just read the 30 year predictions they wrote ten years ago."

What I shall attempt here is the difficult dual task of indicating what will not happen and what will happen in information technology not only in 20 years, but in 100 years. Bravely, I shall try to do both without the aid of the science fiction writer. I will, of course, look at the technology and its limitations—which I really think cannot be done beyond 10 or 20 years—and then at the challenges posed by the powerful social changes that inevitably accompany hardware and software developments.

To place the information resource in perspective consider food and energy, which are of course basic resources of mankind; we need to know how available they are. But that is not enough. We also need the wisdom to manage their distribution. That takes information—the kind of information that does not simply end up with a count of the starving, but that provides the immediate logistics as well as the models and concepts for bringing about distribution promptly, equitably, and efficiently.

In this connection it is interesting to note that there is another striking difference between the three resources. Food and energy challenge us because they are in short supply in major areas of the world. In both cases the challenge seems to be, How do you manage shortage? Information is quite different. It is in quantitative surplus. To be sure, there are great gaps in human knowledge that have yet to be filled by research and study. But the yawning chasm is between what some people have learned, yet others have not put to use. Indeed there seems to be more information around —good and bad—than anyone can use. I have heard it said we are living in a world of information junk, which is reminiscent of critical remarks often made about certain foods.

On top of that, there are other features of information resources that distinguish them from food and energy. Information does not disintegrate when it is used: in fact, consumption generally increases its value. It need not go away—or rot—when you do not use it. And no natural law limits how much of it people can have. The more you have, the more you want, and the easier it is to get.

The trouble is, nobody knows how to measure the worth of information. It often depends on who has it, or who does not have it, and what it takes to generate information when needed. People rarely distinguish between data, information, knowledge, and wisdom. Yet they are as different from one another—and as interlocking—as starch molecules, flour, bread, and the flavorful memory of a superb morning croissant.

The question in information is, How do you handle a situation of plenty? What is even more difficult, since so many individuals are information poor, how do you use the surplus of information in society to overcome the scarcity of information available to individuals?

Information and Communication: The Computer

The key element of course, if you will pardon my announcing it so soon, is the computer, which is not only an information machine, but also a communications device. The two terms—information and communication—are often blurred when they are tossed about loosely, but it is important to make the distinction if one is to look at what may happen in the upcoming years. When information is available in machine-readable form it can be both processed and communicated. Processing permits meaningful manipulations of the contents of the electronic traffic, thus enhancing its value. Communicating, from an engineering point of view, means simply moving electronic traffic from one place to another. It matters little if the signal represents random noise or a Shakespearean sonnet.

Now with this in mind we can take a look at what is happening in the field of information technology. The trend of the

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computer industry, as we all know, has been toward computers that are smaller, faster, and cheaper, to give us more computer power per dollar. The impetus for this increase in computer power has come from several directions. The most important is the improved performance of the electronic circuitry, which has brought switching speeds into the picosecond, or trillionth of a second, range. Since the time taken for an electrical impulse to move from one circuit to the next is a major limitation on computer speed, the circuits have to be packed very close together.

Circuitry

To illustrate this point, let us say that a decade from now there is a need for a basic computer operation at the rate of ten machine cycles per nanosecond, or billionth of a second. Ten cycles per nanosecond is 50 times the speed of the fastest computer today. To build such a machine the designer will have to face the fact that an electrical signal can travel no faster than the speed of light, or only about 3 centimeters (a little more than 1 inch) in 1/10 nanosecond. To avoid deleterious transmission delays we would have to fit all the circuits into a hypothetical computer no bigger than a 1-inch cube, something you could wear on a watch chain, in order to carry out the proposed operation. (Incidentally, this 1-inch cube will be my last mention of inches. By the year 2078 I would expect this nation to be metric at last. Five years ago I helped draft the law that ordained conversion to the metric system in the United States in 10 years. I would think we might have enough time to make it by 2078.)

To get back to our Lilliputian world, I have to point out that in computer electronics—as in Disney World—small is beautiful. When integrated circuits are densely packed, as they would be in our little cube, it takes less energy to drive them fast. Furthermore, the smaller the circuits the cheaper they are to make. Such circuits—300,000 might be needed in the hypothetical computer I have described—would certainly have to be laid out in patterns with dimensions smaller than 1 millionth of a meter, which can only be done with exotic techniques such as x-rays or electron beams. But since each circuit would have to switch at incredibly fast speeds, it would generate heat on the order of a few milliwatts. For the entire miniature computer the power to be dissipated would amount to about 1 kilowatt, enough to operate a two-slice toaster. In today's semiconductor technology—and even in future technology—it is extraordinarily difficult to draw off this amount of heat from 1 cubic inch of circuitry without damage. In short, the power laws of physics make it difficult for us to envision the development of midget supercomputers with silicon semiconductors.

Silicon technology has served us well for 25 years and is likely to continue in this service for a long time to come. Yet it clearly has its limits. Other semiconductors such as gallium arsenide are under investigation. Gallium arsenide may turn out to be faster than silicon, but it too shares the limits of silicon. So we have to start thinking now about other technologies that can support computer progress in the following decades.

Fortunately, a new technology is on the horizon. It looks as if it might take over from silicon and other semiconductors for high-performance processors and give us smallness and high speed with extremely low power dissipation. Called Josephson technology after British Nobelist Brian Josephson of Cambridge University, it uses metal alloys cooled to the temperature of liquid helium, 4.2 degrees above absolute zero. At this temperature, where virtually all molecular motion ceases, many metals lose their normal resistance to the flow of electricity and become superconducting. When two such superconducting metals are put very close together in the form of a thin sandwich, a magnetic field from a nearby current source determines whether electrons will bridge the gap. The gap, by the way, actually contains a dielectric a dozen atoms thick. The electrons set up a rivulet of electricity that tunnels through the sandwich and switches the device.

In IBM's laboratories at Zurich and at Yorktown Heights, New York, fragments of computer circuitry have been built on the Josephson principle and have operated successfully. Individual circuit devices have demonstrated a switching time faster than 20 trillionths of a second. There are still difficulties to be overcome with this technology, but it promises to lead us to a computer that is very small, very fast, and very cold—and, I might add, very expensive, at least initially. In 1973, IBM's Leo Esaki and General Electric's Ivar Giaever shared the Nobel Prize for Physics with Brian Josephson. The three were honored for laying some of the scientific foundations of this new technology of superconducting electronics. It is important to note that these scientists, along with another trio, John Bardeen, Leon Cooper, and Robert Schrieffer, who shared the prize the previous year, have made it possible to understand the fundamentals of Josephson technology at least as clearly as silicon technology. Because the theory is so well established, we are hopeful that progress in Josephson development will be rapid.

Memory

Let us now look at the memory side of the computer and see how it too has changed and where it might be going in its own evolution. One way of approaching the development of computer memory is to compare it with another great intellectual storage facility, the library. The information content of a huge library such as the Library of Congress can be reduced to the language of bits by simply doing a little arithmetic. We are told that, as of September 1977, the Library of Congress had 18,320,256 books and pamphlets. Let us give them credit for 20 million books today. If there are 300 pages in a book, with each page consisting of roughly 1500 letters, this gives us 450,000 letters per book. The 20 million books would thus become 9×10^{12} letters or about 70 trillion bits. Now the IBM 3850 Mass Storage System will hold 3.8×10^{12} bits, which by a process of division informs us that the volume of books in the Library of Congress could be stored in less than 20 IBM 3850's.

So far I have been talking about a future that is almost here, not about the year 2078. To stretch that far I am going to have to rely on the tools of the technological forecaster, since I am not a science fiction writer. But I should warn you that I am on record as ardently opposed to the use of graphical extrapolation as a way to predict the technical future. In fact, I have publicly advocated a ban on the sale of the main tool of the forecaster: semilog graph paper.

Since nobody has taken up my proposal, I will now use semilog graph paper to examine the rate of growth of computer storage capacity available at a given cost—which has averaged nearly 35 percent a year for a couple of decades. Even if that slowed down to 21 percent a year in the future, we can see that in 100 years the same investment that would hold 20 million books in computer storage today would finance 1.5×10^{10} or 15 billion electronic libraries, one each for the 15 billion human beings I expect will be living on the earth in 2078.

Of course, this is a rather daring extrapolation of progress in magnetic storage, as well as in a few other fields. In magnetic storage it implies a surface area of only 3 square angstroms, or the area of one atom, for the magnetization that stores one bit. That is a very small magnetic domain, and I am not sure that this prediction will come about.

Library storage, in terms of information per square centimeter, is fairly primitive when you consider the storage potential of the human brain, and here the figures that we can project become more audacious, if that is possible. Let us, for instance, quantify the capacity of the brain in terms of bits by assuming that each synapse is the equivalent of a storage element. On the best physiological evidence the brain has 10^{13} synapses, or a comparable number of bits. Twenty-five years ago a computer memory packing this much information would have filled a small mountain 500 meters high. Since 1953, main computer memory has shrunk 800 times in size and is continuing to shrink at the same rate.

If we again degrade this rate of progress to 21 percent per year and project a century ahead (more semilog graph paper, please), we come to the astounding conclusion that the information density of the computer will actually outstrip that of the brain—assuming that the pace of human evolution will not suddenly speed up. Of course, the comparison is not exactly fair. There are tricks of association with which the brain stores information that somehow the computer has never matched.

Nonetheless, on the basis of the growth indicated, the computer of the year 2078 will contain the data memory equivalent of 16,000 human brains—the equivalent of a university population, including graduate students. While I am at it, I might add another improbable figure to this project. That figure is cost. If today's largest computer costs $5 million, and the cost per bit of on-line memory and per circuit of logic is decreasing at the rate of only 21 percent a year, then in 2078 the cost of a computer with the power of today's big machines will be extraordinarily low—in fact, 15 billion times lower, or down to 3/100 of a cent. Nobody believes, of course, that this will happen. I expect that some of the largest computers of the year 2078 will have to sell for around the same price as today; of course, the power and usefulness will improve enormously—perhaps by that same factor of 15 billion.

All in all, it does seem unlikely that semiconductor memory—or "magnetic bubble" memory, a new form of storage that may replace magnetic disks—will continue to shrink in size and cost for another 100 years at the same rate we have enjoyed in the last decade. In fact, if we are still using semiconductors 100 years from now and have invented nothing new, we would have only three atoms of space to work with in the memory cells of the computers of that era. This is not much, so we will have to invent something else.

As far as I can see, that something else will have to be a complex three-dimensional memory cell, which will have the power to self-replicate. Do we have a model of this? Of course—it is a strand of DNA, which has a genetic memory of 10^{10} bits of information and is programmed to rebuild itself from its own chemical storage to accommodate new experiences. A molecule of DNA not only has a specific chemical composition, it has a specific structure unique to its information content. Before the 100 years are up, we will probably have to build a biological crystal computer out of something like DNA; in short, we may have to reinvent the brain. Science fiction, of course, has arranged that for us already, which shows that Professors Gell-Mann and Matthias were on the right track. Perhaps we could have found the answers to the computer future in the science fiction plots of 100 years ago.

Access to Information: The Next 100 Years

So far in this survey we have been talking about information already inside the computer, where it moves at high speed and inexpensively. It is interesting to note, however, that the hardest problem concerns how information gets into the computer in the first place—and how you get the needed results out.

Here, too, new technology is on the way to help. The computer of the future will not have to be approached by pushbutton or typewriter key or a punched card. It will respond to speech. This capability will take a decade or so to be fully realized. Then you will need only tell the computer what it should know to have the computer respond. Computers of the future will also be able to "read" by pattern recognition more rapidly than ever, so that visual processing will also become natural to the new and advanced generation of computers. The tyranny of the typewriter's limited character set has already been broken by computer-processed pictures and symbols, which will be added to text to enrich our "written" languages. The computer's ability to read symbols by using pattern recognition logic will be matched by its ability to write symbols, using display screens and nonimpact printers. Two emerging examples of nonimpact printer technologies are printing by ink jets and printing by laser electrophotography.

This trend, already well under way, will ultimately completely obscure the technical distinctions between information technologies. Typewriters, television, movies, telephones, and even radio, records, and tapes will all become interrelated and interchangeable. The printing press is going electronic too, but despite the electronic substitutes the one assured survivor among 1978 technologies in 2078 will be the lowly piece of paper, which will doubtless be made of synthetic cellulose. Many paper jobs may be taken up by electronics, but some uses will be left. Certainly, scientists will still work out original calculations on the backs of envelopes or on restaurant napkins. The letter post service as we know it will have gone out of business by then. People will have to manufacture paper envelopes just to carry them around in their pockets.

In the next 100 years, much information that is stored today may not have to be stored at all. It may be cheaper to reconstitute or reacquire information from basic elements each time the information is needed. It is certainly easier to rebuild a library after it has burned down if its books are stored electronically in safe remote locations.

Today mathematical tables are obsolete. Scientists in the future will doubtless be startled to discover that the 50th edition of the *Handbook of Physics and Chemistry* on my bookshelf actually contains a table of the reciprocals of the integers. Why print such a table? By storing a simple algorithm you can order the computer to build the interesting parts of a table whenever you want them. In some cases the data base is inherent in the world around us. It may be easier—and better—to reobserve something than to retrieve a stored recollection of it. For example, it may be easier and better to ask a satellite to reacquire an up-to-date street map of Chicago when you need it than to rely on city officials to provide current records. We can also obtain updated weather observations, and even actual commuter train arrival times based on direct observation of the train rather than on timetables.

In our present 20th-century world of print and paper, we tend to think of information in terms of documents. In the future, our information machines will permit us to enjoy more immediate access to all kinds of information-gathering capabilities. Documents will become only occasional by-products of information access, not the primary embodiment of it. I can, for instance, see a television viewer of the future ask his home computer for a selective printout of the day's news after he has already heard the headlines and seen some of the action displayed on the screen. He can then remove the written newspaper prepared by his computer and read it at his leisure.

Information interchange will be furthered by advances in communications technology. Well before the year 2078, for instance, the broadest bandwidth capability—for data, voice, and images—will be widely available by means of optical techniques using glass fibers and lasers. A single glass fiber the diameter of a human hair can carry 800 voice conversations, tens of thousands of data messages, or 50 million bits per second—in short, enough capacity to carry the contents of more than 40,000 typical books from the Library of Congress in Washington, D.C., to Los Angeles in 1 hour. At very little additional cost, hundreds of fibers can be packaged in a single cable. These techniques will reduce enormously the cost of communications. Optical technology can eventually be expected to take full advantage of the bandwidth, or traffic-carrying capacity, of the visible light laser—about 600 trillion hertz, or 100 million times the capacity of today's optical fiber systems. That is 1 billion books per second on each optical channel, instead of 40,000 per hour. Even terminals may be affected by lightwave communication. IBM is experimenting with a novel approach that permits terminals and hand-held devices to communicate with other devices in a room without using wires. Each device sends out and receives invisible infrared light pulses that are reflected off the walls.

In the second half of the 100-year period, incidentally, space satellites will no longer be used for point-to-point communication on the earth. Instead, they will be reserved for collecting data from remote or mobile automatic stations, or for broadcasting information simultaneously to very large numbers of receiving stations. No doubt they will also be used to engage in what Anne Branscomb calls "the ultimate diplomacy"—receiving and interpreting information from sources of intelligence in outer space—and beginning what is likely to be a very protracted dialogue.

Personalized Manufacturing and Service

The technology I have discussed so far does offer some challenges for the future, but I suspect that future generations of engineers will be able to meet them successfully. There is another kind of promise that can also be met and that is the promise of personalized manufacturing and service. This is a great step forward from the Industrial Revolution, where economy of production depended on the sameness of each item produced and the manufacturer usually passed service responsibility on to someone else.

The computer, in my view, will make it possible for people to overcome the deficiencies of the Industrial Revolution and at the same time belie the Marxian assumption of worker regimentation arising from mass production. The fact is that with the computer, manufacturers may for the first time make articles on a mass basis, yet have each fit the specific requirements of the intended end user. This is, in fact, the way IBM manufactures custom logic circuits under computer control today. Many other examples can be envisioned.

Let us take a futuristic example from the shoe industry. People are forced to fit their feet into a few basic shapes and sizes of shoes. As a result of imperfect fit, foot trouble is one of the most common medical complaints. But the last on which the shoe is made can be infinitely variable if the shoe machinery is computer-controlled. The computer can take detailed measurements of a person's foot and communicate the data along with style preference to the factory. Then an individually fitted shoe can be made at mass production prices.

All this involves a new personal relationship with the computer, but humans, being intellectually inefficient creatures, may be unprepared for this new interactive role. In the future, the computer will be able to assist people in overcoming their own weaknesses in communication in many ways. It will do this by providing access to incredibly wide worlds of information, along with instructions on how to best use this information in a particular circumstance. This will require development of high-level computer languages, more like natural English. With the help of such a capability we will only have to ask the computer what help it can provide with a particular problem and the computer will guide us through the alternatives to provide an authoritative individualized approach. This may make the computer seem all-powerful—which some mistakenly believe is true today—but I think it is important to distinguish between a powerful servant, which the computer is, and a powerful god, which the computer, for all our hyperbole, is not.

Communicating Through Computers: Human Factors Research

To reach this stage of service, computer software will have to be designed with people in mind, not to replace them, but to let people relate to machines in ways that more nearly resemble the ways people relate to one another. Today two high-speed computers talking to one another through narrowband telephone channels are like two lovers trying to communicate through the post office. But even when communications bandwidths match the internal speeds of computers, people will realize that there is more to communication than the exchange of packets of data.

Consider sociability, the warming-up process that precedes good communication. My wife was involved recently in a computer teleconference project with a number of academic people in different states. Each participant had a computer terminal in his or her home. One professor could not relate to the system. He was impatient with the way his colleagues communicated with one another through the computer. "When I log on to the computer," he typed, "I see personal messages such as, 'how are the kids,' and so on. I don't like to waste time. So next time you want to use the computer, why not just type 'chitchat' before you send the serious message. I'll know you mean to be sociable."

The interesting thing about this reaction, my wife reported, was that when the professor uses the telephone for business, he always starts the conversation with some social comments about friends and family. She suggested that he simply say "chitchat" and get on with it. He disagreed. Evidently he felt the need to start with informal comment to set the mood on the communication instrument familiar to him. But the computer was so forbidding and unfamiliar that he could not relate to it.

Research on this problem—making the computer more friendly to its human masters—is known as human factors research in the United States and as ergonomics internationally. Alphonse Chapanis of Johns Hopkins, who is president of the International Ergonomics Association, did a pioneering study of how people communicate using machines. Observing that most computer languages are highly structured, with disciplined syntax, he wondered if this reflects the way people prefer to communicate when they need to exchange information. To find out, he divided his laboratory into two rooms, each with a terminal and a person. In one room he placed on the floor pieces of a do-it-yourself pushcart. In the other room he provided a set of assembly instructions. He observed the time taken by the individuals in the two rooms to assemble the cart through communication by typewriter terminal. Several pairs of individuals were tested. He found that the job was done most rapidly when the people sent each other fragments of seemingly inefficient verbal traffic. They rarely communicated in structured sentences the way programmers do.

So we may want the computer of the future to generate some sociable chitchat to test the mood of its human master before communication begins. And we may want the computer to generate spontaneous, fragmentary communication, thus making it just human and inefficient enough to be truly effective.

The integration of the computer into the communication patterns of the future will continue to have a powerful impact on many of our social and political institutions. In education, for instance, computers are currently useful but limited tools, yet they hold the potential of altering the role of educational institutions. Let us take universities for example. Today universities are not just generators of knowledge but also distributors, making them poorly paid partners of publishing. Electronic media—television in our time and interactive home video computers in the future—will change that by providing even more effective mechanisms for education—indeed, more effective than the classroom because of the personalized nature of the educational processing. Marshall McLuhan understood this trend years ago when he said, "Children resent time spent in school because it interferes with their education."

In the future, with electronic systems to distribute knowledge, the university will be free to give greater attention to the generation of knowledge. This was its role a century ago—being the center of scholarship. New institutional arrangements that stress human relationships between student and faculty will replace the rigid structure of schools and classrooms we have today—to achieve universal, lifelong education productively, effectively, and in response to each person's needs. For this to happen knowledge will have to achieve its proper value, and knowledge creators, in universities and elsewhere, will have to be paid accordingly by the consumers of knowledge for full value.

Today the worth of this knowledge seems to depend on how well one's textbook sells. This, in turn, depends on marketing and distribution. If we can solve the problem of protection of intellectual property, by the year 2078 there will be an effective market for knowledge in itself, since distribution to the consumer will be easy and direct and very inexpensive.

The computer-communications systems of the future will also continue to stimulate the further development of our liberties and the institutions that protect them. The First Amendment to the Constitution, for instance, concerns the freedom of speech and press and was designed for an era when liberty was protected by the right to buy a handpress and distribute one's own leaflets. Today this is not enough. Very few of us can buy a television station or get a license to operate it to guarantee our right to make a speech.

I believe that we must expand the citizen's right to acquire information and to express himself through the existing media system, as well as to be protected against the misuse of information about him. With the advance of widespread access to the media, which people will have to be assured of in the future, I think that information technology will be able to help guarantee these fundamental rights of equity and privacy and to redefine them for inclusion in the codes of our future society.

The computer has often been accused of being the bureaucrat's tool—the prime instrument that enables government officials to limit our freedom of movement and manipulate information against our interests. Solzhenitsyn, in *Cancer Ward*, makes information bureaucracy very graphic when he writes that "as every man goes through life he fills in a number of forms for the record. . . . There are hundreds of little threads radiating from every man, millions of threads in all. If all these threads were suddenly to become visible the whole sky would look like a spider's web and if they materialized as rubber bands, buses, trams and people would lose the ability to move." Solzhenitsyn went on to express concern that such a cobweb could be manipulated by those in a position to control the threads.

For this Russian author the illuminated cobweb symbolizes strangulation and suffocation by bureaucracy in an authoritarian society. But I think a cobweb is also a description of the social interactions that give us the basis for a democratic society. Without informational interlinkages of this kind we could not have developed the infrastructure that guards our liberty and security, while we seek to share the world's opportunities and resources. Of course, some societies may allow the infrastructure to evolve in a disorganized way—like the mess of ticker tape that inundates a visiting hero in New York—and we may end up with a very confused world. Or one can deliberately unravel the fabric of society as advocated by those who reject contemporary society and seek the simple life in isolation.

Fortunately, there is a better alternative. We can also learn to manage the cobweb, making subwebs, building proper couplings, leaving lines and linkages intentionally vague in some cases and making them precise in others, and so arranging the overall pattern that society maximizes the return to the individual from each interconnection. The principal challenge of the future will be to make this pattern of interdependence ever more flexible, practical, and rewarding for all of us. This is the true challenge for information systems in the year 2078.

Notes

1. The author gratefully acknowledges the very substantial contribution made by Lee Edson to the preparation of this article.