A FEW THOUGHTS ON COMPUTER TECHNOLOGY FOR THE 21ST CENTURY

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We can look back on the 20th century as a century in which we, the members of the human race, have made enormous technical progress. In the last 100 years we have created revolutions in transportation, communication, entertainment, manufacturing, agriculture, medicine, etc. These past years have seen the development or widespread distribution of automobiles, air transport, movies, radio, television, satellite communication, cellular telephones, industrial robots, remarkable medicines, new medical diagnostic techniques, new surgical techniques, implantable pacemakers－the list could go on and on.

For almost as long as I can remember, I have been fascinated by technology. Mankind has developed some remarkable tools over his history, and these tools allow us to perform feats that our ancestors could not even imagine. This last century has been very generous to one who wanted to participate in the development of technology. There have been so many developments that one has a difficult time deciding what area of technology to explore. One of the developments of this last century that was of particular interest to me was the computer. I feel very fortunate to have had the opportunity to work with computers during my career, and now to have my work in that area recognized by the Inamori foundation with this most prestigious award is overwhelming.

Of all of the tools developed by mankind, the computer seems the most versatile, the most universal. Computing power can play a significant role in every one of the areas of technology that I mentioned above. Computers help in navigation, in image processing, in robotic control, in medical diagnostics. New ways to use computers to extend these other technologies are being developed, while the cost of computing power continues to fall rapidly.

The introduction of the new technology has not always been as smooth or as easy as we might have desired, but the fact that so much has been accomplished in 100 years is a testament to the adaptability of the human race. Nevertheless there have been some whose lives were worsened by the new technologies, for example, workers displaced from jobs made obsolete, and people exposed to new hazardous materials. Some people have even taken a hostile view of technology, blaming the new developments for most of the problems we face in today’s life. They argue that computers are partly to blame, that computers are impersonal or isolate us from one another. They suggest we stop all new technology development and return to our previous “simpler” way of life. One view suggests we should all be farmers, growing just what we need, living off the land, heating our homes with wood rather than fossil fuels. As romantic as that concept may appear, I feel that we just can no longer afford that life style. I also feel that technology, and computers in particular, are being unfairly blamed for problems caused by other factors.

What other factor might be important? Consider that the 20th century has been notable in another way besides advances in technology. It has also been a century of an enormous increase in the human population. The population has increased perhaps fourfold in the last 100 years. As of the end of the century, we will have some 100 human beings for every square mile of solid surface on the planet, which area includes such inhospitable places as Antartica, the Sahara Desert, and the peaks of the Himalayas.

One way to view the growth in population is that each of us has four times as many neighbors as did our ancestor of a century ago. But advances in communications may make it seem like an even greater increase because we now see, on television screens in our living rooms, events that take place in some far distant corner of the world. One of the roles of computers is to allow us to cope with this much larger number of people. Just consider the number of telephones and try to imagine handling all of the calls placed today with human operators.

We are not only coming to the end of a century, we are also coming to the end of a millenium. We now have records from perhaps some five millenia of human activity. If we were to continue the current rate of expansion of the human population for just one more millenium, for just ten more centuries, there would come a day when there will not be enough space on the surface of the earth for anything other than people.

This population growth has reached the point where we are finally becoming aware that the planet we occupy is finite, with finite resources. We are just awakening to the fact that our sheer numbers are taxing those resources, and endangering other species. In California, where I live, the delicacy abalone has nearly been fished to extinction. California sardines were fished to extinction years ago. Salmon are threatened by developments along coastal rivers. Actions to remedy the impact of development are being taken, but there is a struggle between the needs of the growing population and the preservation of the environment.

We still have much to learn. In parts of the world the great forests are being cleared to make farmland, which may put our very atmosphere at risk. We burn oil and natural gas as if the underground reservoirs are an infinite supply. Even with this knowledge, we give only lip service to conservation, and our consumption continues to grow.

We are just learning that even the resources for waste disposal are limited. Pollution from dumping trash into the rivers and coastal waters threatens species which have thus far survived. Contamination may be making some of our food sources unhealthy. Even irrigation of land to make it more productive can lead to the accumulation of undesirable minerals and the ultimate poisoning of that land. Models indicate that the burning of fossil fuels is changing the composition of the atmosphere in a way that may warm the planet. Such warming could raise the oceans and leave us with even less solid surface.

Can we return to the earlier, simpler day in which each of us is self-sufficient with our own garden? I do not believe so. There isn't enough arable land to provide the family farms that that vision would make necessary. We can no longer afford to cut and burn trees to heat our homes—the impact on the atmosphere is too great not only from the polluting effects of smoke but also from the loss of oxygen regeneration that the trees provide. Consider that local authorities in California now ask us not to burn wood in our fireplaces because of its impact on air quality.

So much for the romantic life style. We cannot all be gentlemen farmers—it's too inefficient and there isn't enough land. A better use of the land is for most of us to live in high-rise buildings so less land is used for housing and more is available for farming.

Not only has the population of the world increased, but so has the life span of human beings increased significantly during the century. In the U.S.A., life expectancy has grown from 47 years at the beginning of the century to 76 years at the end of the century. Much of this increase in life expectancy has resulted from progress in medical technology. Not only has this increase in life span contributed to population growth, but it also impacts the distribution of age within the population, which in turn impacts demand on resources. It is highly likely that continued progress in medical technology may further increase our life spans, which adds to the problem of population growth. It is also very difficult to justify cutting off research which eliminates the suffering caused by illness.

Another factor which may well affect demand on resources is communications. We have improved communications around the world and brought down the cost of wide-band transmission to the point where television images, telephone conversations and Internet access are available almost everywhere on the planet. As the various peoples of the world become more aware of differences is life style, most particularly differences in distribution of resources, we may well find that there will be a rising demand for a more equitable distribution of those resources. Those of us who currently live in the wealthier nations may be expected to share more of that wealth with the poorer nations.

If we are to survive as a species and still preserve a satisfactory life style, we are going to have to limit our numbers and we are going to have to learn to use the resources of our planet more efficiently.

How do we use resources more efficiently? The answer is with the judicious use of technology. We are already seeing how technology can help with some of these problems.

It takes less energy to send an electronic signal around the world than it does to send a human. Improvements in communications can eliminate the need for some travel and thereby save the excess energy that the travel would require. Entertainment in our homes can save energy by eliminating our traveling to some central location for amusement. Improved insulation combined with more intelligent control can reduce the energy needed to make us comfortable. Developments in agriculture can help us to produce the food we need with less impact on the land, and to use less precious land for a given amount of food production. Even here computing can play a role, both in helping analyze data leading to better crops and more efficient feeding schedules and in planning the optimum watering and fertilization schedules.

There are many more places where computing can improve the efficiency with which we use energy and other resources. Even the distribution of those resources can be made more efficient by the use of computing power. While the current standard of living for the average human may be worse than we might desire, without modern technology we would be in a far worse condition.

I consider myself very fortunate not only to have been born in this century but also to have fallen in love with science and technology at a very early age. As a result I have been able to earn a living by indulging in my hobbies.

My first introduction to science was via chemistry. One of my earliest memories was seeing my uncle, who is only twelve years older than I, mixing two colorless liquids and producing a brilliant red color. It seemed like magic, and I wanted to learn how to do such magic.

As a child, one has very little power, very little control over one’s life. The child must usually do what the parents ask, must attend school as the state demands. But the magic of technology grants power to those who understand it. When one understands science and technology, one can predict what will happen when known combinations are tried. Knowing how to accomplish a desired result or knowing how to fix some piece of equipment gives one a feeling of personal power.

As an example, consider electronics. No one has ever seen an electron, so electronic circuit operation is based on various theories. These theories predict that various combinations of electronic components will produce certain results. The electronics engineer designs his circuit based on the theories and expects it to work as the theories predict. I still get great satisfaction from building an electronic circuit that I have designed, and seeing it perform as the design predicted.

There are many areas of science and technology one might study. As I indicated before, my first love was chemistry. Not only did my uncle demonstrate some chemical reactions, but he also gave me some of his college textbooks and I read and re-read them. By the time I was ten years old, my parents had reluctantly gotten me a chemistry set. My uncle helped me add to it. Many things were explained by chemistry —what soap was, how acids could eat holes in your clothes, even how some substances could be dangerous.

When I was twelve years old, I got an introduction to a new area of technology. My uncle gave me a subscription to Popular Science Magazine, which reported on many developments in science. In one issue I saw an advertisement for a free catalog of electronic supplies offered by Allied Radio. I sent for the catalog and soon began ordering books on electronics. Seeing my interest, my parents gave me a short-wave radio kit for Christmas and my father helped me to assemble it. Now I had a new type of magic—I could listen to stations from around the world—even Radio Moscow, which provided a view of events that differed considerably from the U.S.A. media of 1950.

I continued to study both electronics and chemistry. While in high school I saw an advertisement for cathode-ray tubes of the type used in oscilloscopes. I ordered one and built a crude oscilloscope. However, as a high school senior, I won a trip to Washington, D.C. in the Westinghouse Science Talent Search. The topic of the science project that won me the trip was the synthesis of hydrocarbon fuels from carbon dioxide and hydrogen. Such synthesis would become desirable when the finite supplies of fossil fuels ran out. Even in 1954, I was concerned about the limits of the planet.

When it was time to go to college, I was forced to make a decision between chemistry and electronics. College programs are divided into such categories. My uncle, by then a chemical engineer, suggested that the job market for chemists was limited, so I chose electrical engineering as a course of study and I was accepted by Rensselaer Polytechnic Institute (R.P.I.).

At the beginning of the summer between high school and college, my father got me an interview in the electronics laboratory at the company where he worked, General Railway Signal Company (G.R.S.). They offered me a summer job and I worked there every summer from 1954 through 1959. That job gave me my first experience with transistors, which had been developed only a few years before.

When I graduated from R.P.I., I chose Stanford University for graduate study. My studies at Stanford started in the field of transistors and other solid state circuit devices, and that led to an involvement with integrated circuits. The summer job experience at G.R.S. also got me interested in a problem faced by the railroads. Railway cars were often lost or their locations unknown. That led to the question of whether a way to read the numbers off passing railway cars might be developed. That question led to my Ph.D. thesis and my involvement with computers.

When it came time to choose a topic for a Ph.D. thesis, I mentioned the railway car number reading problem. I was told to meet a new professor at Stanford, Dr. Bernard Widrow. Dr. Widrow was interested in computers that had learning capability, and it appeared some type of learning would be needed to perform the kind of pattern recognition that would be needed to read railway car numbers. We developed several concepts for learning processes, and needed some way to check them out. We first built some models that we manipulated by hand to perform the learning algorithms, but soon realized we needed a better tool for the study. Dr. Widrow ordered an I.B.M. model 1620 computer.

The 1620 was the first computer that I actually got to program. Again it seemed magic that we could take a concept for a learning procedure, code that procedure for the computer, and then the computer would execute the procedure and produce results that we could study. We could even have the computer work all night on a problem while we went home and slept.

The computer seemed like a very desirable tool, but it was very expensive. Had we purchased it outright, the 1620 would have cost about as much as the annual salaries of some ten engineers. Computers cost so much that one of the conditions for their use was how to keep them busy. People made up problems so that they could justify having the expensive tool.

After receiving my Ph.D. in 1962, I stayed at Stanford as a Research Associate, working in the area of what are now called "neural networks." As much as I enjoyed the academic environment, I was intrigued by industry. In the academic world, if you published a good idea your colleagues would praise you. In the world of business, your good ideas would be praised by customers spending their money. In 1968 I received a call from Bob Noyce who was founding a new company to make semiconductor memory products. I applied and got the job and became Intel Corporation's employee number twelve.

My initial responsibilities at Intel were related to the applications for semiconductor memories. I was expected to produce application information for Intel products, and also to meet with prospective customers to determine their needs and expectations. Hopefully, those customer inputs would be useful in defining the type of memory product to produce.

I also did some computer programming, such as writing simulators for the types of MOS circuits being developed at Intel. MOS, which stands for Metal-Oxide-Silicon or Metal-Oxide-Semiconductor, is an integrated circuit manufacturing process, in particular the one used for the densest, most complex logic and memory circuits. Some of this programming got me involved with minicomputers, which had become quite popular by that time. Minicomputers were being designed into semiconductor test equipment, and were being used in laboratory environments. Not only were minicomputers smaller in size than the larger mainframe computers, they were also much less expensive. However, the typical minicomputer still cost as much as half of an engineer's annual salary. Some minicomputers were remarkably simple in their architecture. In spite of the simple architecture, suitable programming allowed them to perform some very complex tasks.

A few months after its founding, Intel agreed to manufacture integrated circuits for a family of calculators to be built by Busicom of Japan. Even though Intel expected to be primarily a memory manufacturer, it was felt that this custom business could result in needed cash flow. I was assigned to work with three engineers who came to Intel from Japan to finish and transfer their design. As I began to understand the design, I began to get concerned that the complexity and the number of different chips needed to allow this one family of circuits to implement many different models of calculators would overload Intel's limited design capability. The number and complexity of the chips could also make it difficult to meet the cost targets for the calculators.

My experience with minicomputers suggested to me that the architecture could be simplified if a suitably programmable architecture were used. The design as proposed did have some programmability, but I felt the architecture could be improved by reducing the complexity of the processor while replacing any lost functionality by additional programming. That led to my proposing an architecture of a very simple general purpose computer that could be programmed to perform most of the calculator functions. This approach was ultimately accepted and, with the help of my colleagues, brought to reality. The architecture was sufficiently simple that the central processing unit could be realized as a single chip.

Initially, a contract was signed that gave exclusive rights to the chips to Busicom, although there were clauses that anticipated the possibility that Intel might sell the chips to others. If the first devices had remained limited to use only in the Busicom calculators, it might not have created the revolution that followed. Fortunately, circumstances led to Intel's offering the microprocessor for much more general usage.

Two events led to this broader availability of the single chip processor. One was from negotiation with Busicom. The other was the undertaking of a second microprocessor development, almost in parallel with the Busicom chip family.

Shortly after Intel committed to build the first microprocessor for Busicom, a customer came to Intel with a request for a special memory for a computer terminal which contained a simple central processing unit. Stanley Mazor and I concluded after a brief study that the central processing unit for the terminal was not much more complex than the one to be developed for the Busicom calculators, and that led to the second microprocessor project at Intel. Ultimately, both processors were announced for general use, and soon hundreds of applications for microprocessors appeared. Those applications led to requests for upgrades to the original devices, and improvements in semiconductor process technology allowed those upgrades to become reality.

Over the subsequent years, more and more applications for microprocessors have been found, and the microprocessor has made possible the personal computer revolution. It now seems so obvious that the microprocessor should have been developed, but at the time the decisions to first make and then sell the microprocessor were filled with trepidation. There was no guarantee that Intel would be successful with the early products or that our customers would be able to apply them properly. There were major questions about how they should be supported. Fortunately, the products were announced and they were successful.

I look back on that development of the first microprocessor with pride, not just because we developed a successful product, but because that product represented the cooperation of people of different backgrounds and the cooperation of two great nations, two great economic powers. It was especially satisfying to me because some of my early childhood memories were of these two nations in conflict. The result of those same two nations engaged in mutually beneficial cooperation should be a lesson for the whole world.

The underlying semiconductor technology has made enormous advances since the first microprocessor was developed, and those advances have allowed modern microprocessors to offer truly amazing performance. We now pack into a few cubic centimeters more computing power than would have fitted into a large room a few decades ago. As we move into the 21st century, we have a very powerful tool. The real question is whether we will take full advantage of what this computing power can offer.

A lot of the media attention to the microprocessor today is related to usage for

Internet access. Other uses well known to the public are word processing tasks and a few other standardized applications such as spreadsheets and data bases. As interesting as these uses are, and I do not mean to imply they are unimportant or inferior uses of microprocessors, I believe there are even more important applications for microprocessors.

Partly because of the publicity given to the Internet access application, the general public, and in some cases the technical public, is becoming less and less aware of other applications of microprocessors, most notably those applications for microprocessors in what is termed “embedded control.” Embedded control microprocessors make our automobile engines more efficient and help reduce the pollutants they produce. Embedded control microprocessors in our appliances can help make them more efficient users of energy. Embedded control microprocessors also make appliances easier to use, and can operate to make it more difficult to damage or misuse an appliance. Embedded control microprocessors can offer navigation aids to drivers, and add intelligence to our telephones. However, because they are embedded, they often are invisible.

There are still many areas where we can utilize more embedded bits of computer intelligence. Some applications still await solutions. For example, much work has been done toward building computers which can understand human speech, but the abilities of the current systems still leave much room for improvement. Part of the problem is that much of our understanding of the spoken word depends on the context of the words, and that context relies on a body of knowledge most humans have but computers still lack. As memory becomes cheaper, we may be able to build more intelligence into systems, including much of that fundamental knowledge that most humans acquire over their lifetimes.

There are many other areas where fundamental research into computing is needed. We have made much progress in robotics, and now use robots to improve our manufacturing capability, but we can expect to use future robots for many more tasks. Some of these tasks will require robots with much better pattern recognition capabilities. Experiments are already being made which may lead to robotic automobiles. We should be able to make automobiles safer and more fuel efficient if we can reduce their dependence on human control. Interactive automobiles may cooperate to reduce the number of times brakes are applied, and to travel more closely together. More efficient use of roads and highways could even reduce the amount of land we pave over.

Robots in our homes are another possible use for computing that may improve energy efficiency and also provide services to improve our comfort and save us from unpleasant chores. Robots capable of understanding ordinary human speech should be especially helpful.

Speech processing for language translation is another area that could be very useful. We could very well expect to have automatic translation as part of our international telephone systems and as a built-in service of the Internet.

Who will perform the research necessary to extend computer capability? Who will build computing power into an increasing number of applications? It will have to be the future generations of computer scientists and engineers. For us to develop the next generation of computer scientists, we must ensure that our young people become interested in these new applications for computers.

One of my concerns is that as popular opinion increasingly sees computers used only for Internet access, there will be less and less awareness of the embedded control applications that bury computing power in our appliances, even such computing power as might be buried in the Internet. Unless those less well-known uses for computing power remain interesting to our young people, they will cease to inspire research, and progress toward the broadest uses for computing will slow or cease altogether.

You make think that I am unnecessarily concerned about finding young people to continue extending computer capability. However, my fears are based on actual experience. I remember the early days of microprocessor development. At that time most of the glamor in computing was associated with the large mainframe computer. As we tried to recruit talented young people to come to Intel to work on microprocessors we were constantly frustrated—the brightest graduates wanted to be working on something bigger and more exciting. It was not until the media discovered the microprocessor and began to present microprocessors as exciting and important that we found the bright young college graduates actually seeking to work in our arena.

I have often been asked if we visualized the popularity of the personal computer when we were developing and announcing the first microprocessors. I must admit that we did not. The applications we envisioned were those that we now call embedded control. I am very grateful for personal computers, and I find them a wonderful tool for my work, whether for simple word processing or for circuit design and simulation. Nevertheless, I still find embedded control applications of microprocessors fascinating, and my hope is that future generations will find them equally fascinating and that they will continue to be developed for many generations to come.