THE MICROPROCESSOR AND I: IT ALL STARTS WITH THE APPLICATION

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When I was informed that I was to receive the 1997 Kyoto Prize in Advanced Technology, I was overwhelmed with great excitement and delight. It is indeed a great honor and I am extremely proud of this Prize. I understand that this honor signifies that the microprocessor we developed has been recognized as a “technology to open up a new era.” I also understand that this Kyoto Prize is a medal for not only inventors and developers of the world's first microprocessor, the 4004, but also many individuals who have recognized this newly created technology, disseminated it worldwide, employed it in many applications, and contributed to its further development. Personally, the Kyoto Prize has strengthened my pride in my having devoted myself exclusively to microprocessor development these past 28 years. I am particularly pleased to receive this honor in Kyoto, a beautiful historical city, where various cultures, new theories and thoughts, and creative enterprises have been born and nurtured throughout its long history.

Regarding myself, I am not a specialist in semiconductors or electricity. Neither am I a computer specialist. At the beginning of my career, I did not have any special purpose, but somehow I have continued working in this field for nearly three decades. It has not been easy: it has been stressful to lead development as a frontrunner these three decades. However, I was able to develop myself through a series of creative developments, where one successful development always created a demand for another. While I was developing microprocessors in the U.S., I had so much fervor for the work that I needed to cool myself down. This is why I began reading the novel *Kashin*, written by Ryotaro Shiba. The hero of this novel is Zoroku Murata (also known as Masujiro Ohmura, a historic figure of the 19th century). In the novel, there is a passage: “Zoroku Murata lived only to satisfy others’ demands. He never desired to do anything for himself, but used his technical expertise in accordance with others’ needs.” I felt a strong affinity with Zoroku Murata, who lived up to the demands of his time, going a way that God prepared for him, paying little attention to his own desires. Today's presentation title is "The Microprocessor and Myself," and I would like to speak about how I became involved in the development of microprocessors.

I was born in Shizuoka Prefecture in 1943. Shizuoka is home to beautiful Mt. Fuji and to Suruga Bay, and it enjoys a mild climate and a relaxing atmosphere. My father ran an apparel and accessory shop, and was very fond of anything novel. My mother had a strong sense of justice, hated anything unfair, and was very strong-minded. From my parents, I inherited obstinacy and persistency, as well as my preference for anything new and novel. This character of mine was very useful for development work, which I had to start from scratch. In our neighborhood, there were six movie theaters. As a child, I often went to see movies. I also liked painting pictures. As my father was dealing in apparel, I made a long picture scroll showing the history of costumes from ancient times to the present. That was when I was in the fifth year of elementary school (eleven years old). I was rather a reckless boy, since I loved to go swimming amid high waves whenever a typhoon came to my hometown. When I was a senior student at the junior high school, I lost three fingers while playing with rockets. Although my mother encouraged me to study law, rather than natural science, I wanted to become a chemist, since I loved experiments, handicraft, and drawing.

I entered Tohoku University and studied organic chemistry in Professor Ito's laboratory. Professor Ito had an overwhelming enthusiasm about chemistry research. He demonstrated to us students the ideal state of a researcher, through his lectures, researches, and discussions. Comprising Associate Professor Takeshita and many graduate students on master and doctoral courses, Professor Ito's laboratory team had a sort of solemn atmosphere that prohibited us undergraduate students from doing anything by halves. I decided to study one of the research themes of Tohoku University: the characteristics of hinokitiol, an ingredient of *hinoki*, a Japanese cypress, in terms of its reaction speed. This was the first research that I conducted in my life. Before I joined the laboratory, I read several books on scientific methodology and experiment planning methods. However, I soon found a great difference between lay persons and specialists in the manner in which they collected, read, and compiled papers, and even in ways they cleaned experiment tools. In the study of hinokitiol, I had to sample and analyze this compound in various reaction stages over the course of time. Since the experiment took nearly one week, I found that if I did not work hard in the initial stages, I would have a huge amount of work to do at the end. Through this study, I learned important lessons concerning research attitudes and methods: I should do everything thoroughly and completely; and experimental schedules must be prepared and carried out based on backward calculation.

Before graduation, I had difficulty in finding a job, due to the recession in the chemical industry, and perhaps due partly to my handicap. Fortunately, the Professor Ito introduced me to Busicom Corp., which sold computers, and I decided to join the company. For my graduate thesis, I used a motor-driven calculator to analyze my experiment data. By then, computers were already in practical use for determining organic structures. Since I had loved anything novel, I was determined to challenge the new field of electronic computers, rather than chemistry. Since I learned scientific methodology, I did not have any worries about entering this new field.

In 1967, I joined Busicom Corp, which was then developing and marketing manual calculators, electronic desktop business calculators incorporating transistors; selling scientific calculators, accounting machines, and electronic computers; and was developing software. Desktop calculators, incorporating vacuum tubes, were first developed in the early 1960s by ANITA in the UK. Before long, Japanese manufacturers successfully developed and began high-volume production of new calculators, comprising transistors, diodes, resistors, magnetic core memories, and other components. Just like personal computers are the boom today, calculators were then the stars of business machines and scientific computers. In Busicom Corp., I was assigned to the computer division, and received programming training at Mitsubishi Electric Corporation, a computer manufacturer. I found myself extremely interested in the study of programming languages: Fortran, Cobol, and Assembler. I learned everything as quickly as water penetrates into sand. Making programs is never difficult, if you have learned languages and you are accustomed to thinking logically. To build really helpful programs for practical use, however, requires thorough knowledge on a specific application. Moreover, you must have a strong affinity to that specific application field. When I finished my three-month training, I was assigned to make programs for business applications, not for scientific applications, unfortunately. Although I studied business during the following two months, I found no interest in that field. Accordingly, I asked the company for a transfer to the calculator division. One month later, I was transferred to Nippon Calculating Machines Company, Busicom's subsidiary in Ibaraki City, Osaka Prefecture, which was developing and marketing calculators. My half-year experience in programming and this half-year lag in starting my career in the calculator division determined the rest of my life. Had I been assigned to join the calculator division half a year earlier, I should not have been involved in the microprocessor development project, which changed my whole life.

Looking into the past decades, system construction technologies have undergone breakthroughs roughly every ten years. Such breakthroughs have brought about advanced technologies or the "technologies to open up a new era." In 1951, the development of transistors opened up the "circuit age," when engineers became able to design systems by building circuits with transistors. The development of integrated circuits in 1961 brought about the "logic age," when system design required engineers only to understand the functions of the system to develop; think logically; build up logic; and realize the logic with integrated circuits. Fortunately, I was transferred to the calculator division during the era when the IC's were replacing transistors. If I had been transferred half a year earlier, I could not have used my talent or experience in programming. There are two books that I read enthusiastically when I was transferred to the calculator division. These books, which I shall never forget, are *Digital Electronic Computers* written by Mr. Takahashi and *Logical Mathematics and Digital Circuits* by Mr. Udagawa. For three months, I read these books every day, until they became worn out. I still treasure these books, which provided me with basic technological knowledge. My first task at the calculator division was to implement a calculator prototype using IC's. At that time, the logic size of one calculator was small enough to be stored in one person's brain. Calculators then employed hard-wired logic, in which wires were used instead of programs. Since the circuit comprised an asynchronous counter and a keyboard, it was easy to understand the system and logic, although it was difficult to build up the logic.

In the spring of 1968, two years after graduation from Tohoku University, I had my first opportunity to develop calculators. Shortly before, I was transferred to Electro-Technical Industries, Busicom's plant in Tokyo. By then, Japan was already a major supplier of calculators, developing customers' original equipment. To comply with a wide variety of customer demands, however, conventional hard-wired logic came to a deadlock, since it requires logic design and manufacturing for each respective product type. To solve this problem, Technological Manager Tamba, who had experience in computer technology, suggested the use of programmed logic in calculators. His idea was that, instead of using hard wires, programs should be used to alter calculator designs. Luckily, I was the only staff member that had programming experience. I decided to develop a processor that used TTL circuits (typical IC’s), so as to develop calculators, in a short period, of different specifications given by OEM (original equipment manufacturing) customers. I developed stored program logic, in which programs are stored in memories, just like in a computer, and I finally succeeded in the development of a calculator with a printer. For memories that stored programs, I used ROMs (read-only memories); ROMs are currently used in program cartridges for game machines. Like a game machine, a calculator can have different functions, by changing ROM contents. The processor I developed was a decimal computer, which, like an abacus, handled n-digit decimal data, instead of binary data, comprising n-numbers of “0” and “1.”

In the latter half of the 1960s, the U.S. semiconductor industry began to apply LSI (large-scale integrated circuit) technologies to DRAM memories, which are now in wide use, as the main memory in personal computers. Japan’s calculator industry was also interested in the use of LSIs as a means to develop products of higher performance, wider diversity, lower price, lighter weight, and higher reliability. In this climate, Busicom, in cooperation with an American survey company, began selecting an American semiconductor manufacturer with whom to tie up, and collecting necessary technological information for LSI designs. At the end of 1968, Busicom formed a project team to develop LSIs. As a tie-up partner, Busicom selected Intel, a company then newly established by the late Dr. Noyce, because the company owned silicon gate MOS processing technology, a new-generation semiconductor processing technology enabling the production of high density and high performance LSIs. Through this tie-up with Intel, Busicom intended to develop general-purpose LSIs for various business machines with a wide variety of I/O functions, in addition to computing power. Such machines included business calculators, scientific calculators, billing machines, and bank window terminals. By June 1969, Busicom had already determined the specifications of macroinstructions for decimal computers, which permitted more applications than conventional non-programmable logic; They had also prepared programs for calculators, decided to use only LSIs for system configurations, and prepared logic circuit diagrams for the majority of LSIs. At that time, Busicom did not know that Intel had no specialists in logic design, which was a great misjudgment.

In June 1969, one year earlier than the debut of the Boeing 747, I left Tokyo International Airport in a Boeing 808, notorious for its narrow seats and terrible cushions. It took 20 hours to reach San Francisco via Honolulu. It was my first business trip to the U.S., and I felt a little nervous, since I had little confidence in my English speaking ability. However, my excitement and ambition to learn about everything there was greater than the concerns of my new tasks in an unknown land. At San Francisco Airport, I was welcomed by Dr. Hoff, who drove me to a hotel in Mt. View, where Intel was located. Only one year after its establishment, Intel was then a small company with less than 125 employees. Its office building of 2,000 square meters appeared homely. Intel rented the office and manufacturing facilities. At first impression, I wondered if Busicom should have contracted such important business to Intel. Before long, however, I found that Intel employed five ph.D.s and was enthusiastically promoting DRAM and PROM developments. The Busicom project involved Dr. Hoff, who was familiar with computer software and circuits; and Mr. Mazor, a software engineer.

Recalling the days when we first began discussing the development processes, I think of the phrase “the throes of birth.” It was so difficult to get Intel’s engineers to understand Busicom’s ideas concerning the functions of a calculator, particularly the functions of a keyboard, display, and printer; LSI specifications; and logic circuit diagrams. The major factors of this difficulty were that there were only a few companies in the U.S. that were developing calculators and that Intel had no logic designers. Hoff, however, showed a great interest in stored program logic; macroinstructions for decimal computers; and calculator programs, which I proposed to use. In my poor English I explained to him calculator macroinstructions, programs, and system configurations.

One day in the latter half of August 1969, when the co-development had almost reached a deadlock, Hoff suddenly rushed into my room with several sheets of paper in his hand. He looked very excited, when he showed me a block diagram, comprising three boxes of the processor framework. He suggested that instead of my proposal of an n-digit decimal computer, comprising macroinstructions, we should develop a 4-bit binary computer capable of handling 1-digit decimal data. In other words, he suggested that the macroinstructions should be prepared by combining lower-level macroinstructions with programs. This was the“first cry”of a newly born microprocessor. Hoff also proposed that we should decrease the number of LSI types to develop. What led to the new concept of the 4-bit binary computer were specific demands of calculators and the initial idea of producing a decimal computer with LSIs.

Back in 1968, Busicom successfully introduced stored program logic into calculators. A major factor of this achievement was that rather than making an incremental improvement, I adopted a radical innovation by introducing a new-generation logic. However, my proposal to Intel in 1969 concerned an incremental improvement of my former idea and the use of LSIs. In contrast, Hoff’s proposal was much more creative.

With this idea of Hoff’s, the “development” of microprocessors started in a real sense. There is a great difference between “invention” and “development”: whereas “invention” refers to the realization of an idea, “development” refers to the production of practical products within a certain period, by optimizing functions, performance, and costs. Through discussions of Hoff’s idea in terms of instructions, functions, and system configurations, we gradually discovered what was lacking in his initial idea. Since his idea concerned basic frameworks, there were many obscure points concerning controlling methods of such I/O devices as a keyboard, display, and printer; system configuration with only LSIs; and the need to use more expensive, larger-capacity memories, to decrease the number of necessary chip types. To apply his idea to calculators required further discussions. I found it particularly difficult to persuade Intel, which intended to develop only a processor, to adopt Busicom’s proposal of building up a system with LSIs only. At that time, memories were used by computer manufacturers, and were extremely expensive. For instance, a 256-byte memory, which has only 1/8,000 capacity of today’s 16-M bit DRAM, amounted to one quarter of the average starting salary of Japanese workers. Accordingly, for its calculators, Busicom was not allowed to use memories that exceeded the cost of a 1-kbyte. However, Intel’s approach to memories was much different from Busicom’s, since Intel was a memory manufacturer, while Busicom was a system manufacturer. It is an interesting coincidence that the performance of the 4004 is exactly 1/8,000 of today’s microprocessors used in personal computers.

During the four months between August and December 1969, Hoff, Mazor, and I invented many devices, for which, I now believe, we could have obtained patent rights. Although none of them appeared to have extraordinary features, combined with the microprocessor, they had great potential for obtaining patent rights. The first such invention was a convert instruction from binary data to decimal data. This instruction is effective in enhancing performance, and drastically reducing the memory capacity. The second invention was interpreter loading and executing method. When personal computers were newly developed, Basic, a programming language developed by Microsoft was most influential. With the advent of the “Internet age,” JAVA, a language developed by Sun Microsystems, made its debut. At the time of their debut, both languages adopted interpretive methods, by which each term in a program was translated into processor instructions. Like these languages, calculators also have a specific language for calculators, and require an interpreting function. Therefore, we developed an interpreter using a microprocessor. The interpreter halved the necessary memory capacity for applications, and, in turn, led to the third invention. Regarding this third invention, the most important issue was that software replaced the hard-wired circuits in real-time control of I/O devices. However, before succeeding in this invention, we were worried if real-time control of I/O devices would be possible with software, since our system incorporated only a low-performance microprocessor and low-capacity memories. We knew that it would be possible if keyboard functions were suspended when the system was printing, computing, and displaying. However, we also knew that such calculators would not sell. To develop a calculator that would sell, we actually built up programs for various important functions to control I/O devices, and examined instructions, performance, and program step numbers. In the end, we were able to control I/O devices with software, by combining the macroinstruction interpreter, our second invention, with new instructions, and the LSI for output port, which had been newly developed for controlling the keyboard, display, and printer. By December 1969, the specifications of instructions, functions, and system configuration were determined through the programming of major calculator functions.

At the end of December 1969, I returned to Japan, since it appeared that it would take a long time before the two companies would sign the official contract. In Japan, I built practical programs for calculators, again; reconfirmed the specifications of instructions, functions, and system configurations; and finalized the specifications. Intel’s manual of the 4004 contained many charts and diagrams, since Intel was afraid that we might misunderstand explanations in English. The official contract was finally concluded in March 1970. In early April, I crossed the Pacific Ocean alone to visit Intel again. The purpose of this trip was to confirm Intel's finished design. Intel had promised that it would employ two more engineers to complete the design. I was a little worried, however, since, in an agreement other than the official contract, there was a passage that, if so demanded by Intel, I would help with logic design, layout verification, and preparation of test programs. When I reached Intel, I was introduced to a new staff member who had joined Intel the previous week. He was Dr. Faggin, a leading engineer in Silicon Gate Technology. To my great disappointment, I found that my concern had come true: no progress had been made on the project since I left Intel several months previously, nor were the new staff given sufficient explanation about the task. What was worse still was that Intel had only two layout designers, besides Faggin, and no logic designers. Not knowing what else to do, I explained the specifications and internal logic of the calculator. We decided that I would be responsible for the 4004's logic design, logic simulation, and the preparation of test programs; whereas Faggin would be responsible for all the remaining tasks. Hoff made me a simulator with which to simulate the logic. Busicom's staff in Tokyo prepared a verification board for the 4004, using ICs, based on the logic diagram I made, and we decided to verify the logic simultaneously with the simulation of the processor. Faggin and I then worked like workaholics, tackling the tasks eleven hours a day from Monday through Saturday. As a result, we completed the design of four LSIs in as little as eight months. Since there were only two layout designers, we adopted transistors for the logic design of the 4004, so as to use the logic design also as a circuit and layout design. At that time, a semiconductor's layout was two-dimensional, just like a calculator board design. Accordingly, I was able to take advantage of my experience in calculator board design. I was really excited and greatly moved when the layout of the 4004 was completed, just as the logic diagram that I had drawn.

After completing the development of the 4004, I began my original task: development of calculators. First of all, I produced a calculator prototype, by mounting a ROM compatible memory made from a standard memory with a RAM memory for the 4004, an I/O port, and a card reader to read calculator programs. Next, I verified programs by reading programs with the card reader. Fortunately, the programs were intact, and I was able to develop calculators successfully. For me, the 4004 was only a necessary component of the calculator, so I was more delighted when I completed the calculator with a printer in March 1971 than I was at the moment of the successful development of the 4004. I still remember the feeling in my finger when I first touched the calculator's start button. In actuality, when you press the start button, the system goes into an initial state and halts. It is the moment you release the button when the system really starts. For me, it is rather easy to press the button but I always feel tense when I release the button, since that is the moment when I will know the result of my several years of hard work. If a system works, I will know that I have succeeded in the development; if it does not, my colleagues will leave the laboratory one by one, leaving me alone, and I will know that I have failed. Whenever I release the button, I feel as if the strong tension could break my heart. Just as a mother, having suffered terrible birth pains, cannot but love her baby, developers cannot but love the product that they have produced through pain.

The success of the 4004 is attributable to the cooperation between engineers of various development fields: applications, computers, software, LSIs etc. By exchanging our expertise and ideas in an interdisciplinary way, and by addressing a great many problems with patience and a challenging spirit, we sowed the seeds of a new technology and grew a finished product.

The world's first microprocessor, the 4004, was applied not only to calculators, but also to cash registers, bank window terminals, and many other office machines. The debut of microprocessors with software replaced the conventional hardware logic circuit networks comprising ICs of the former "logic age," bringing about the new "program age." Microprocessors, which became the "technology to open up a new era," had two outstanding impacts. First, microprocessors paved the way to the development of one-chip, "intelligent" microcomputers. At the same time, microprocessors allowed young engineers access to the power of computers, which had been exclusively possessed by computer companies. This permitted the creative development of personal computers, workstations, and computer games, which in turn led to growth in the software industry, and paved the way to the development of high-performance microprocessors. In 1981, IBM commercialized personal computers, which opened up the "age of OS and GUI." Then, the debut of the WWW in 1991 started the "age of the Internet and languages." Whatever new technology will appear in 2001, that technology will surely herald the "communication age."

Since 1971, the year of the 4004's development, 26 years have passed. These years have seen the development of processors that have over 100 architectures. In a broad interpretation, "architecture" is defined as "computer structures, frameworks/concepts, and specifications that ensure the processing of a wider variety of greater and more complex problems at higher speed, with greater flexibility, operability, and reliability, permitting reduction in production costs." Architectures are created based on ideas, and ideas reflect the thoughts and characteristics of respective developers. The extraordinary characteristics that constantly "pour out of individuals" have brought about many creative developments. At the same time, new architectures have always been created to satisfy the specific demands of new applications. In other words, we can put it like this: in the beginning, there were application demands, and this was all that existed.

Since creative development refers to the development of a product that does not yet exist, engineers involved in creative development can be likened to explorers who go into an unmapped territory without a compass. Engineers and explorers share two contrasting feelings: hope for success and fear of failure. In addition, engineers can be likened to artists or religionists, who create their own world. To conceive a new concept in creative development, an engineer must be armed with the firm belief that his mission is nothing but development, and must be determined to go his own way, never following another's tracks. Since no one knows what a developer is thinking, however, the developer is unlikely to be understood by others. At first, innovative ideas may be ignored or underestimated. In most cases, "excellent" engineers tend to evaluate others' ideas rather than their own. However, they must have confidence in their ideas, and should be encouraged to set forth their ideas repeatedly; if their proposals are turned down, that is probably because they were not good enough in explaining their ideas, or others were not wise enough to understand them. Creative development requires strong resolution, persistency, determination, and quick and arbitrary decision-making, rather than excellent but vulnerable brains that tend to act like a critic. The essential point of creative development is detaching oneself from one's desire to use what is now available. It is never easy to abandon past achievements, conventional technologies, and know-how. To take the first step towards success, however, an engineer must analyze his/her past achievements and currently available technologies, and extract only the essence, eliminating the remainder. In other words, incremental improvement cannot be creative development. In the development of next-generation microprocessors, engineers must also use next-generation semiconductor processes. This, in turn, may make obsolete many current development and design techniques, and logic and circuit layout, all being based on the former-generation semiconductor processes. In coming days, engineers should not believe in what they believe in today.

In creative development, it is imperative to carry out everything twice as fast as others. You must learn to work at high speed while you are young. Please remember that products are just like perishable goods. No matter how good they are, obsolete products will not sell. No matter how excellent architectures a microprocessor has, if you spend too long a time in development, you will lose the opportunity to commercialize it. In other words, I recommend that you seek to attain 97% satisfaction, not 100%. In a sense, all microprocessors that have been marketed were unfinished. Since humans have the ability to grow, one development always brings about new ideas, which brings about another development. Accordingly, development is endless optimization. The key to success in development is to plan the schedule, based on a backward calculation, taking into consideration available resources, such as human resources and CAD and other tools, and to stop development at the optimal point. With regard to design, logically coherent design with beautiful configurations is likely to prove its value in later years. I have another piece of advice concerning development. At the initial development stages, believe in your potential, since it is most essential to develop your creativity. In later stages, however, doubt everything, since you have to verify designs and examine product qualities, which requires extreme accuracy.

Finally, I would like to compare a development that has many complex problems to the fine cutting of a precious jewel. Like a jeweler who discovers, cuts, and polishes the mineral into a glittering jewel, engineers pour all their wisdom into creative development, and they find endless delight in the development process.

Thank you for your kind attention.