The Age of the Digital Nomad

Commentary on "The Age of the Digital Nomad – Impact of CMOS Innovation"

This is an introductory comment on the paper published in the winter 2013 issue of IEEE Solid State Circuits Magazine to describe a new lifestyle opened by CMOS innovation.

"Digital Nomad" (English version) was published in 1997 by the author together with David Manners, a technical writer in the UK. The Chinese version, with the title meaning "Nomadic Company Workers", was published in the next year followed by the Japanese version.
This book describes a forecast of lifestyle changes which would come in the near future where pocket-size intelligent universal terminals would be realized by the semiconductor technology innovation, which would relieve people from the constraints of time and place.

In 2007, exactly 10 years after the publication of "Digital Nomad", iPhone was released from Apple, and it triggered the start of the era of intelligent universal terminals. People are now able to work and play by freely manipulating smartphones and tablets in trains and airports. See image below.
Many books related to "Nomad" were published and even "Nomad Cafe" appeared from around 2010, and now we can call it the era of digital nomad.
It was the power of semiconductor innovation that has enabled large scale social transformation like this, and CMOS innovation played the central role here.

The IEEE Solid State Circuit Magazine (Winter 2013) on which this paper was published featured a collection of papers on low power ICs, and the guest editor for this issue was Toshiaki Masuhara (then Executive Director of LEAP). This paper was written by his invitation.

I remember my struggle in English writing with a dictionary in my hand in the summer heat to meet the dead line of September 2012.

"Digital Nomads" in the train

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The Age of the Digital Nomad —Impact of CMOS Innovation—

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"Digital Nomad" has become the catchphrase that describes a new lifestyle in which people have been freed from constraints of time and location, thanks to the progress of mobile intelligent devices and high speed communication networks. A book with this title was published in 1997 by the author and David Manners of the United Kingdome-based *Electronics Weekly* [1]. The first version was written in English; Japanese and Chinese versions the following year. Figure 1 shows photographs of the books and the authors.

Fig. 1 "Digital Nomad" published in 1997 and picture of co-authors

We have observed gradual changes in lifestyle from the traditional way to the nomadic way, notably in the past decade. It was quite common, by the turn of the 21st century, for a large number of people to commute to their workplaces every morning, for example offices in the centers of large cities, at 9 or 10a.m., either in cars or in trains every morning, and to leave in the evening at 5 or 6p.m. The regular movement of people, back and forth, creates the phenomena of heavy traffic for cars and the "rush hour" of trains.

In the time frame of the mid-1990s, when the book was published, cell-phones were just about to take off, but their capabilities were limited to talking. The situation is quite different today with the emergence of personal and intelligent mobile devices such as mobile PCs, tablet PCs, and smart-phones; most of us are enjoying the nomadic lifestyle in one way or another. Figure 2 shows a conceptual image of the “d*igital nomad”* [2]. If you have an intelligent mobile terminal, you can access any kind of information through the network. You don’t have to be at your office at 9a.m. sharp every morning anymore. You therefore have more freedom from the constraints of time and location. There are three essentials that support this comfortable nomadic lifestyle: an intelligent mobile terminal, a high speed communication network, and cloud computing. Without these essential modern infrastructures, the changes in our lifestyle would have been quite difficult. As shown in the figure, Steve Jobs of Apple, Inc. played a big role in launching the age of the d*igital nomad* .

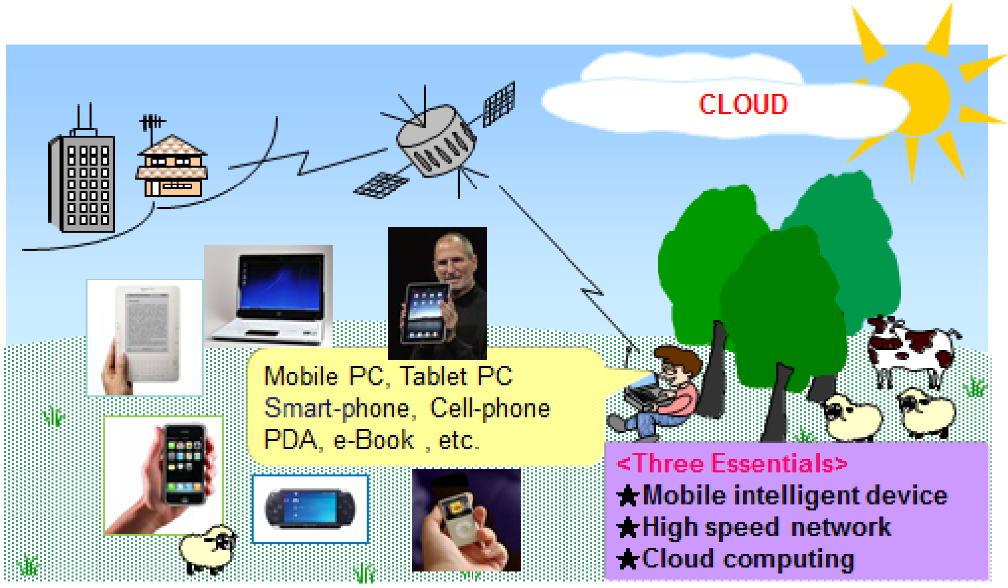


Fig. 2 Conceptual image of “Digital Nomad”

Figure 3 shows the general trend of electronic equipment, one in which everything is getting smaller and smarter, pointing the way to the “nomadic tool.” Computer, consumer, and communication products are all converging in a single category, intelligent mobile devices, which are collectively called “digital consumer products.” In the past, there were clear boundaries between the consumer, computer, and communication markets, but these boundaries are now disappearing, resulting in “market convergence”. There are two major driving forces behind the trend of market convergence; first, the digitalization of information and second, CMOS innovation. This article provides a brief history of CMOS innovation and its impact on our society from a macroscopic viewpoint rather than a technical one.

Fig. 3 Market convergence driven by digitalization of information and CMOS innovation

If we look back on the historical evolution of electronic equipment, it can be seen that progress has been made in such a way that the following four requirements are satisfied;

1) more intelligence (or higher information processing capability)
2) smaller size (for better portability)
3) lower power (for longer battery life)
4) lower cost (for more affordability as a personal device)

These basic requirements lead to the formulation of a *"figure of merit"* for electronic equipment, as shown below [3]:

$$\text{Figure of Merit} = \frac{(\text{Intelligence})}{(Size) \times (Cost) \times (Power)}$$

where the intelligence term needs to be defined for each type of equipment. For example, "MIPS" can be used for a general purpose computer, "MOPS" for a signal processing system, and "FLOPS" for a numerical calculation system. The rest of the parameters--size, cost, and power -- are self-explanatory. It should be noted, however, that the size of a device cannot be reduced beyond what is useful for the human interface, as in the case of calculator, which has already reached its minimum size.

Generally speaking, the higher the f*igure of merit*, the higher is the value of the nomadic tool. Semiconductor technology has made progress toward maximizing the f*igure of merit*. CMOS Innovation has played the most important role in this regard, and it has been the fundamental force moving our society toward a nomadic lifestyle.

History of CMOS Innovation

CMOS has come a long way since F. M. Wanlass presented the idea at ISSCC in 1963 [4]. This was followed by the first commercial products, introduced by RCA in 1968. Historically, CMOS devices were far superior to others in terms of power dissipation, but they were slower and more expensive, and integration density was lower compared with other devices. This situation has not changed by the late 1970s; the common understanding of the industry or "industry consensus" of those days can be summarized as below:

1) The mainstream device will remain NMOS.
2) Bipolar will be utilized for analog and high speed applications
3) Gradually, PMOS will be phased out
4) CMOS will remain a special device for niche market where low power is an absolute necessity.

A big change in this situation occurred in 1978, when Hitachi pioneered the reengineering of the CMOS based on the invention of twin-well CMOS by Y. Sakai and T. Masuhara, then at Hitachi's Central Research Lab. (CRL) [5]. The joint engineering team of CRL and Hitachi's semiconductor division made a bold attempt to develop high speed 4K Static RAM (SRAM) based on the new technology that would compete with Intel's 2147, the highest-speed device of the time. The team overcame various difficulties, and the initial target was achieved. The result was presented at ISSCC 1978 by T. Masuhara who led the project [6].

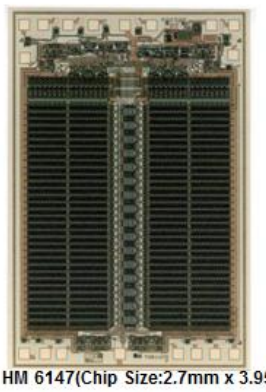
Table 1 compares the features of NMOS and CMOS 4K SRAM. Intel's 2147 chip was based on NMOS technology and had an access time of 55-70 ns. Hitachi's 6147 was pin-compatible with Intel's 2147 but was based on re-engineered CMOS technology. The 6147 achieved the same speed as the 2147, but the power dissipation was only 1/8 in active mode and 1/15,000 in standby mode as compared with the 2147. The 6147 from Hitachi was an epoch-making device and garnered a great deal of attention in technical circles.

	2147 / Intel (1977)	6147 / Hitachi (1978)
Product	HMOS 4K Static RAM	HiCMOS 4K Static RAM
Technology	NMOS	Twin-Well CMOS
Speed	55 / 70 ns	55 / 70 ns
$I_{Active}/I_{Standby}$	110 mA / 15 mA	15 mA / 0.001 mA
Chip Size	16.2 mm^2	11.5 mm^2

Table 1 Comparison of parameters for NMOS and CMOS 4K SRAM

I was in charge of the memory/microprocessor business operation of Hitachi's semiconductor division in this time frame, and my responsibility was to make the new CMOS device a commercial success. There are three critical steps for any new technology to become a commercial success; first, development of competitive devices; second, cost-effective mass manufacturing; and third, marketing and sales for revenue. These three steps are quite different in nature, and different kinds of people are engaged in each step. They have to be carefully organized in order for all project members to work toward the same goal, sharing the same mission and philosophy. Achieving that was my major role.

The first CMOS device from Hitachi, the 6147, was intended to show the technical superiority of the new CMOS device as compared with NMOS devices, and it was a great success from an engineering point of view. Hitachi was awarded IR-100 for this development, as shown in Fig. 4. The 4K SRAM 6147 clearly marked a mile stone in the history of semiconductor: it changed the direction of technology from NMOS to CMOS.



HM 6147(Chip Size:2.7mm x 3.95mm)

Fig.4 1979 IR-100 awarded to CMOS 4K SRAM (left), and chip photo of HM6147(right)

Due to the limited market size of the 4K device, we had to introduce a product with a much larger market size in order to obtain the commercial success. That product was the 16K SRAM. In those days, 16K SRAM was the most advanced product in terms of density, and its market size was estimated to be much larger than that of 4K SRAM. A big project was organized with the goals of developing, manufacturing, and commercializing the device and establishing it in the number-one position in the world among similar devices. Members in each section did their best to reach this common goal. The 16K SRAM project was successfully completed, and commercial samples were prepared and delivered to potential customers.

In a sense, the project was a challenge to the late-1970s industry consensus that held that NMOS was the mainstream semiconductor industry device. A typical comment we heard from our competitors in those days went like this: "Hitachi's new CMOS chip would be great if it could be produced in volume". As mentioned previously, development and manufacturing are quite different. It is true that even if an excellent device has been developed, its value will be diminished if it is not producible in volume. We therefore had to demonstrate that the new CMOS devices were producible en masse in as cost-effective a way as commercial items.

Our potential customers also had some concerns about our CMOS device since no other chip companies were following in our foot-steps, which meant that there was no "second source" for the device. I therefore had to visit customers by myself--especially the strategic ones--in order to explain the basic philosophy of our CMOS direction, including our supply capability and future prospect. Through direct contact with customers, I became confident that if we had a big inventory, their concerns would mostly disappear. The big inventory says, indirectly, that the device is mass-producible. So I embarked on a strategy to build an inventory of 16K SRAM under the name of "strategic inventory," since the inventory level of commodity memories was kept under strict control.

Production went very smoothly, and a strategic inventory was built more rapidly than I expected. We were ready to ship any amount of the new 16K SRAM. Orders from customers did not arrive, however. The inventory level reached a critical point where the top managers began to pay strong attention, and a big question was raised about our strategy to sell CMOS instead of following the industry-standard NMOS approach. A very drastic directive from the top was about to be issued to change the direction of the technology from CMOS back to NMOS. And at almost the same instant, a goddess of business smiled on us; we began receiving big orders from customers. Our 16K SRAM business grew nicely, and Hitachi became the number-one producer of 16K memory chips in the world in 1981.

With the commercial success of 16K SRAM, confidence in CMOS was established inside Hitachi. Our next strategy was to expand the adoption of CMOS technology to other devices, including MPUs, MCUs, logic circuits, and DRAMs. The 8-bit microprocessor was the first to follow in this direction; the first CMOS MPU, the HD6301, was introduced to the market in 1981. Table 2 summarizes the comparison of 8-bit MPUs based on CMOS and those using NMOS that had been developed previously. As can be seen from the table, the CMOS version was twice as fast, and its power dissipation was 1/30 in active mode and 1/7,000 in standby mode of that of the NMOS MPUs. The success of the CMOS 8-bit MPU contributed to setting a new technological direction for microprocessors and logic devices.

		6801 / Hitachi (1979)	6301 / Hitachi (1981)
Product		8bit MPU	8bit MPU
Technology		4 Micron NMOS	3 Micron CMOS
Speed		1 MHz	1 MHz, 1.5MHz, 2MHz
Power	Active	900 mW	30 mW (f = 1MHz)
	Standby	70 mW	0.01 mW
Pin Count		40 Pins	40 Pins

Table 2 Comparison of parameters for NMOS and CMOS 8bit MPU

Soon after the introduction of our CMOS 8-bit MPU, Epson (then Shinshu-Seiki) started a project to develop an “all CMOS computer” using two CPU chips from Hitachi. The project was a great success, and the new product, called the HX-20, was introduced to the market in 1982[7]. It was marketed by the company as “the world’s first hand-held computer” and is often named as one of the mile-stone products of the company. It may well be appropriate to call it the ancestor of the nomadic tool.

During the early and mid-1980s, there were a lot of arguments in the semiconductor industry about whether the future mainstream product would be NMOS or CMOS. The discussion was first initiated in digital ICs, as witnessed by the 1981 ISSCC Panel on “CMOS vs. NMOS for VLSI.” Similar shifts from bipolar technology to BiCMOS technology and then to CMOS technology were also seen in analog and communication ICs in mid-1980s and beyond. DRAMs and flash memories followed this direction in a similar time frame due to the necessity to implementing functions such as high -sensitivity sense amplifiers, redundancy, and voltage conversion on the same chip. Meanwhile, during the 1990s and later, a gradual shift of opinion in favor of CMOS was also observed in high-end processors for servers. In the final stage, RF devices also shifted to CMOS, as witnessed by a 2001 ISSCC panel discussion on the “Years of RF-CMOS.”

Figure 5 summarizes the evolution of semiconductor device structures and shows them converging to CMOS. Simply stated, it is obvious that the past several decades could be described as a period of “CMOS convergence.” The original CMOS devices developed by RCA were applied primarily to ultralow-power equipment, such as military applications in which speed was not an issue. The next big markets for CMOS were watches and calculators, both of which also did not require high speed.

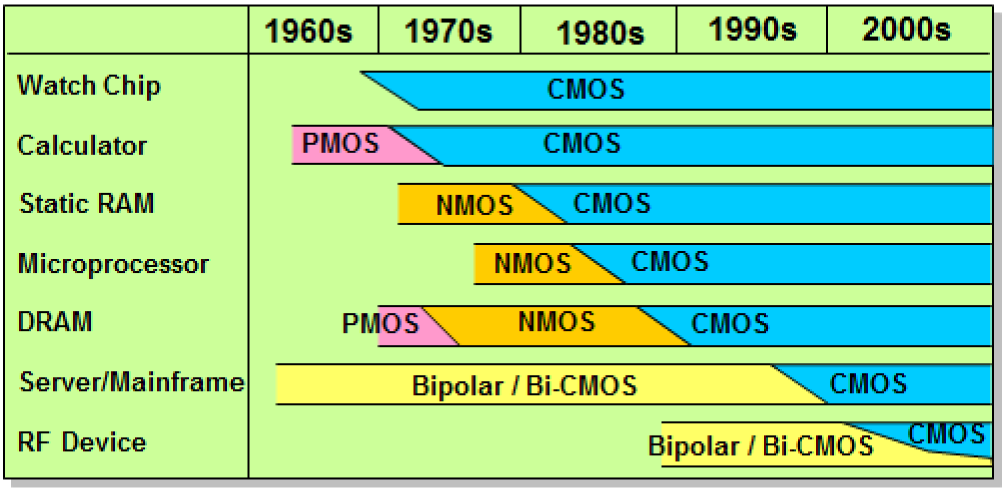


Fig. 5 Evolution of device technology converging to CMOS

Hitachi's introduction of high-speed CMOS SRAM--the 4K 6147 and the 16K 6116--in the late 1970s demonstrated, for the first time in the industry, that CMOS could match NMOS in terms of performance while maintaining its low-power feature. All the other device types, such as MPUs, DRAMs, and flash memories, followed the same course as SRAM, as shown in the Figure. Then the technology shift was also seen for mainframes, which had been based on bipolar or BiCMOS technology. Here is some interesting testimony from the head of a giant computer company, Louis V. Gerstner, the ex-IBM Chairman and CEO, from his memoir *Who Says Elephants Can't Dance?* [8].

This is how Gerstner describes the effect of CMOS on IBM's main frame business;

- IBM's mainframe sales were declining because of a precipitous drop in market share.
- The technical team made a bold move to a totally different architecture: from bipolar to CMOS.
- Had IBM not made the decision to go with CMOS, it would have been out of the mainframe business by 1997.

With the technological shift of servers and mainframes to CMOS, nearly all electronic equipment today, from small to big and from mobile to stationary, is based on CMOS. It can be said that CMOS innovation laid the foundation of today's civilization.

Future Prospects *Technological Aspects*

One of the major changes expected for future semiconductors is a diversification of technological direction. One direction would be to keep on enhancing device performance and integration density through the extension of Moore's Law [9]; this is often called the "more Moore" direction. On the other hand, there are newly emerging devices in the semiconductor industry, such as sensors, MEMS devices, display devices, power devices, and bio chips, whose functions depend on utilizing the basic properties of materials rather than just shrinking the devices. These are sometimes called "more than Moore" (MTM) devices and are expected to make great contributions to newly opening markets such as robotics, medical and health care, the smart grid, and sensor networks.

It is quite likely that CMOS will remain in the mainstream of device structures for “more Moore” direction in the foreseeable future, since there is no sign of the emergence of a new device that can replace CMOS. One strength of CMOS in IC technology is that it serves many functions, including digital logic, memories, buffers, clock trees, analog, RF, voltage generation and power supply, temperature compensation, and ESD protection. The future, however, is not a simple extrapolation of past trends, and CMOS will take different paths of innovation as it moves ahead, as discussed below.

CMOS chips will keep increasing in integration density on a monolithic chip by shrinking the device geometry, introducing new materials, and adopting new device structures such as the FinFET. Increasing the density on a chip will however become ever more difficult. There are two reasons for this. First, the feature size of the device is fast approaching the theoretical limit determined not only by physical constraints but also by increasing leakage currents and parameter variations. Second, investment for device development and for manufacturing is becoming prohibitively expensive. Due to these difficulties, extending Moore’s Law will become harder than before.

A countermeasure for this issue is the 3-D integration of chips. Various new technologies, such as through silicon via (TSV), are being developed, and they will contribute to the realization of 3-D integration. TSV is a technology that can connect chip to chip by opening holes through the Si chips. Figure 6 shows the historical evolution of device structures used to extend Moore’s Law. It can be seen from the figure that CMOS has played the major role over the past several decades in extending the trend. Looking to the future, the 3-D integration of CMOS chips will extend Moore’s Law for one or more decades, and it will contribute to increasing the figure of merit for electronic equipment.

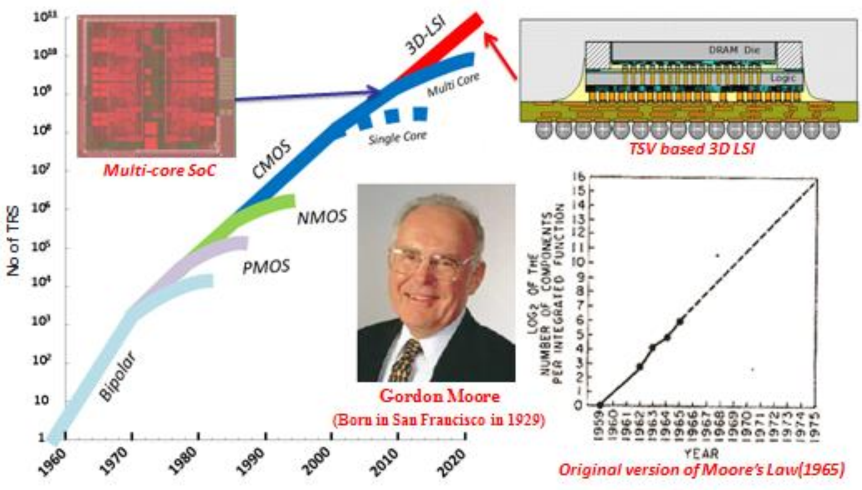


Fig. 6 Device evolution to extend Moore’s Law

Application Aspects

We will see the emergence of new markets in the coming decades with the further innovation in semiconductor technologies. Currently, the digital consumer market is driving the semiconductor industry, where smartphones and tablet PCs are the hottest items. What will come next? An interesting discussion was held at the ISSCC 2000 panel session regarding the ultimate nomadic tool, called "When Can I Buy a Dick Tracy Watch for Christmas?" With the further increase of figure of merit values, it may not be very long before we get a Dick Tracy Watch as a Christmas item, at least from the technological viewpoint.

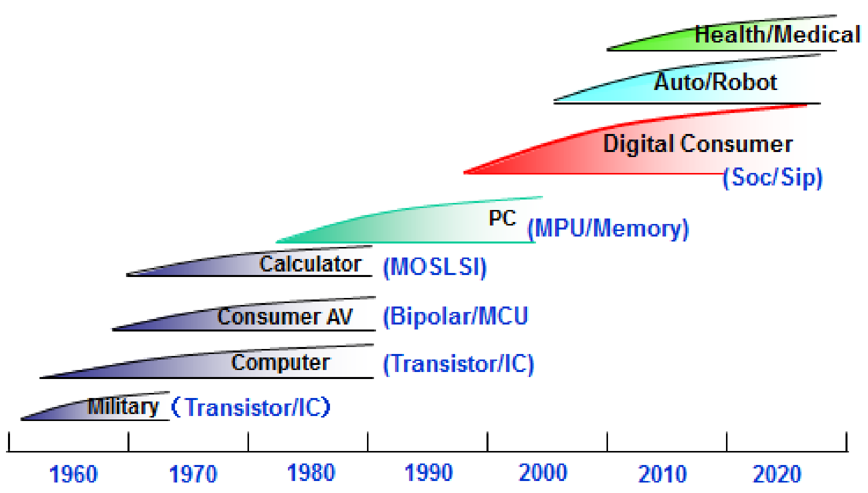


Fig. 7 Evolution of application market

Figure 7 shows the evolution of major semiconductor markets over the past several decades and forecast that looks beyond the digital consumer market. The emerging market will include the new automotive market, including EVs and HEVs, robotics, medical and health care, and sensor network market.

Among those emerging markets, robotics will be the most challenging for chip technology and will become the next technology driver of the semiconductor industry. Figure 8 shows a prediction of robot intelligence made by Hans Moravec of Carnegie Mellon University [10], [11]. Generally speaking, the intelligence of today's robot is far inferior to human intelligence, especially in the field of pattern recognition and language understanding.

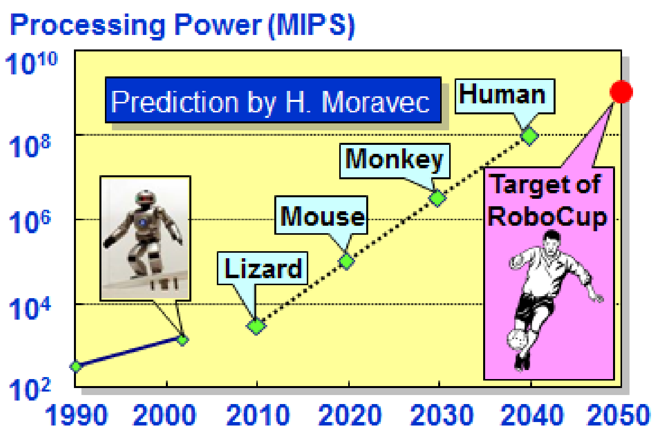


Fig. 8 Rise of robot intelligence towards RoboCup in 2050

But robot intelligence is expected to increase dramatically in the coming decades, owing primarily to the progress of high-performance and low-power CMOS innovation combined with 3-D integration technology. Although it is not simple-to compare the intelligence of a robot and a human being, one way of looking at the evolution of a robot's intelligence to the level of human intelligence by 2040 is shown in Fig. 8. It is interesting to note that one goal, known as the "RoboCup," is set to be achieved in 2050 [12]. The RoboCup is a very ambitious project whose goal is to have a team of robots play soccer against a human team in 2050 and win. Will it really be achieved? It is clear that an enormous amount of pattern processing, matching, and recognition needs to be done in the robots or by accessing the "big data" stored in the data center. In either case, much higher integration and higher power efficiency is needed for processing and storage than is available now. No one knows for sure if this goal can be achieved, except for one thing; the answer will depend very heavily on the progress of semiconductor technology, where the challenge is to achieve human-level intelligence within the limits of allowable power consumption.

We are facing a very interesting and challenging future .

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