Lecture 7. The Microchip

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Introduction

Looking inside our desktop computers, laptops, and smartphones, following wires inside our cars, elevators, fridges, wrists watches, radios and audio equipment, searching through circuitry controlling "smart" trains, airplanes, spacecraft, process control and test equipment, taking off covers of electronic equipment, we don't see vacuum tubes any more. Instead, we see electronic boards populated with all sorts of tiny devices. Some of them are rectangularly shaped black blocks of plastic with numerous metal leads extending out of them and into the board. We call them **integrated circuits**.

Fig. 1. A smart phone's circuit board with integrated circuits. Source: unknown.

In fact, what we see are not "circuits" themselves as they are packaged in plastic or ceramic, mostly non-transparent enclosures.

Integrated circuits are small and use little energy; but they can implement electronic circuits of immense complexities. That's why large calculators could be turned into pocket-sized gadgets and large mainframe computers into small servers, desktops, and laptops.

In this lecture we shall trace the development of an integrated circuit from an invention of the transistor to the microprocessor. We shall discuss the impact of these inventions on our society that was to get an unrestricted access to computing and information.

What are integrated circuits?

If we carefully strip an integrated circuit of its plastic shell, we shall see a small rectangular surface–the chip itself–with a number of metal leads connected to it.

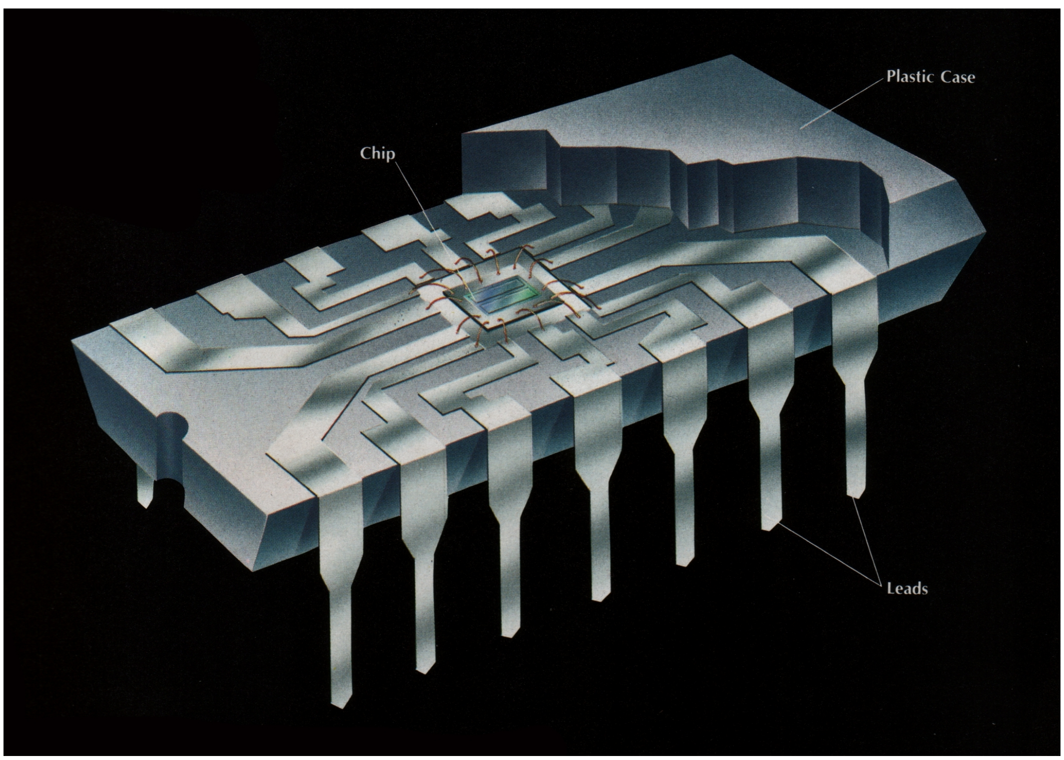

Fig. 2. Inside a chip. Source: *The Chipmakers*, Time-Life Books (1988).

These leads are used to power the chip and to communicate with it. To unravel the secret of a chip, we must place the chip under a microscope.

Under high magnification, a chip is a flat area covered with tiny electronic components interconnected with flat ribbon-like wires (or paths). The majority of these electronic components are **transistors** – minuscule electronic switches, that play the same role as vacuum tubes or electromagnetic switches in early computers. The main advantages of transistors over other switches is that they can be made small, million of times smaller than vacuum tubes used to build the ENIAC.

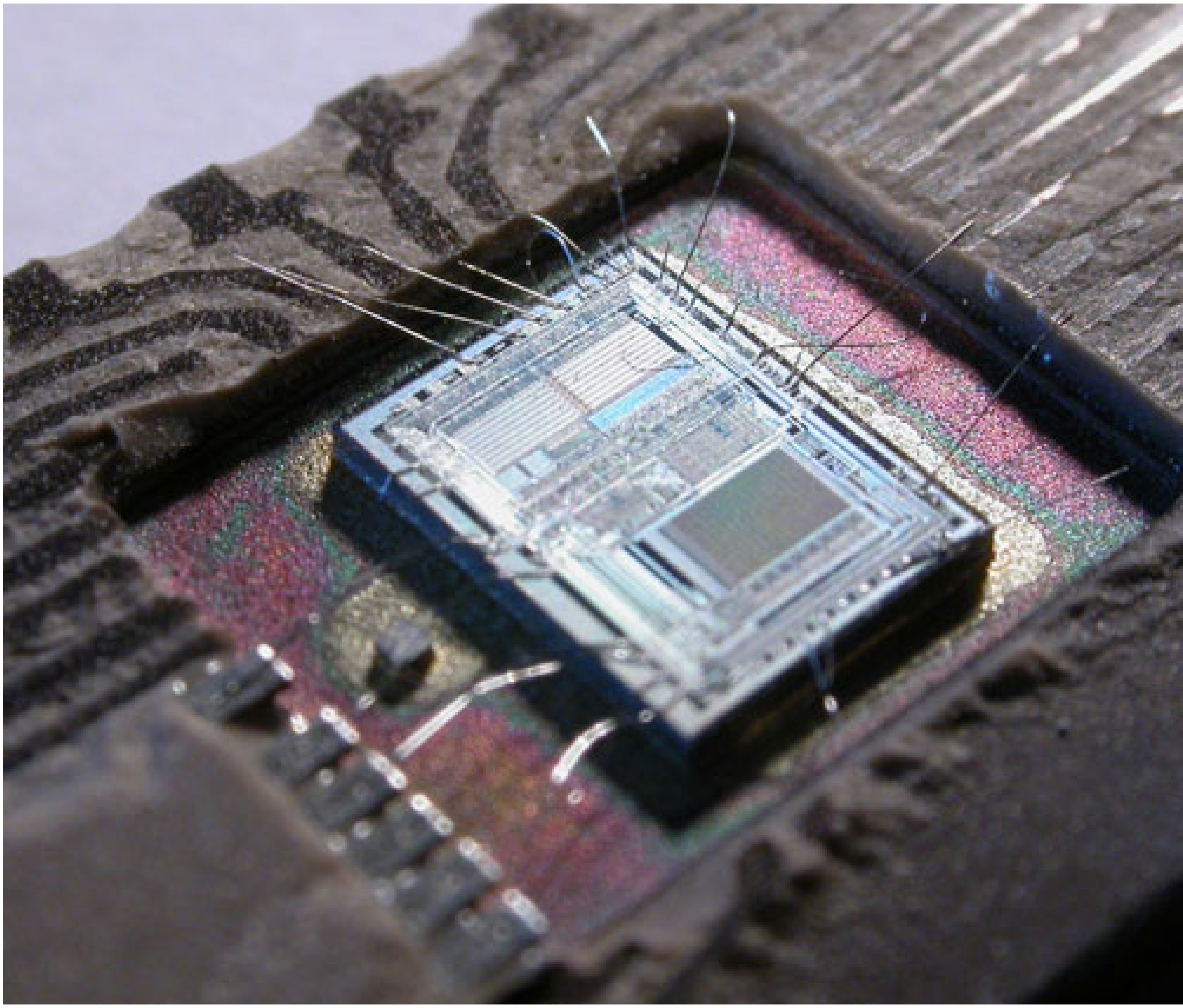

Fig. 3. The chip revealed: this chip contains thousands of transistors deposited on a tiny piece of silicon. Photograph by Ioan Sameli.

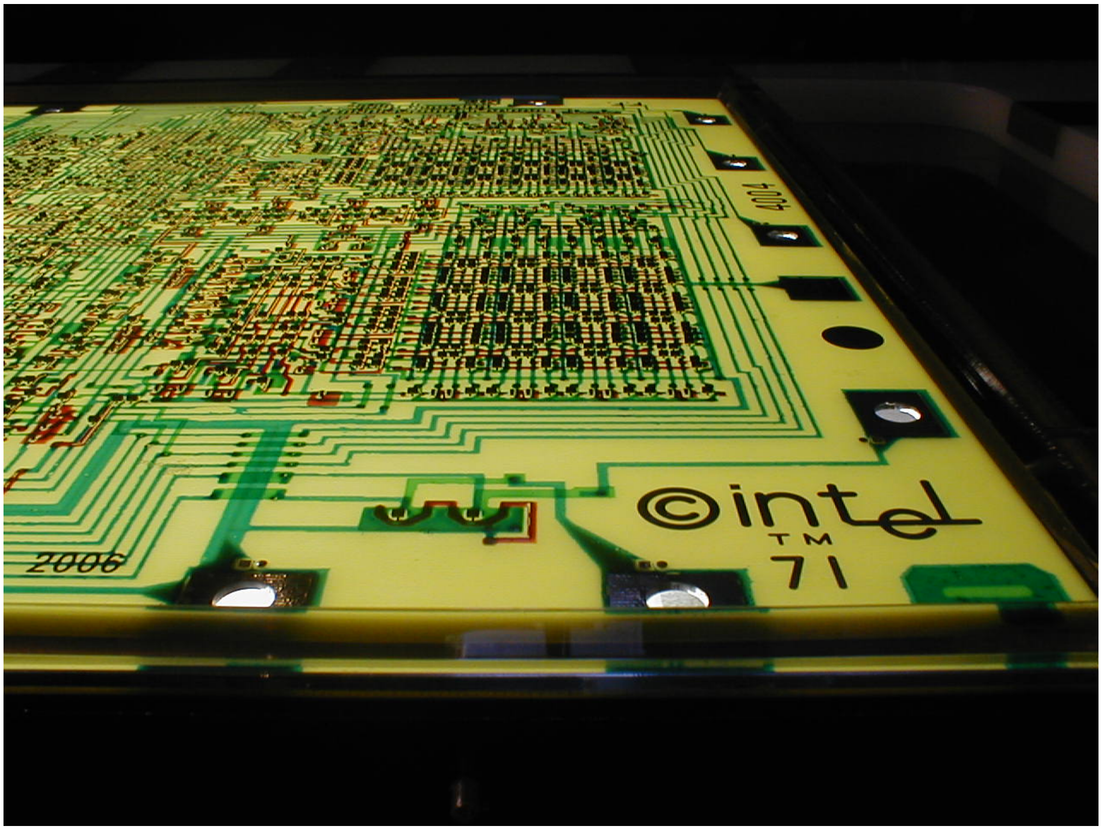

Fig. 4. Transistors inside Intel's first microprocessor – the 4004; the 4004 chip had 2,3000 transistors deposited on 2mm by 3mm piece of silicon. Source: http://www.4004.com

What's a transistor?

The transistor is an electronic switch that allows or disallows the flow of electrical current through it. Vacuum tubes and electromagnetic relays can do that as well but transistors are tiny, highly-reliable, fast, and require small amounts of energy to operate. In addition, we have learned how to construct electronic circuits with millions of them residing on little surfaces of silicon.

In 1971, the Intel 4004 processor–the most complex electronic device put together–had 2,300 transistors. In 2010, an Intel Core processor held 560 million transistors, enough to build approximately 30,000 ENIACs on a single chip! (Recall that the ENIAC was built of about 19,000 vacuum tubes).

The transistor's invention was, as it is usually the case with inventing, not an a sudden occurrence of a brilliant idea. There were various people involved in various periods of time. Some even claim that the transistor's origin lies in technology recovered by the US Air Force from an alien spacecraft recovered at Roswell, New Mexico in 1947. What can be said without any doubts is that it was the work done at Bell Labs by William Shockley, John Bardeen, and Walter Brattain at the end of the 1940s that kick-started a transistor-powered revolution in electronics and created the foundations for our present day digital reality.

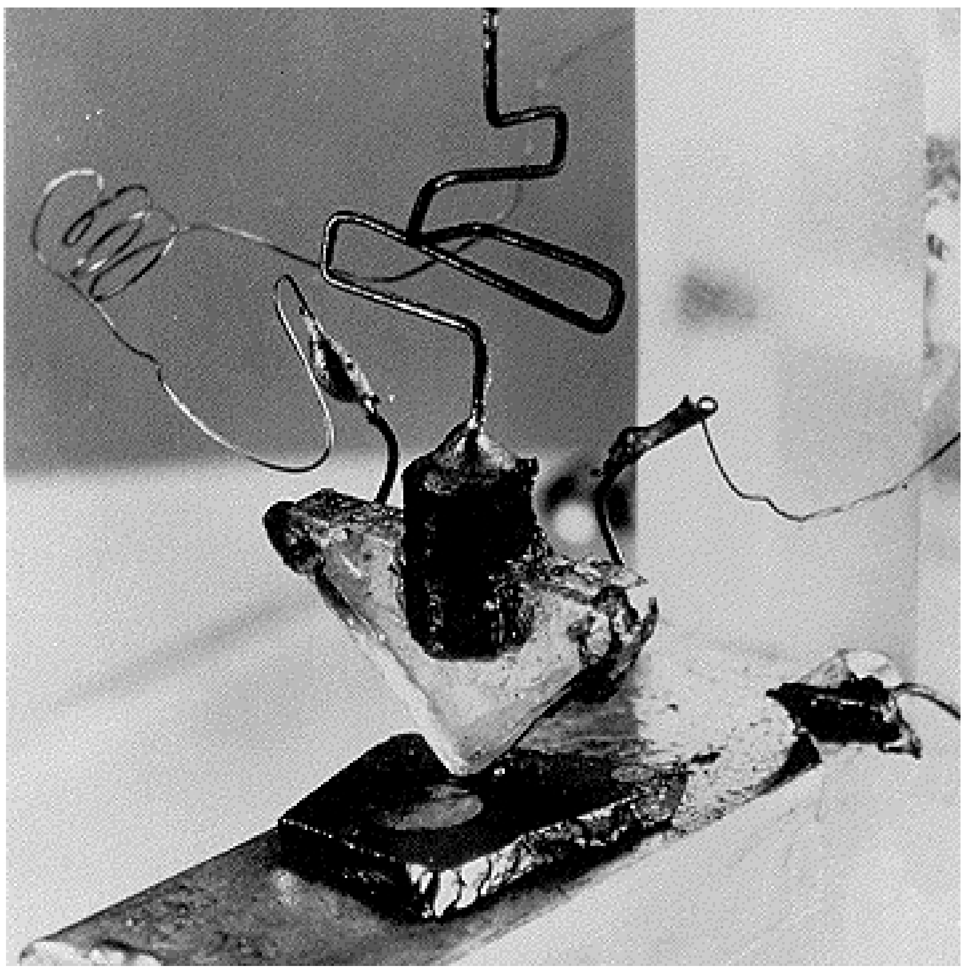

Fig. 5. The Bell Lab's prototype transistor. Source: unknown.

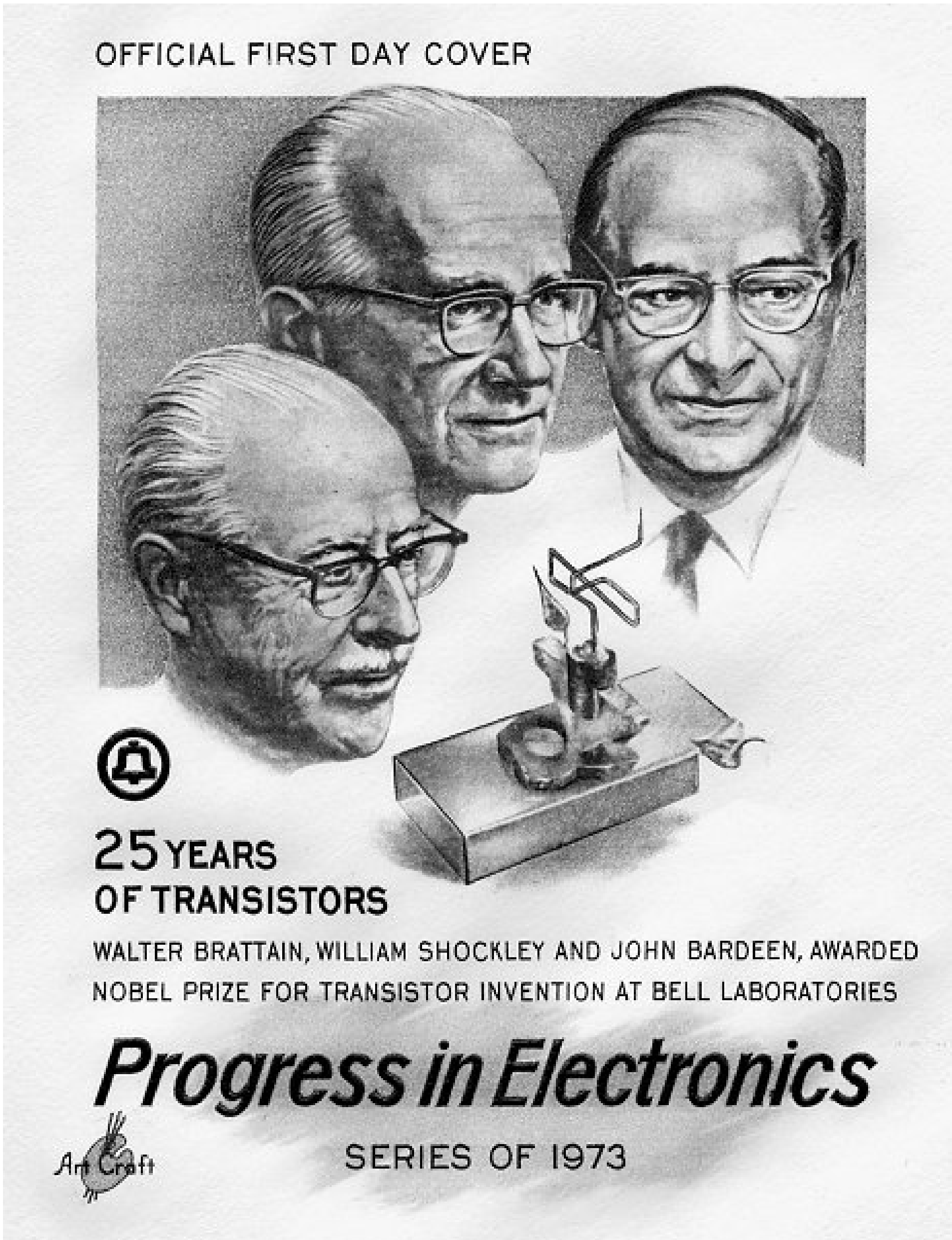

Fig. 6. 1973 envelope cover commemorating Bell Labs W. Shockley, J. Bardeen, and W. Brattain's Nobel Prize award for their work on the transistor. Source: unknown.

Brief Time-line of the Transistor:

1925-28: Physicist Julius Lilienfeld patented his transistor in Canada and U.S. He did not provide a prototype or working application.

1947: William Shockley, John Bardeen, and Walter Brattain, physicists at Bell Laboratories, created the first working transistor (still large).

1952: The first transistor-based commercial product: hearing aids from Sonotone, Maico, and Acousticon.

1953: First transistor radios: before laptops and smartphones of today they were the most popular electronic communication device in history.

1953: The University of Manchester Transistor Computer (experimental).

1955: IBM introduced a transistor-based IBM 608 calculator replacing a similar device, the 604, built with 1,200 vacuum tubes. The 608 used 2,200 transistors, was much smaller, used 95% less energy and was very reliable.

Fig. 7. A variety of transistors, c. 1970s-90s. Source: unknown.

Fig. 8. A 1955 ad for Raytheon 8-transistor radio. Source: unknown.

The transistor was also a promise of a new era in the consumer electronics industry. In just a few years from the transistor's creation, the device delivered on its promise: not only it replaced vacuum tubes in radios, TV sets, audio equipment, computers and all sorts of other electronic devices but also allowed the manufacturing of new, highly reliable equipment in areas such as health, automotive, and space sciences.

The transistor revolutionized both the concept design and manufacturing. It allowed the development of miniaturized, portable, batter-powered electronic products that could withstand mechanical shock and vibration and operate for years without defect.

Fig. 9. A 1964 ad for RCA transistors. Source: unknown.

Fig. 10. A 1957 ad for Admiral transistor-based consumer electronics products.

The more transistors the better...

In the early 1950s, as transistors were getting smaller and faster, many in the electrical engineering community envisioned an electronic device that would integrate several discrete components (transistors, diodes, resistors, capacitors) into a circuit by, first, making all of them of a single chip of silicon and, then, interconnecting them with wires laid on the surface of the chip.

In 1958, Jack Kilby, an engineer at Texas Instruments (TI), build such a device–the first integrated circuit–and TI announced the chip's "discovery" in January 1959. In recognition of his work, Kilby work was awarded Nobel Prize in physics and was even commemorated on post stamps.

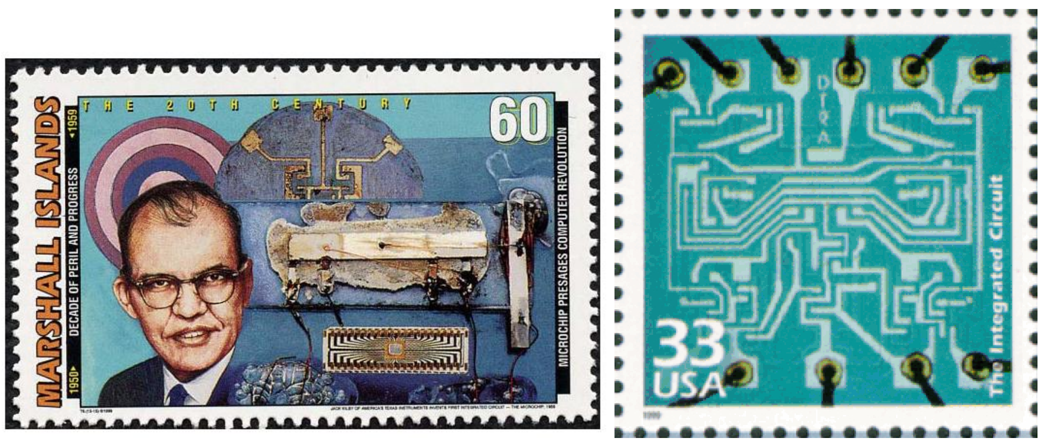

Fig. 11. A Marshall Islands stamp (left) and a US stamp (right) commemorating Kilby's invention of the integrated circuit.

In 1959, Kilby's ideas were improved by Robert Noyce (of Fairchild) who also used the concept of a "flat" transistor invented by Jean Hoerni at Fairchild to build his circuits. Noyce demonstrated how to integrate several transistors and other components on a flat area of silicon without interconnecting wires. His work resulted in the prototype of all modern integrated circuits.

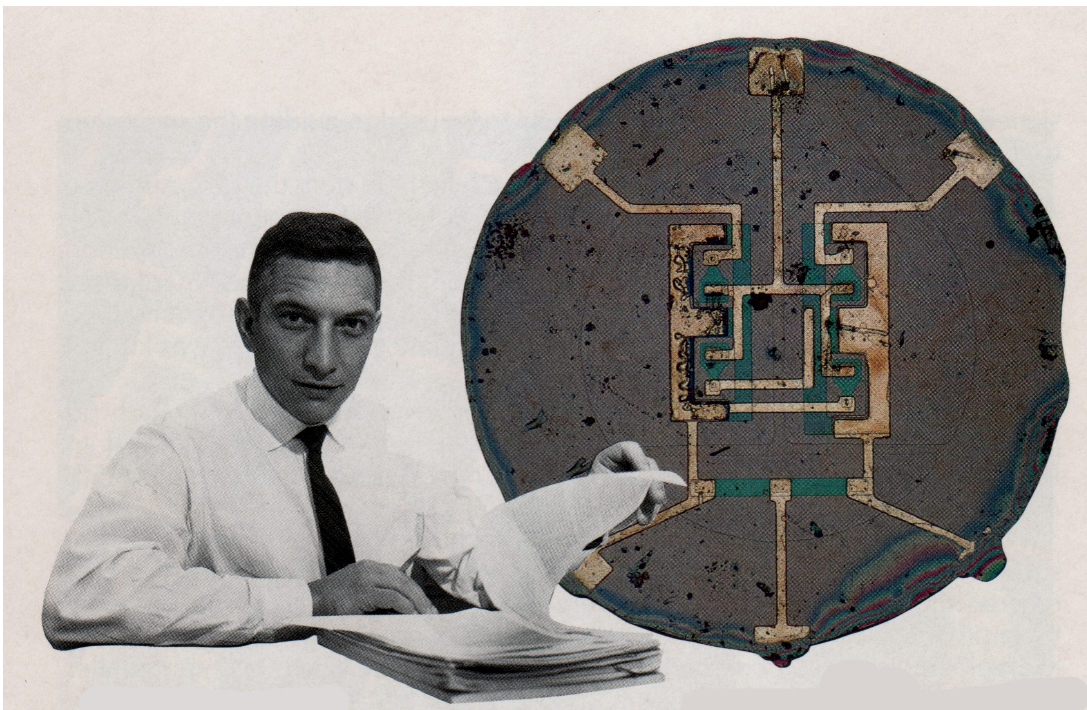

Fig. 12. Robert Noyce and his 1959 integrated circuit (magnified!!) with 4 transistors. Source: *The Chipmakers*, Time-Life Books (1988).

In 1961, both Fairchild and TI had a technology to manufacture integrated circuits with tens of transistors on them. The demand from the US military, space program and, soon after, computer industry, made circuit development and manufacturing a very profitable business for both companies.

The Minicomputers

The era of miniaturization initiated by the transistor had a profound impact on the computer industry. Vacuum tube mainframe computers were replaced by their transistorized clones. The new computers were much more reliable and smaller; however, they were still expensive served the same type of well-funded customers.

By the mid-1960s, the inexpensive transistor and advancements in computer architectures also resulted in the development of a new generation of computers. The knowledge of computers had gradually spread, and so had the need for affordable computing. The next generation of computer hardware–**minicomputers**–made computing on demand a reality for mid-size companies and organizations. Minicomputers were less expensive to own (or lease) and operate than mainframes. They were also smaller, transportable and more reliable. Because of these features, minicomputers were widely used as business machines, research workstations, industrial controllers, and data collection and processing stations.

Minicomputers, such as the immensely popular PDP-8s manufactured by Digital Equipment Corporation, changed the face of academic computing, as they were popular choices to support research and teaching.

The minis were not supposed to compete with mainframes or to challenge the mainframe business culture. Instead, the minis created a sizable, and soon quite lucrative, market of its own. The rapid demand for such computer equipment created a vibrant minicomputer industry and unveiled new application areas unserved by mainframes. The minis created a new generation of computer users, and a new computing paradigm based on direct interaction of a user with the hardware – a prelude to personal computing.

My own PDP-8

One of the most successful minicomputer companies was the Digital Equipment Corporation (DEC) founded by Kenneth H. Olsen and Harlan Anderson in 1957. DEC's first computer–the PDP-1–was not a remake of some vacuum tube computer, as it was frequently the case with other manufacturers (such as IBM whose transistor-based 7090 computer was a remake of the vacuum tube giant the 709). It was a new design that incorporated all that the new transistor technology had to offer at the end of the 1950s.

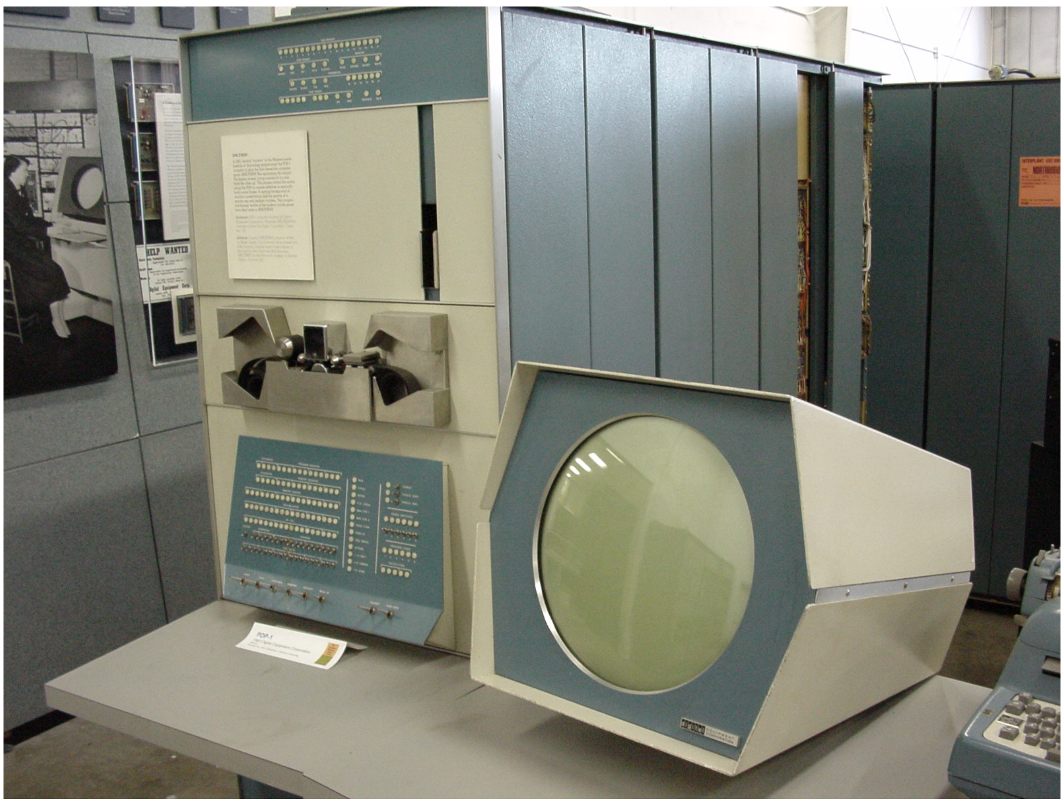

Fig. 13. The DEC PDP-1 computer at the Computer History Museum, Mountain View, Ca. Photograph by Z. Stachniak.

Note: the famous Space War game, possibly the earliest computer video game ever written, was implemented on MIT's PDP-1 by a number of students in 1961/62. That game was immensely popular in the computing world.

The computer that ignited the minicomputer market was DEC's PDP-8 mini introduced in 1965. As the historian Paul Ceruzzi explained in his book [1],

> *The PDP-8's success, and the minicomputer phenomenon it spawned, was due to a convergence of a number of factors, including performance [high speed], storage [new type, core], packaging [small, modular designed, easy to operate], and price [$18,000 on introduction].*

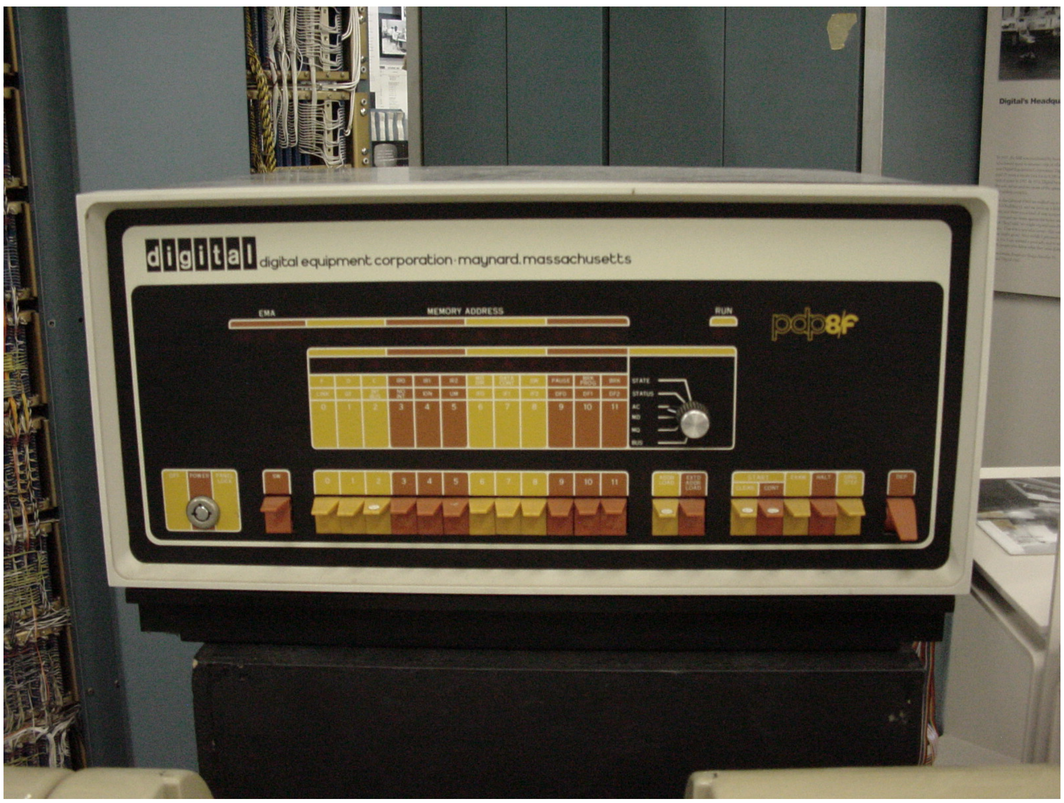

Fig. 14. The DEC PDP-8 computer at the Computer History Museum, Mountain View, Ca. Photograph by Z. Stachniak.

The PDP-8s were small and could be placed on desks. And they were sold by thousands to research labs, educational institutions, and businesses. DEC was selling as many PDP-8's as IBM was shipping its 360 mainframes. The PDP-8s and myriad of over minis demonstrated for the first time that computers do not need to be large and expensive to be useful.

The Microprocessor

The rapid advancements in the semiconductor process technologies in the second half of the 1960s, and the ever increasing transistor count on a single integrated circuit (from two, to tens, to hundreds) opened up a possibility of depositing the essential circuitry of a computer (the so-called central processing unit or CPU) on a single integrated circuit and to manufacture such a circuit in an economic manner. When such integrated circuits finally arrived on the commercial market they would be called **microprocessors** – micro computers on tiny pieces of silicon.

The calculator industry, too, was taking advantage of a fast pace of the semiconductor industry's development and began manufacturing smaller, more portable, and less expensive products. Some companies, such as Sharp, Texas Instruments, and Busicom, were aiming at further savings by implementing calculator logic circuits using integrated circuits with more than one thousand transistors on them.

The introduction of the world's first microprocessor has its roots in the calculator industry. On April 28th, 1969, Intel Corporation of Santa Clara, California (co-founded by Robert Noyce and Gordon Moore in 1968), signed a provisional agreement with a Japanese firm Busicom to design and manufacture a kit of integrated circuits for the Busicom desk-top calculators.

Busicom wanted Intel to design and manufacture several integrated circuits implementing various calculator functions. But in 1969, Intel was still a young company (without sufficient number of employees to work on all these chips in addition to Intel's main line of products – the semiconductor memory chips.

This is why one of Intel's first employees Ted Hoff proposed to replace most of the Busicom calculator's chips with a single integrated circuit which was to function as a simple but general purpose programmable computer. Busicom agreed to pave the way to the design and development of the world's first commercial microprocessor – the 4004.

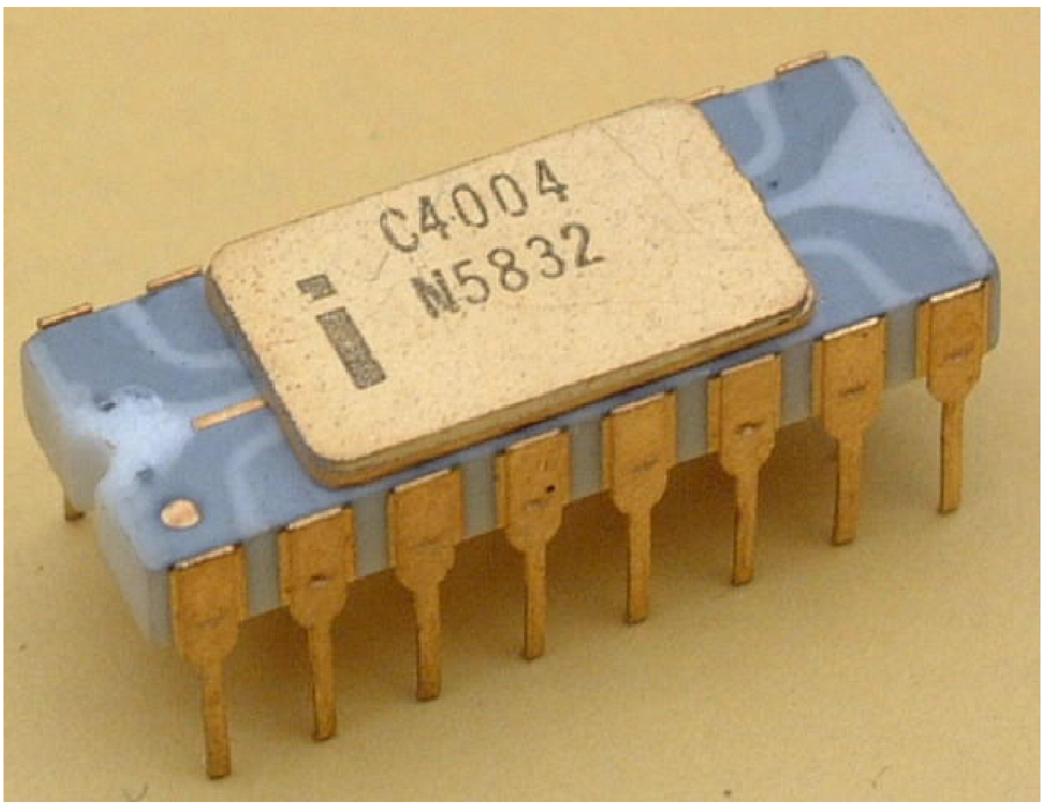

Fig. 15. The Intel 4004 – the first commercial microprocessor (1971). Source: unknown.

By mid 1971, the design efforts of Hoff and three other engineers: Stanley Mazor, Federico Faggin and Busicom's engineer Masatoshi Shima resulted in fully functional 4004 microprocessor and its supporting chips. In Fall of that year, Intel announced the coming of "computer on a chip" and a "new era in computer electronics".

Fig. 16. The Busicom 141-PF – the world's first microprocessor-powered calculator. Source: http://www.4004.com

As explained by Hoff in an interview with Z. Stachniak,

> *My goal was not to develop a single chip computer – rather just [to] make the calculator set more cost effective. It just happened that when the design was done, we realized that this chip set could do a lot more than just make calculators.*

Indeed, since late 1971, the 4004 was no longer viewed solely as a calculator chip but as a miniature computer that could be employed in a number of applications from calculators, to cash registers, lab equipment, medical equipment, and traffic light controllers.

In a short period of time, companies around the world were joining Intel in the microprocessor club by successfully depositing central processing unit circuitry onto wafers of silicon, including a Canadian company Microsystems International Limited which had its first microprocessor working in 1972.

The microporcessor was a ”necessary invention”, a generic example of a scientific, technical, and technological chain of events culminating in a paradigm-changing invention. In June 1981, Gary Killdal, the designer of one of the first and most successfull operating systems for personal computers commented on this process in the following way: “Microprocessors are a direct result of our pattern of refinement through engineering. Just as a Boeing 727 is a refined version of the original Wright Brothers' invention, the microprocessor is a consequence of ”fine tuning” by scientists and engineers who strive to understand, simplify, and add function to mankind's tools.” [See [4]].

It took Intel more than half a decade to fully realize how significant and profitable the microprocessor business could be (Intel was founded as a manufacture of computer memory chips). But when it did, it started to have a bigger effect on the lives of people than any other computer, semiconductor, or electronics company. After four decades of microprocessor manufacturing, Intel remains an industrial icon symbolizing the modern era of digital computing.

In just a few decades following the introduction of the first microprocessors, world's most complex devices ever conceived, our technological reality is saturated with microprocessor-powered devices. More importantly, microprocessors delivered the promise of the *personal computer* – the promise to extend and enrich one's intellectual and social abilities by means of an affordable, general-purpose computer for personal use.

References

1. P. Ceruzzi, *A History of Modern Computing*, MIT Press (1998).

2. Z. Stachniak, The MIL MF7114 Microprocessor. *IEEE Annals of the History of Computing*, October-December 2010 (vol. 32 no. 4) pp. 48-59.

3. Z. Stachniak, Intel SIM8-01: A proto-PC, IEEE Annals of the History of Computing, January-March 2007 (vol. 29 no. 1), pp. 34–48.