

Cell-Phone Circuit Architecture

Electronic circuits are contained in just about every gadget we use in daily living. In fact, electronic sensors, computers, and displays are at the operational heart of most major industries, from agricultural production and transportation to healthcare and entertainment. The ubiquitous cell phone (Fig. 1-1), which has become practically indispensable, is a perfect example of an integrated electronic architecture made up of a large number of interconnected circuits. It includes amplifier circuits, oscillators, frequency up- and down-converters, and circuits with many other types of functions (Fig. 1-2). Factors such as compatibility among the various circuits and proper electrical connections between them are critically important to the overall operation and integrity of the cell phone.

Usually, we approach electronic analysis and design through a hierarchical arrangement where we refer to the overall entity as a *system*, its subsystems as *circuits*, and the individual circuit elements as *devices* or components. Thus, we may regard the cell phone as a system (which is part of a much larger communication system); its audio-frequency amplifier, for example, as a circuit, and the resistors, integrated circuits (ICs), and other constituents of the amplifier as devices. In actuality, an IC is a fairly complex circuit in its own right, but its input/output functionality is such that usually it can be



Figure 1-1: Cell phone.

represented by a relatively simple equivalent circuit, thereby allowing us to treat it like a device. Generally, we refer to

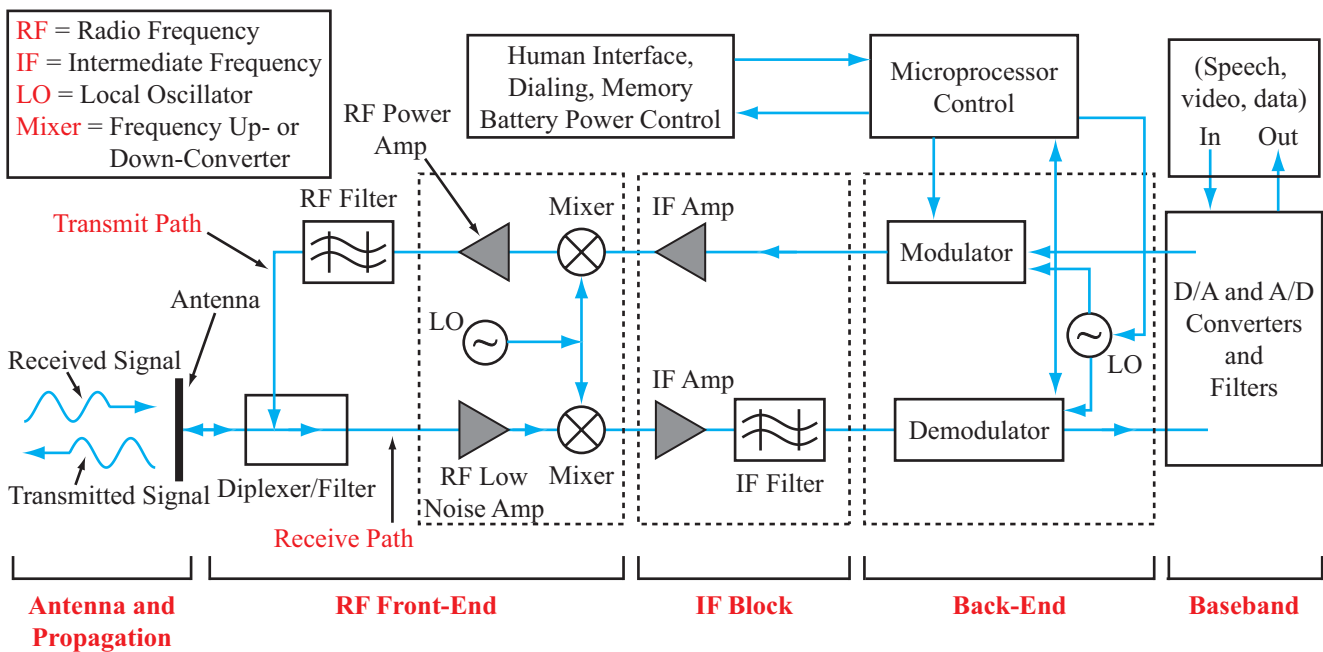


Figure 1-2: Cell-phone block diagram.

devices that do not require an external power source in order to operate as *passive devices*; these include resistors, capacitors, and inductors. In contrast, an *active device* (such as a transistor or an IC) cannot function without a power source.

This book is about *electric circuits*. A student once asked: “What is the difference between an *electric* circuit and an *electronic* circuit? Are they the same or different?” Strictly speaking, both refer to the flow of electric charge carried by electrons, but historically, the term “electric” preceded “electronic,” and over time the two terms have come to signify different things:

An electric circuit is one composed of passive devices, in addition to voltage and current sources, and possibly some types of switches. In contrast, the term “electronic” has become synonymous with transistors and other active devices.

The study of electric circuits usually precedes and sets the stage for the study of electronic circuits, and even though a course on electric circuits usually does not deal with the internal operation of an active device, it does incorporate active devices in the circuit examples considered for analysis, but it does so by representing the active devices in terms of equivalent circuits.

An *electric circuit*, as defined by *Webster’s English Dictionary*, is a “complete or partial path over which current may flow.” The path may be confined to a physical structure (such as a metal wire connecting two components), or it may be an unbounded channel carrying electrons through it. An example of the latter is when a lightning bolt strikes the ground, creating an electric current between a highly charged atmospheric cloud and the earth’s surface.

The study of electric circuits consists of two complementary parts: *analysis* and *synthesis* (Fig. 1-3). Through analysis, we develop an understanding of “how” a given circuit works. If we think of a circuit as having an input—a stimulus—and an output—a response, the tools we use in circuit analysis allow us to relate mathematically the output response to the input stimulus, enabling us to analytically and graphically “observe” the behavior of the output as we vary the relevant parameters of the input. An example might be a specific amplifier circuit, in which case the objective of circuit analysis might be to establish how the output voltage varies as a function of the input voltage over the full operational range of the amplifier parameters. By analyzing the operation of each circuit in a system containing multiple circuits, we can characterize the operation of the overall system.

As a process, synthesis is the reverse of analysis. In engineering, we tend to use the term *design* as a synonym for synthesis. The design process usually starts by defining the operational specifications that a gadget or system should meet,

and then we work backwards (relative to the analysis process) to develop circuits that will satisfy those specifications. In analysis, we are dealing with a single circuit with a specific set of operational characteristics. We may employ different analysis tools and techniques, but the circuit is unique, and so are its operational characteristics. That is not necessarily the case for synthesis; the design process may lead to multiple circuit realizations—each one of which exhibits or satisfies the desired specifications.

Given the complementary natures of analysis and synthesis, it stands to reason that developing proficiency with the tools of circuit analysis is a necessary prerequisite to becoming a successful design engineer. This textbook is intended to provide the student with a solid foundation of the primary set of tools and mathematical techniques commonly used to analyze both *direct current (dc)* and *alternating current (ac)* circuits, as well as circuits driven by pulses and other types of waveforms. A dc circuit is one in which voltage and current sources are constant as a function of time, whereas in ac circuits, sources vary sinusoidally with time. Even though this is not a book on circuit design, design problems occasionally are introduced into the discussion as a way to illustrate how the analysis and synthesis processes complement each other.

Review Question 1-1: What are the differences between a device, a circuit, and a system?

Review Question 1-2: What is the difference between analysis and synthesis?

1-1 Historical Timeline

We live today in the age of electronics. No field of science or technology has had as profound an influence in shaping the

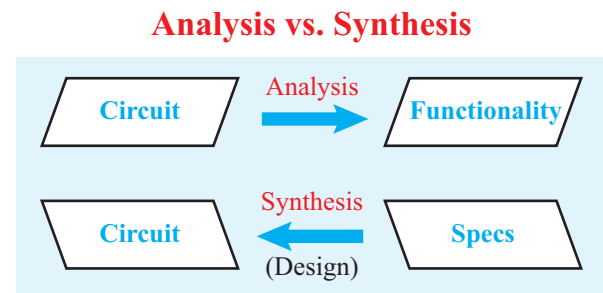


Figure 1-3: The functionality of a circuit is discerned by applying the tools of circuit analysis. The reverse process, namely the realization of a circuit whose functionality meets a set of specifications, is called circuit synthesis or design.

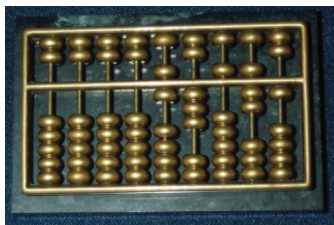
operational infrastructure of modern society as has the field of electronics. Our computers and communication systems are at the nexus of every major industry, from food production and transportation to health care and entertainment. Even though no single event marks the beginning of a discipline, electrical engineering became a recognized profession sometime in the late 1800s (see chronology). *Alexander Graham Bell* invented the telephone (1876); *Thomas Edison* perfected his incandescent light bulb (1880) and built an electrical distribution system in a small area in New York City; *Heinrich Hertz* generated radio waves (1887); and *Guglielmo Marconi* demonstrated radio telegraphy (1901). The next 50 years witnessed numerous developments, including radio communication, TV broadcasting, and radar for civilian and military applications—all supported by electronic circuitry that relied entirely on vacuum tubes. The invention of the *transistor* in 1947 and the development of the *integrated circuit* (IC) shortly thereafter (1958) transformed the field of electronics by setting it on an exponentially changing course towards “smaller, faster, and cheaper.”

Computer engineering is a relatively young discipline. The first *all-electronic computer*, the ENIAC, was built and demonstrated in 1945, but computers did not become available for business applications until the late 1960s and for personal use until the introduction of Apple I in 1976. Over the past 20 years, not only have computer and communication technologies expanded at a truly impressive rate (see Technology Brief 2), but more importantly, it is the seamless integration of the two technologies that has made so many business and personal applications possible.

Generating a comprehensive chronology of the events and discoveries that have led to today’s technologies is beyond the scope of this book, but ignoring the subject altogether would be a disservice to both the reader and the subject of electric circuits. The abbreviated chronology presented on the next few pages represents our compromise solution.

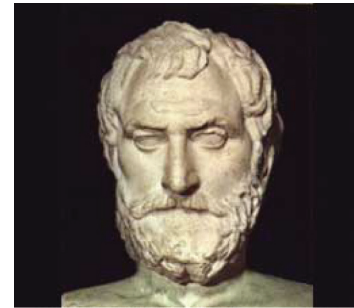
Chronology: Major Discoveries, Inventions, and Developments in Electrical and Computer Engineering

ca. 1100 BC **Abacus** is the earliest known calculating device.



ca. 900 BC According to legend, a shepherd in northern Greece, **Magnus**, experiences a pull on the iron nails in his sandals by the black rock he was standing on. The rock later became known as **magnetite** [a form of iron with permanent magnetism].

ca. 600 BC Greek philosopher **Thales** describes how amber, after being rubbed with cat fur, can pick up feathers [static electricity].



1600 **William Gilbert** (English) coins the term **electric** after the Greek word for amber (*elektron*) and observes that a compass needle points north to south because the Earth acts as a bar magnet.

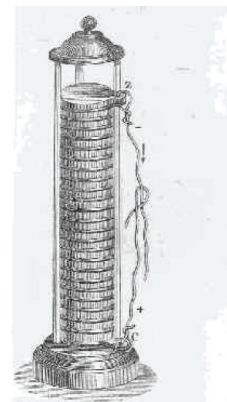
1614 **John Napier** (Scottish) develops the **logarithm** system.

1642 **Blaise Pascal** (French) builds the first **adding machine** using multiple dials.

1733 **Charles François du Fay** (French) discovers that **electric charges** are of two forms and that like charges repel and unlike charges attract.

1745 **Pieter van Musschenbroek** (Dutch) invents the Leyden jar, the first electrical **capacitor**.

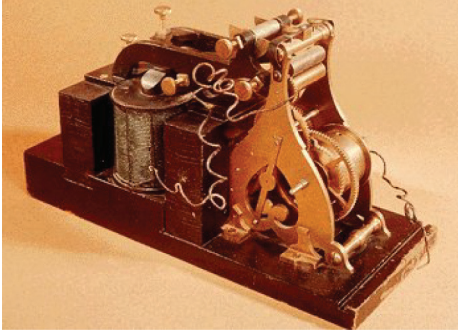
1800 **Alessandro Volta** (Italian) develops the first electric battery.



1827 **Georg Simon Ohm** (German) formulates **Ohm’s law** relating electric potential to current and resistance.

1827 **Joseph Henry** (American) introduces the concept of **inductance** and builds one of the earliest electric motors. He also assisted Samuel Morse in the development of the **telegraph**.

1837 **Samuel Morse** (American) patents the **electromagnetic telegraph** using a code of dots and dashes to represent letters and numbers.

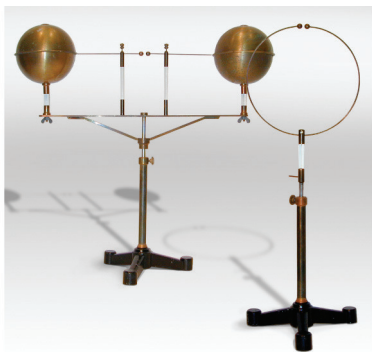


1876 **Alexander Graham Bell** (Scottish-American) invents the **telephone**: the rotary dial becomes available in 1890, and by 1900, telephone systems are installed in many communities.



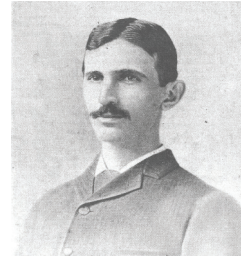
1879 **Thomas Edison** (American) demonstrates the operation of the **incandescent light bulb**, and in 1880, his power distribution system provided dc power to 59 customers in New York City.

1887 **Heinrich Hertz** (German) builds a system that can generate **electromagnetic waves** (at radio frequencies) and detect them.



Courtesy of John Jenkins (sparkmuseum.com)

1888 **Nikola Tesla** (Croatian-American) invents the **ac motor**.



1893 **Valdemar Poulsen** (Danish) invents the first **magnetic sound recorder** using steel wire as recording medium.



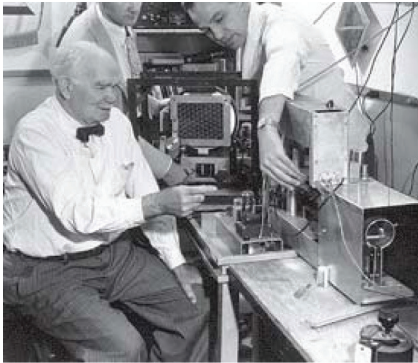
1895 **Wilhelm Röntgen** (German) discovers **X-rays**. One of his first X-ray images was of the bones in his wife's hands. [1901 Nobel prize in physics.]



1896 **Guglielmo Marconi** (Italian) files his first of many patents on **wireless transmission** by radio. In 1901, he demonstrates **radio telegraphy** across the Atlantic Ocean. [1909 Nobel prize in physics, shared with Karl Braun (German).]



- 1897** **Karl Braun** (German) invents the **cathode ray tube (CRT)**. [1909 Nobel prize, shared with Marconi.]
- 1897** **Joseph John Thomson** (English) discovers the **electron** and measures its charge-to-mass ratio. [1906 Nobel prize in physics.]
- 1902** **Reginald Fessenden** (American) invents **amplitude modulation** for telephone transmission. In 1906, he introduces **AM radio broadcasting** of speech and music on Christmas Eve.
- 1904** **John Fleming** (British) patents the **diode vacuum tube**.
- 1907** **Lee De Forest** (American) develops the **triode tube** amplifier for wireless telegraphy, setting the stage for long-distance phone service, radio, and television.



- 1917** **Edwin Howard Armstrong** (American) invents the **superheterodyne radio receiver**, dramatically improving signal reception. In 1933, he develops **frequency modulation (FM)**, providing superior sound quality of radio transmissions over AM radio.
- 1920** Birth of **commercial radio broadcasting**; **Westinghouse Corporation** establishes radio station KDKA in Pittsburgh, Pennsylvania.



- 1923** **Vladimir Zworykin** (Russian-American) invents **television**. In 1926, **John Baird** (Scottish) transmits TV images over telephone wires from London to Glasgow. Regular **TV broadcasting** began in Germany (1935), England (1936), and the United States (1939).



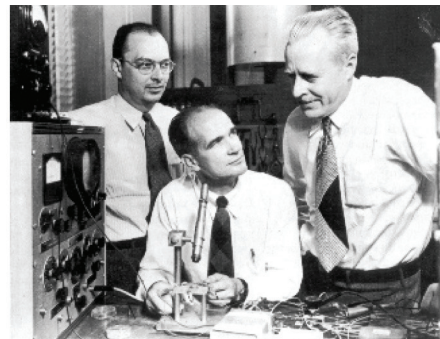
- 1926** **Transatlantic telephone service** established between London and New York.
- 1930** **Vannevar Bush** (American) develops the differential analyzer, an **analog computer** for solving differential equations.



- 1935** **Robert Watson Watt** (Scottish) invents **radar**.
- 1945** **John Mauchly** and **J. Presper Eckert** (both American) develop the ENIAC, the first **all-electronic computer**.



- 1947** **William Schockley**, **Walter Brattain**, and **John Bardeen** (all Americans) invent the junction **transistor** at Bell Labs. [1956 Nobel prize in physics.]



- 1948 **Claude Shannon** (American) publishes his *Mathematical Theory of Communication*, which formed the foundation of information theory, coding, cryptography, and other related fields.
- 1950 **Yoshiro Nakama** (Japanese) patents the **floppy disk** as a magnetic medium for storing data.
- 1954 **Texas Instruments** introduces the first AM **transistor radio**.

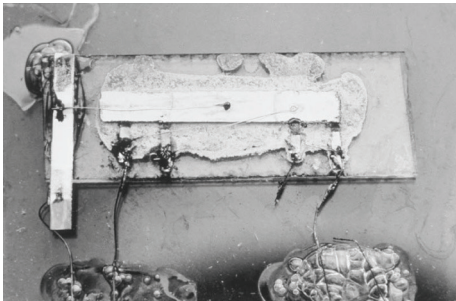


Courtesy of Dr. Steve Reyer

- 1955 The **pager** is introduced as a radio communication product in hospitals and factories.
- 1955 **Navender Kapany** (Indian-American) demonstrates **optical fiber** as a low-loss, light-transmission medium.
- 1956 **John Backus** (American) develops **FORTRAN**, the first major programming language.

```
C  FORTRAN PROGRAM FOR
PRINTING A TABLE OF CUBES
DO 5 I = 1, 64
ICUBE = I * I * I
PRINT 2, I, ICUBE
2  FORMAT (1H, I3, I7)
5  CONTINUE
STOP
```

- 1958 **Charles Townes** and **Arthur Schawlow** (both Americans) develop the conceptual framework for the **laser**. [Townes shared 1964 Nobel prize in physics with Aleksandr Prokhorov and Nicolay Bazov (both Soviets).] In 1960 **Theodore Maiman** (American) builds the first working model of a laser.
- 1958 **Bell Labs** develops the **modem**.
- 1958 **Jack Kilby** (American) builds the first **integrated circuit (IC)** on germanium, and independently, **Robert Noyce** (American) builds the first IC on silicon.



- 1959 **Ian Donald** (Scottish) develops an **ultrasound** diagnostic system.
- 1960 **Echo**, the first passive communication satellite is launched and successfully reflects radio signals back to Earth. In 1962, the first **communication satellite**, Telstar, is placed in geosynchronous orbit.



- 1960 **Digital Equipment Corporation** introduces the first **minicomputer**, the PDP-1, which was followed with the PDP-8 in 1965.

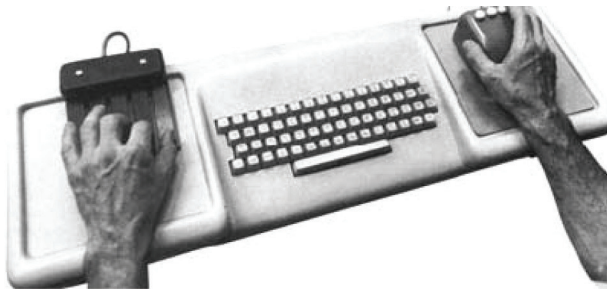


- 1962 **Steven Hofstein** and **Frederic Heiman** (both American) invent the **MOSFET**, which became the workhorse of computer microprocessors.
- 1964 **IBM's 360 mainframe** becomes the standard computer for major businesses.
- 1965 **John Kemeny** and **Thomas Kurtz** (both American) develop the **BASIC** computer language.

```
PRINT
FOR Counter = 1 TO Items
PRINT USING "##.", Counter;
LOCATE , ItemColumn
PRINT Item$(Counter);
LOCATE , PriceColumn
PRINT Price$(Counter)
NEXT Counter
```

1965 **Konrad Zuse** (German) develops the first [programmable digital computer](#) using binary arithmetic and electric relays.

1968 **Douglas Engelbart** (American) demonstrates a [word-processor](#) system, the mouse pointing device, and the use of a [Windows-like](#) operating system.



1969 [ARPANET](#) is established by the U.S. Department of Defense, which is to evolve later into the Internet.

1970 **James Russell** (American) patents the [CD-ROM](#), as the first system capable of digital-to-optical recording and playback.

1971 **Texas Instruments** introduces the [pocket calculator](#).



Courtesy of Texas Instruments

1971 **Intel** introduces the 4004 four-bit [microprocessor](#), which is capable of executing 60,000 operations per second.

1972 **Godfrey Hounsfield** (British) and **Alan Cormack** (South African–American) develop the [computerized axial tomography scanner \(CAT scan\)](#) as a diagnostic tool. [1979 Nobel Prize in physiology or medicine.]

1976 **IBM** introduces the [laser printer](#).

1976 **Apple Computer** sells [Apple I](#) in kit form, followed by the fully assembled [Apple II](#) in 1977, and the [Macintosh](#) in 1984.

1979 Japan builds the first cellular telephone network:

- 1983 cellular phone networks start in the United States.
- 1990 [electronic beepers](#) become common.
- 1995 [cell phones](#) become widely available.

1980 **Microsoft** introduces the [MS-DOS](#) computer disk operating system. Microsoft Windows is marketed in 1985.

1981 **IBM** introduces the [PC](#).



1984 Worldwide [Internet](#) becomes operational.

1988 First [transatlantic optical fiber cable](#) between the U.S. and Europe is operational.

1989 **Tim Berners-Lee** (British) invents the [World Wide Web](#) by introducing a networking hypertext system.

1996 **Sabeer Bhatia** (Indian-American) and **Jack Smith** (American) launch [Hotmail](#) as the first webmail service.

1997 [Palm Pilot](#) becomes widely available.



1997 The 17,500-mile [fiber-optic cable](#) extending from England to Japan is operational.

2002 Cell phones support video and the Internet.

2007 The power-efficient [White LED](#) invented by **Shuji Nakamura** (Japanese) in the 1990s promises to replace Edison's lightbulb in most lighting applications.

Technology Brief 1: Micro- and Nanotechnology

History and Scale

As humans and our civilizations developed, our ability to control the environment around us improved dramatically. The use and construction of tools was essential to this increased control. A quick glance at the scale (or size) of manmade and natural is very illustrative (Fig. TF1-1). Early tools (such as flint, stone, and metal hunting gear) were on the order of tens of centimeters. Over time, we began to build ever-smaller and ever-larger tools. The pyramids of Giza (ca., 2600 BCE) are 100-m tall; the largest modern construction crane is the K10,000 Kroll Giant Crane at 100-m long and 82-m tall; and the current (2007) tallest man-made structure is the KVLV-TV antenna mast in Blanchard, North Dakota at 0.63 km! Miniaturization also proceeded apace; for example, the first hydraulic valves may have been Sinhalese valve pits of Sri Lanka (ca., 400 BCE), which were a few meters in length; the first toilet valve (ca., 1596) was tens of centimeters in size; and by comparison, the largest dimension in a modern microfluidic valve used in biomedical analysis chips is less than 100 μm !

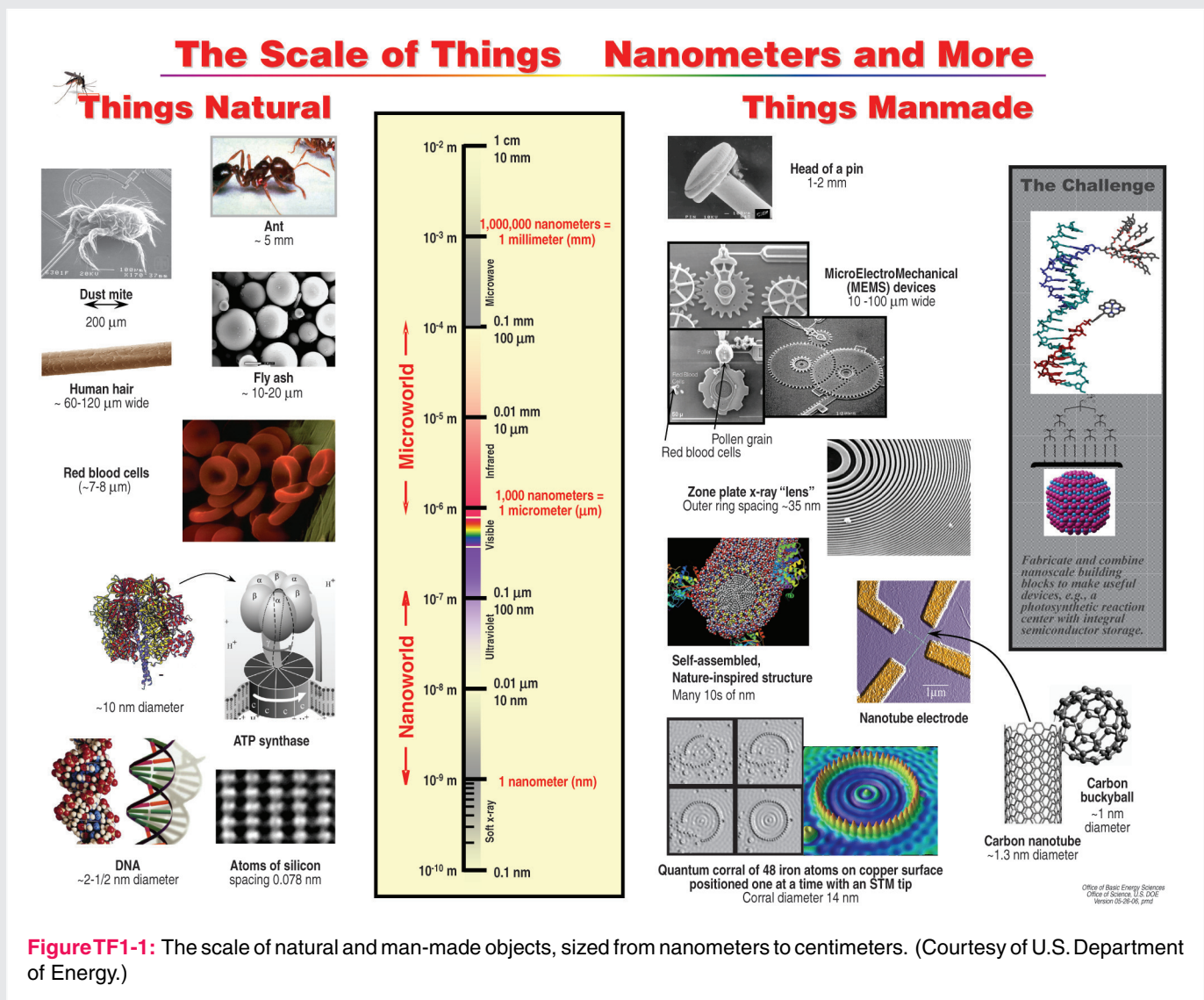


Figure TF1-1: The scale of natural and man-made objects, sized from nanometers to centimeters. (Courtesy of U.S. Department of Energy.)

In electronic devices, miniaturization has been a key enabler in almost all of the technologies that shape the world around us. Consider computation and radio-frequency communications, two foundations of 21st-century civilization. The first true automated computer was arguably the first Babbage Difference Engine, proposed by Charles Babbage to the Royal Astronomical Society (1822). The complete engine would have had 25,000 moving parts and measured approximately $2.4 \text{ m} \times 2.3 \text{ m} \times 1 \text{ m}$. Only a segment with 2000 parts was completed and today is considered the first modern calculator. The first general-purpose electronic computer was the Electronic Numerical Integrator and Computer (ENIAC), which was constructed at the University of Pennsylvania between 1943 and 1946. The ENIAC was 10-ft tall, occupied 1,000 square feet, weighed 30 tons, used $\sim 100,000$ components and required 150 kilowatts of power! What could it do? It could perform simple mathematical operations on 10-digit numbers at approximately 2,000 cycles per second (addition took 1 cycle, multiplication 14 cycles, and division and square roots 143 cycles). With the invention of the semiconductor transistor in 1947 and the development of the *integrated circuit* in 1959 (see *Technology Brief 7* on IC Fabrication Process), it became possible to build thousands (now trillions) of electronic components onto a single substrate or *chip*. The 4004 microprocessor chip (ca., 1971) had 2250 transistors and could execute 60,000 instructions per second; each transistor had a “gate” on the order of $10 \text{ } \mu\text{m}$ (10^{-5} m). In comparison, the 2006 Intel Core has 151 million transistors with each transistor gate measuring 65 nm ($6.5 \times 10^{-8} \text{ m}$), and it can perform 27 billion instructions per second when running on a 2.93 GHz clock!

Similar miniaturization trends are obvious in the technology used to manipulate the electromagnetic spectrum. The ability of a circuit component to interact with electromagnetic waves depends on how its size compares with the wavelength (λ) of the signal it is trying to manipulate. For example, to efficiently transmit or receive signals, a wire antenna must be comparable to λ in length. Some of the first electromagnetic waves used for communication were in the 1-MHz range (corresponding to $\lambda = 300 \text{ m}$) which today is allocated primarily to AM radio broadcasting. [The frequency f (in Hz) is related to the wavelength λ (in meters) by $\lambda f = c$, where $c = 3 \times 10^8 \text{ m/s}$ is the velocity of light in vacuum.] With the advent of portable radio and television, the usable spectrum was extended into the megahertz range 10^2 to 10^3 MHz or ($\lambda = 3 \text{ m}$ to 30 cm). Modern cell phones operate in the low gigahertz (GHz) range ($1 \text{ GHz} = 10^9 \text{ Hz}$). Each of these shifts has necessitated technological revolutions as components and devices continue to shrink. The future of electronics looks bright (and tiny) as the processing and communication of signals approaches the terahertz (THz) range (10^{12} Hz)!

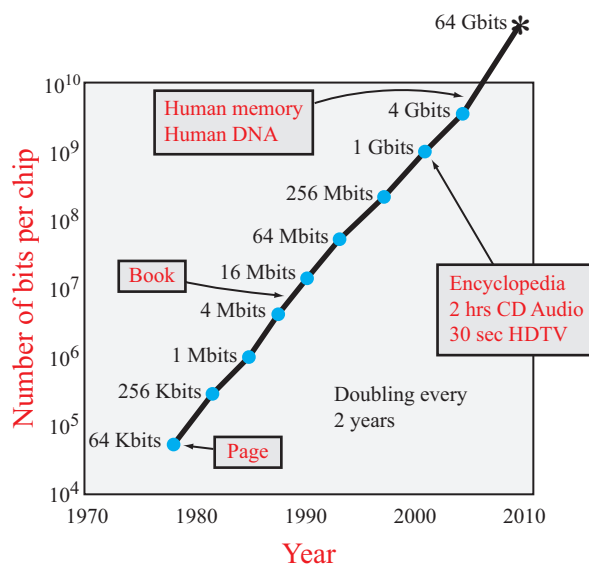


Figure TF1-2: Chip capacity has increased at a logarithmic rate for the past 30 years. (Courtesy of Jan Rabaey.)

Scaling Trends and Nanotechnology

It is an observable fact that each generation of tools enables the construction of a new, smaller, more powerful generation of tools. This is true not just of mechanical devices, but electronic ones as well. Today’s high-power processors could not have been designed, much less tested, without the use of previous processors that were employed to draw and simulate the next generation. Two observations can be made in this regard. First, we now have the technology to build tools to manipulate the environment at atomic resolution. At least one generation of micro-scale techniques (ranging from microelectromechanical systems—or MEMS—to micro-chemical methods) has been developed which, useful onto themselves, are also enabling the construction of newer, nano-scale devices. These newer devices range from 5 nm ($1 \text{ nm} = 10^{-9} \text{ m}$) transistors to femtoliter (10^{-15}) microfluidic devices that can manipulate single protein molecules. At these scales, the lines between mechanics, electronics and chemistry begin to blur! It is to these ever-increasing interdisciplinary innovations that the term *nanotechnology* rightfully belongs.

Second, the rate at which these innovations are occurring seems to be increasing exponentially! Consider *Fig.TBI-2* and *TBI-3* and note that the y-axis is logarithmic and the plots are very close to straight lines. This phenomenon, which was observed to hold true for the number of transistors that can be fabricated into a single processor, was noted by Gordon Moore in 1965 and was quickly coined “Moore’s Law” (see *Technology Brief 2: Moore’s Law*).

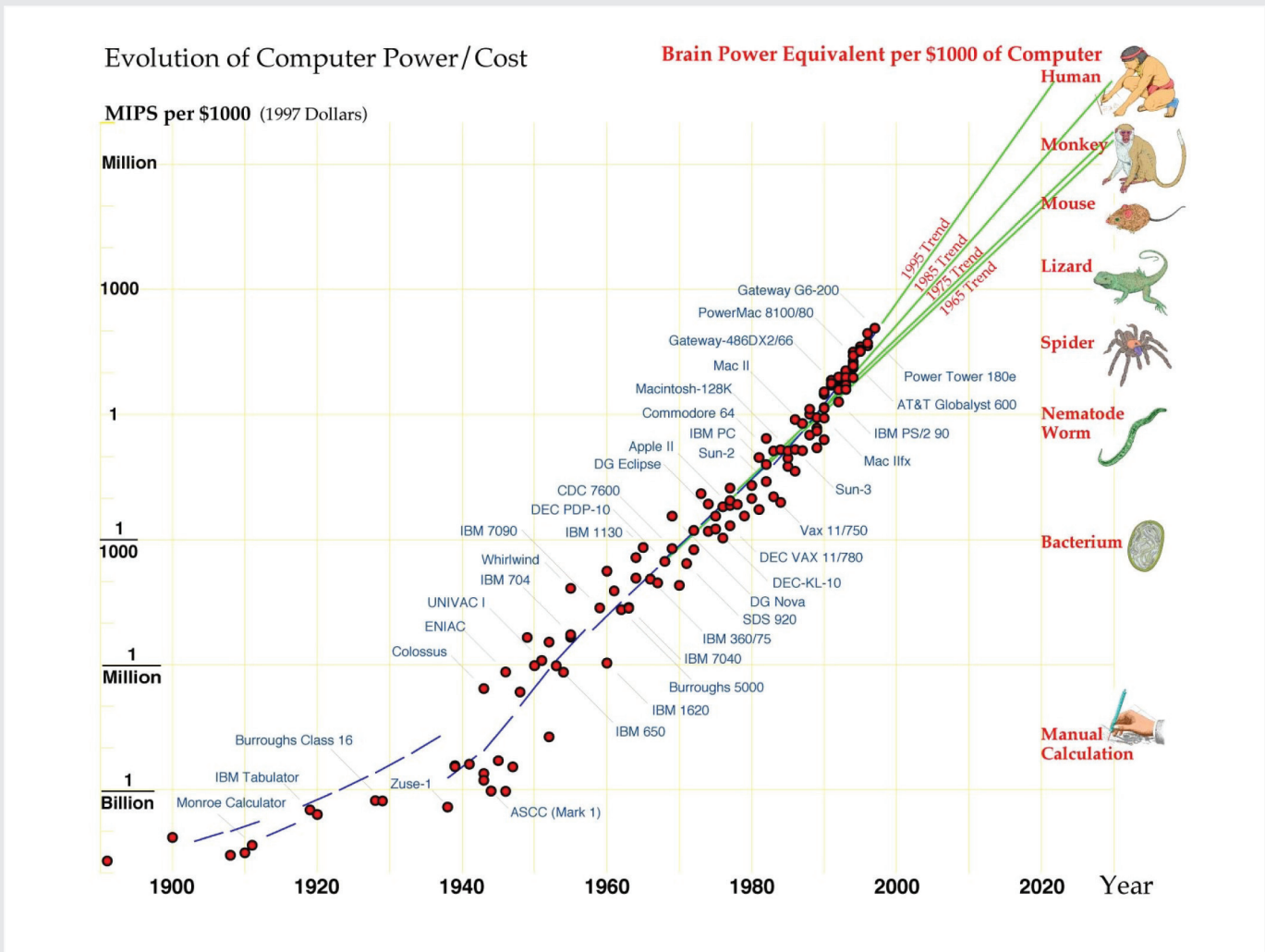


Figure TF1-3: Time plot of computer processing power in MIPS per \$1000 (From “When will computer hardware match the human brain?” by Hans Moravec, *Journal of Transhumanism*, Vol. 1, 1998.)

Technology Brief 2: Moore's Law and Scaling

In 1965, Gordon Moore, co-founder of Intel, predicted that the number of transistors in the minimum-cost processor would double every two years (initially, he had guessed they would double every year). Amazingly, this prediction has proven true of semiconductor processors for 40 years, as demonstrated by Fig. TF2-1.

In order to understand *Moore's Law*, we have to understand the basics about how transistors work. As we will see later in Section 3-7, the basic switching element in semiconductor microprocessors is the *transistor*: All of the complex components in the microprocessor (including logic gates, arithmetic logic units, and counters) are constructed from combinations of transistors. Within a processor, transistors have different dimensions depending on the component's function; larger transistors can handle more current, so the sub-circuit in the processor that distributes power may be built from larger transistors than, say, the sub-circuit that adds two bits together. In general, the smaller the transistor, the less power it consumes and the faster it can switch between binary states (0 and 1). Hence, an important goal of a circuit designer is to use the smallest transistors possible in a given circuit. We can quantify transistor size according to the smallest drawn dimension of the transistor, sometimes called the *feature size*. In the Intel 4004, for example, the feature size was approximately $10\ \mu\text{m}$, which means that it was not possible to make transistors reliably with less than $10\text{-}\mu\text{m}$ features drawn in the CAD program. In modern processors, the feature size is $0.065\ \mu\text{m}$ or $65\ \text{nm}$. (Remember that $1\ \text{nm} = 10^{-9}\ \text{m}$.)

The questions then arise: How small can we go? What is the fundamental limit to shrinking down the size of a transistor? As we ponder this, we immediately observe that we likely cannot make a transistor smaller than the diameter of one silicon or metal atom (i.e., ~ 0.2 to $0.8\ \text{nm}$). But is there a limit prior to this? Well, as we shrink transistors such that they are made of just one or a few atomic layers (~ 1 to $5\ \text{nm}$), we run into issues related to the

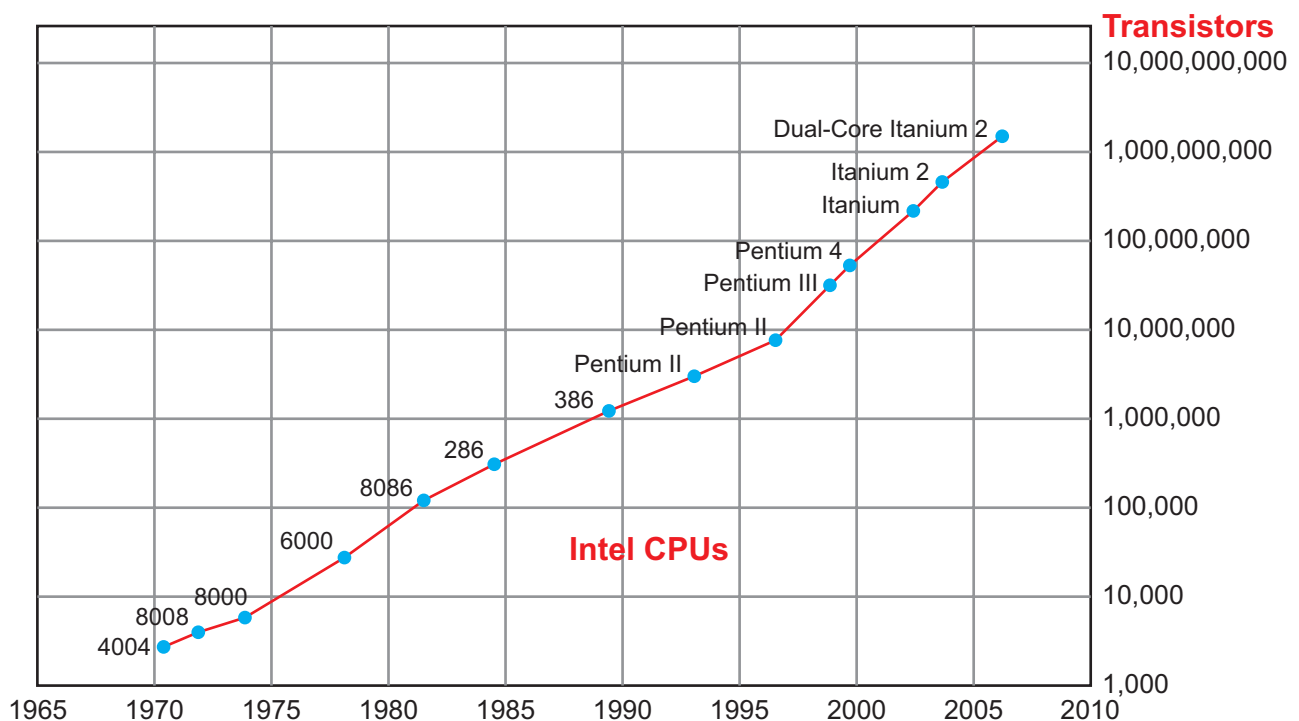


Figure TF2-1: Moore's Law predicts that the number of transistors per processor doubles every two years.

stochastic nature of quantum physics. At these scales, the random motion of electrons between both physical space and energy levels becomes significant with respect to the size of the transistor, and we start to get spurious or random signals in the circuit. There are even more subtle problems related to the statistics of yield. If a certain piece of a transistor contained only 10 atoms, a deviation of just one atom in the device (to a 9-atom or an 11-atom transistor) represents a huge change in the device properties! (Can you imagine your local car dealer telling you your sedan will vary in length by ± 10 percent when it comes from the factory!?) This would make it increasingly difficult to economically fabricate chips with hundreds of millions of transistors. Additionally, there is an interesting issue of heat generation: Like any dissipative device, each transistor gives off a small amount of heat. But when you add up the heat produced by 100 million transistors, you get a very large number! Figure TF2-1 compares the power density (due to heat) produced by different processors with the heat produced by rocket engines and nuclear reactors.

None of these issues are insurmountable. Challenges simply spur driven people to come up with innovative solutions. Many of these problems will be solved, and in the process, provide engineers (like you) with jobs and opportunities. But, more importantly, the minimum feature size of a processor is not the end goal of innovation: It is the means to it. Innovation seeks simply to make *increasingly powerful* processors, not smaller feature sizes. In recent years, processor companies have lessened their attempts at smaller, faster processors and started lumping more of them together to distribute the work among them. This is the idea behind the dual and quad processor cores that power the computers of the last few years. By sharing the workload among various processors (called *distributed computing*) we increase processor performance while using less energy, generating less heat, and without needing to run at warp speed. So it seems, as we approach ever-smaller features, we simply will transition into new physical technologies and also new computational techniques. As Gordon Moore himself said, "It will not be like we hit a brick wall and stop."

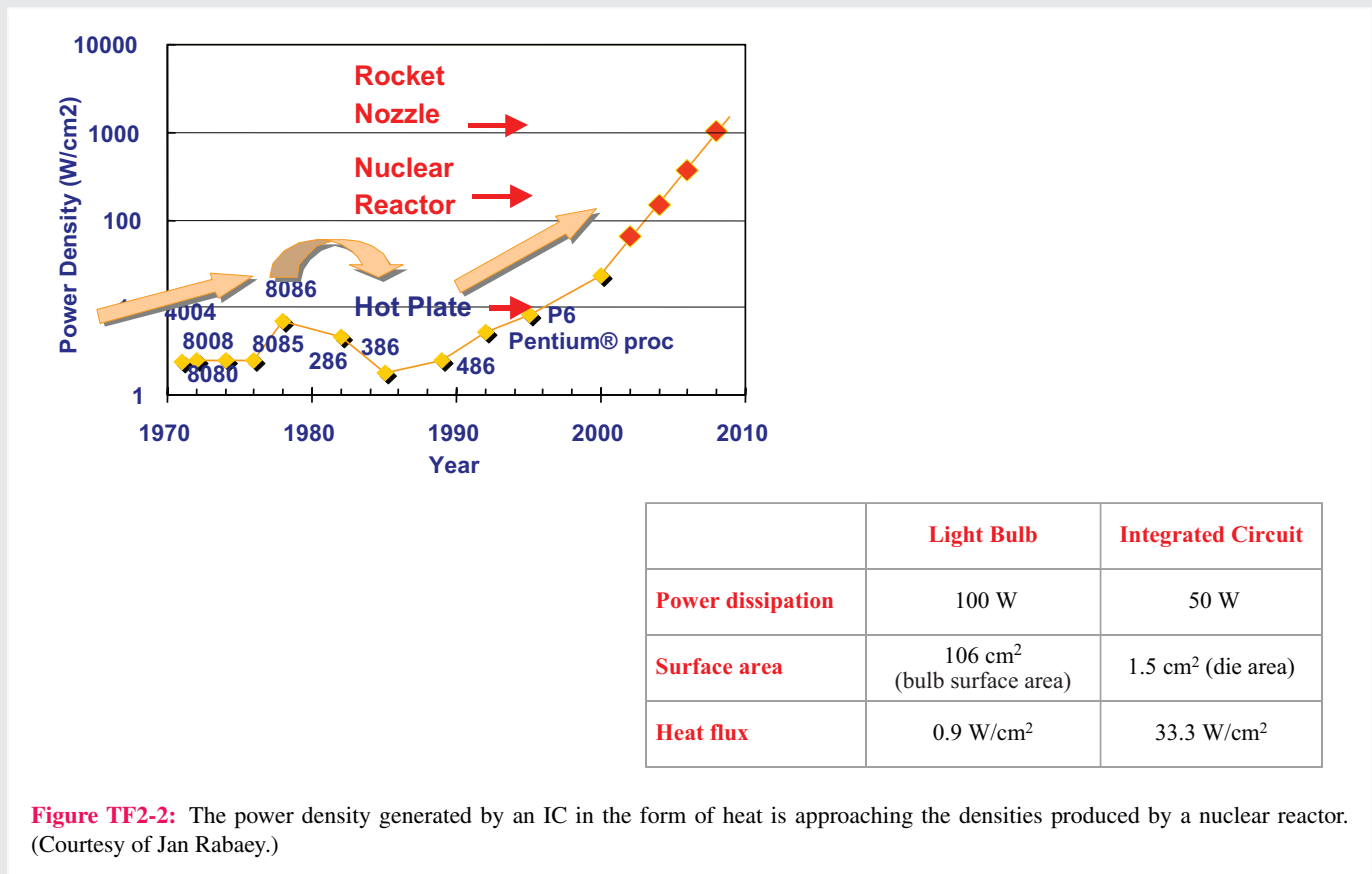


Figure TF2-2: The power density generated by an IC in the form of heat is approaching the densities produced by a nuclear reactor. (Courtesy of Jan Rabaey.)