Chap. 5 Engineering Bits and Bytes

5.1 Introduction

- Scientists: discover the physical laws of nature and invent new products and ideas.
  Engineers: apply these physical laws in designing and fabricating products that meet the needs of society.

  *Transistors invented by physicists in 1947; Over the last 60+ years, physicists, chemists, and engineers have miniaturized its size down to about 22 nm in 2011.

- Bits and bytes: What are they? Why are they important? How do they work?

5.2 Electronics on a Chip Size

5.2.1 Definitions: Big Picture

- Relate the understanding of electronics to biological, medical, and computer applications.

1) Semiconductors: A class of materials of which chips are made

2) Wafers and chips: A wafer is a flat slice of a single crystal semiconductor material, called a "substrate" onto which ICs are fabricated.

3) Packaging: Encapsulation of chips to protect them from the environment

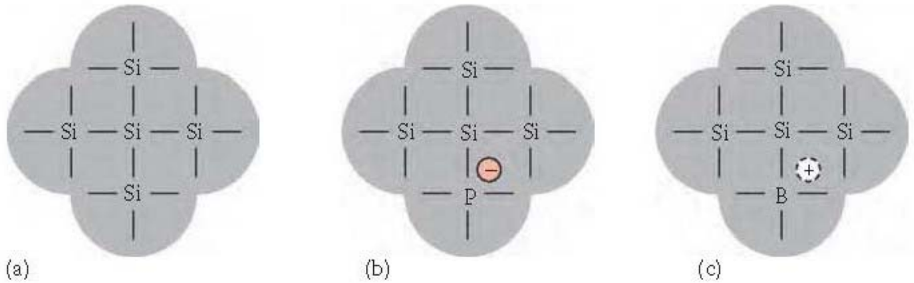


Figure 5.1 Illustration of different types of silicon (Si) semiconductor bonding: (a) intrinsic semiconductor, (b) n-type doping of semiconductor, and (c) p-type doping of semiconductor. Lines indicate covalent bonding between silicon atoms (gray).

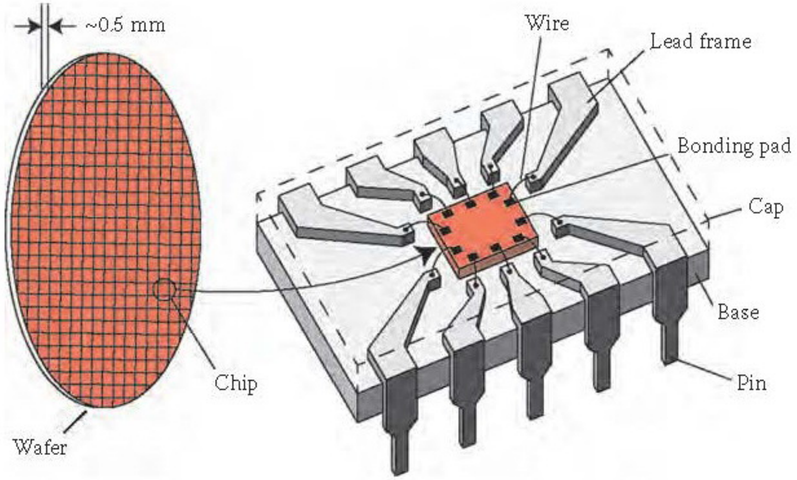


Figure 5.2 Illustration of wafer, integrated circuit, chips, connectors, pins, base (plastic), and cap (dc

5.2.2 Resistors

1) Resistor design

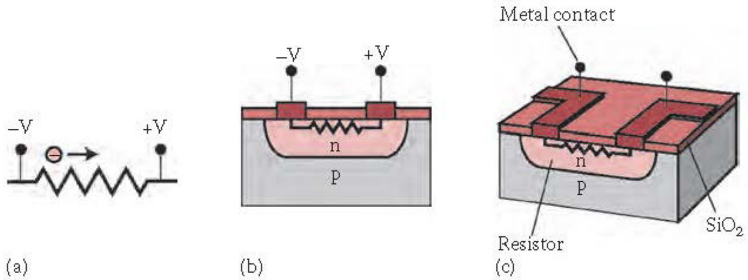


Figure 5.3 Illustration of a (a) symbol for a resistor. (b) Cross section of a resistor (n-type) on a chip between metal contacts with a voltage drop (–V) and (+V). (c) 3-D view of an n-type resistor under a SiO$_2$ insulating layer on a chip. [Adapted from Miller, R. and Miller, R.E., *Electronics the Easy Way*, 4th edn., Barron's Educational Series, Inc.

2) Resistor analogy: fluid flow

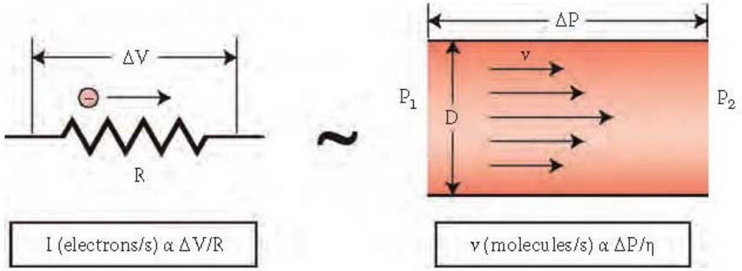


Figure 5.4 Illustration of how electrons flowing through a resistor are similar to fluid molecules flowing through a pipe. Here I (electrical current = electrons per second) is proportional to the applied voltage drop (ΔV) divided by resistance (R). For a fluid, the flow velocity (molecules per second) is proportional to the pressure drop (ΔP) divided by the fluid viscosity (η) for a pipe of diameter (D).

3) Resistor analogy: circulatory system

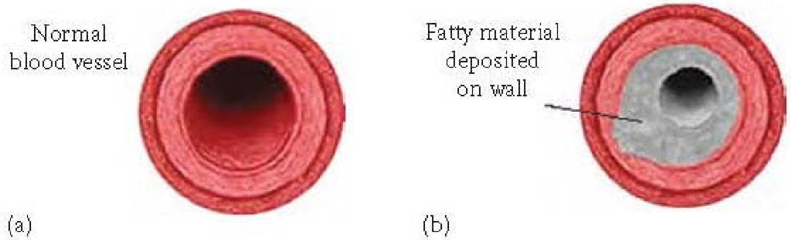


Figure 5.5 Cross-sectional illustrations of (a) normal blood vessel and (b) vessel with fatty deposits.

*The fluid flow rate depends on the resistance in our arteries and viscosity in our blood.

4) Resistor analogy: diffusion – mass flow of particles

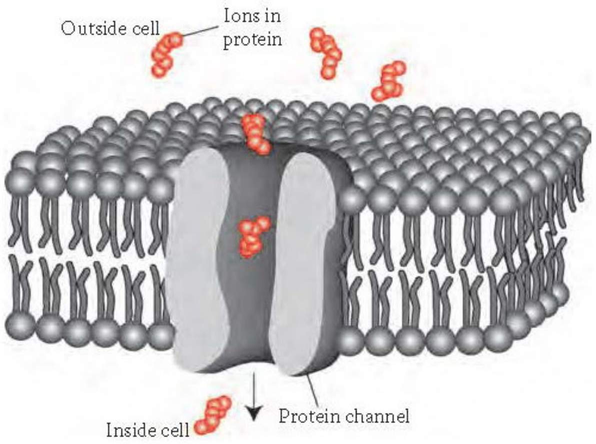


Figure 5.9 Illustration of protein channel in bilayer membrane showing the diffusion of molecules through the channel and entering the cell. The diffusion direction is indicated by the arrow (along the z-axis).

5.2.3 Capacitors

1) Capacitor design

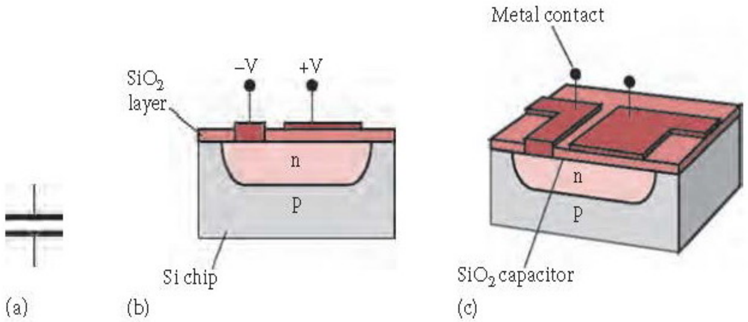


Figure 5.10 Illustration of a (a) symbol for a capacitor. (b) Cross section of a silicon chip showing the SiO$_2$ capacitor as a thin layer that insulates the metal contacts with a voltage drop (–V) and (+V). (c) A 3-D top view is shown of the SiO$_2$ layer on a chip. [Adapted from Miller, R. and Miller, R.E., *Electronics the Easy Way*, 4th edn., Barron's Educational

2) Capacitor analogy: Neuron signaling

- Neuron: a nerve cell that has protruding electrical cables and connections between them.

*Human memory and learning are stored in the neurons that are located in the hippocampus of the cerebral cortex (near the center of our brain).
*Average human brain contains about 100 giga (10^{11}) neurons. Each neuron contains 4 basic parts: nerve cell, axon, dendrite, and synapse.
*The axon is a long cable protruding from the nerve cell. The dendrite is just the cable (similar to the axon) of an adjacent nerve cell.
*The chemicals allow the signal to be transmitted from axon to dendrite.

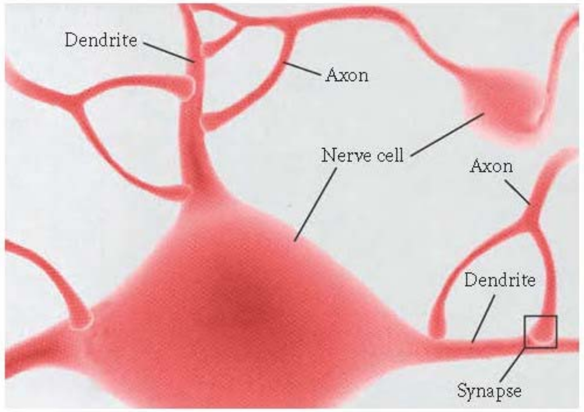


Figure 5.11 Illustration of neuron-to-neuron connections. The neurons are nerve cells with attached cables (axons and dendrites) that are connected to each other at the synapse. Electrical signals are transmitted from one neuron to another, which occurs in memory recall. [Adapted from Fields, D., *Sci. Am.*, 292(2), 75, February 2005.]

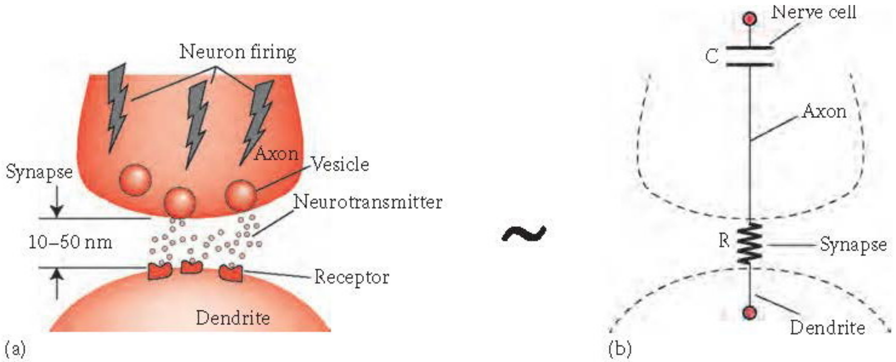


Figure 5.12 (a) Illustration of neuron "firing" and neurotransmitters being released from vesicles in the axon. The neurotransmitters diffuse across the synapse and are absorbed by the receptors on the surface of a dendrite. (b) This process can be modeled using an R–C (resistor–capacitor) circuit that simulates the signaling process. The model is similar to (~) the electrochemical process that occurs between neurons. [Adapted from Fields, D., *Sci. Am.*,

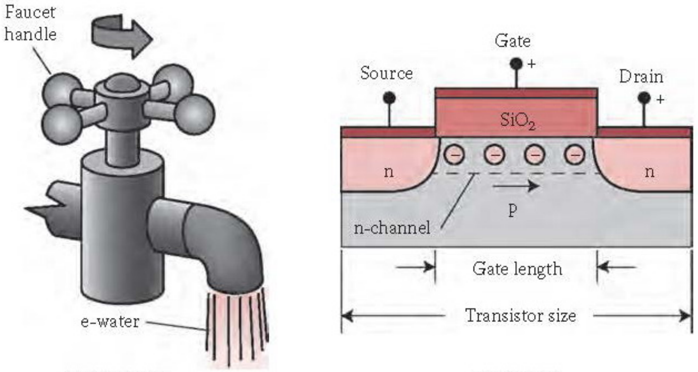
- Synapse : the gap or connection between the axon and dendrite. It enables one nerve to communicate with each other.

  *Our brain has over one peta (1015) connections in it.

  *The axon-dendrite connection at the synapse is a nanoprocess because the gap across the synapse is ~10 to 50 nm.

  *The firing process causes the vesicles in the axon to release neurotransmitters (chemicals like dopamine and serotonin). These neurotransmitters diffuse across the synapse and bind to protein receptors on the dendrites.
- If either “firing” at the nerve cell malfunctions or the diffusion of neurotransmitters across the synapse malfunctions, memory retrieval becomes impaired: This is what happens to people who acquire Alzheimer’s disease.

5.2.4 Transistors



Water faucet

Transistor

Figure 5.13 Illustration of water flow analogy to electron flow in FETs. Turning the handle of the water faucet counterclockwise regulates the water flow from the source, which is analogous to electron flow through an “npn” transistor. The cross section of a FET is also shown in the figure.

1) Back-gated (bottom gate) transistor

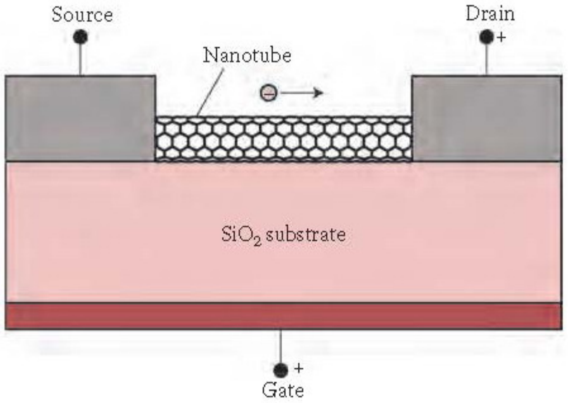


Figure 5.14 Cross-section illustration of a "back-gated" FET switch design incorporating a nanotube. The nanotube takes the place of the n-channel in Figure 5.13, and the SiO_2 layer and gate are turned upside down under the nanotube. Electrons move from source to drain.

2) Neuron transistor

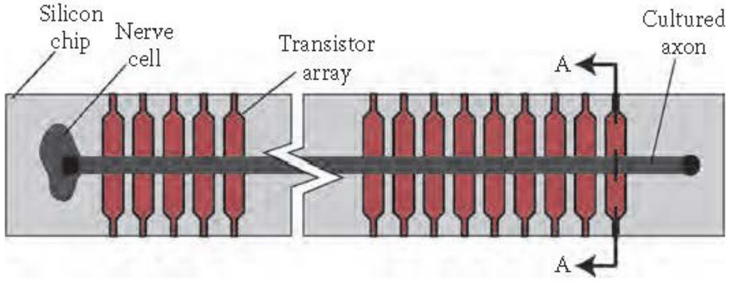


Figure 5.15 Top view illustration of a rodent's nerve cell and cultured axon placed on top of a silicon chip with an array of transistors evenly spaced along the length of the axon. Section A–A is taken through a transistor and axon. A voltage (not shown) is applied across the neuron (nerve cell and axon). [Adapted from Lieber, C. et al., *Science*, 313, 1100, 2006.]

5.2.5 Junction Diodes

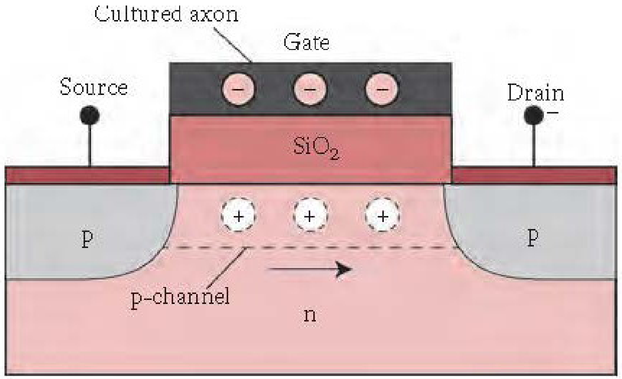


Figure 5.16 Illustration of Section A–A from Figure 5.15 which is rotated 90°, so it can be compared to the FET switch in Figure 5.13. A pnp transistor is used, because the cultured axon becomes that gate, which is negatively charged. A negative bias is placed at the drain, and the charge carriers in the transistor are holes. As the electrons are passed over the SiO$_2$ layer, holes are conducted through the p-channel to the drain.

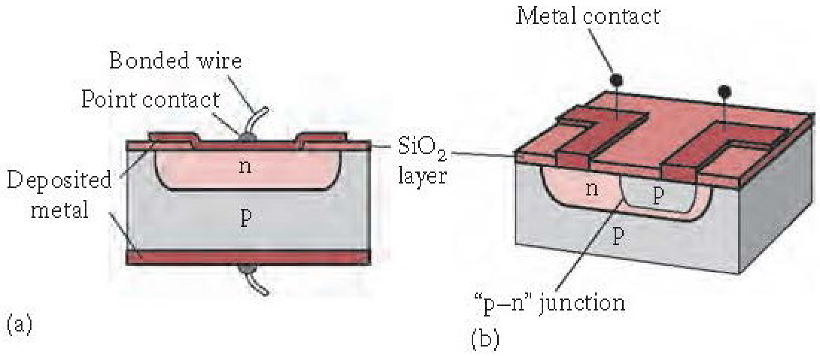


Figure 5.17 Cross-sectional illustration of two junction diodes. (a) Shows a ~1950s vintage macroscopic junction diode and (b) shows a modern nanoscopic junction diode on a chip. [Adapted from Miller, R. and Miller, R.E.,

5.2.6 Integrated Circuits

1) IC design

- In 1958, J. Kilby (Texas Instruments) and R. Noyce (Fairchild Semiconductor) co-invented IC. First, a circuit layout or diagram of various components is created. Second, this diagram is then converted into architecture on a chip, showing the individual components and connections. Finally, the design is fabricated using a photo-lithographic etching process.

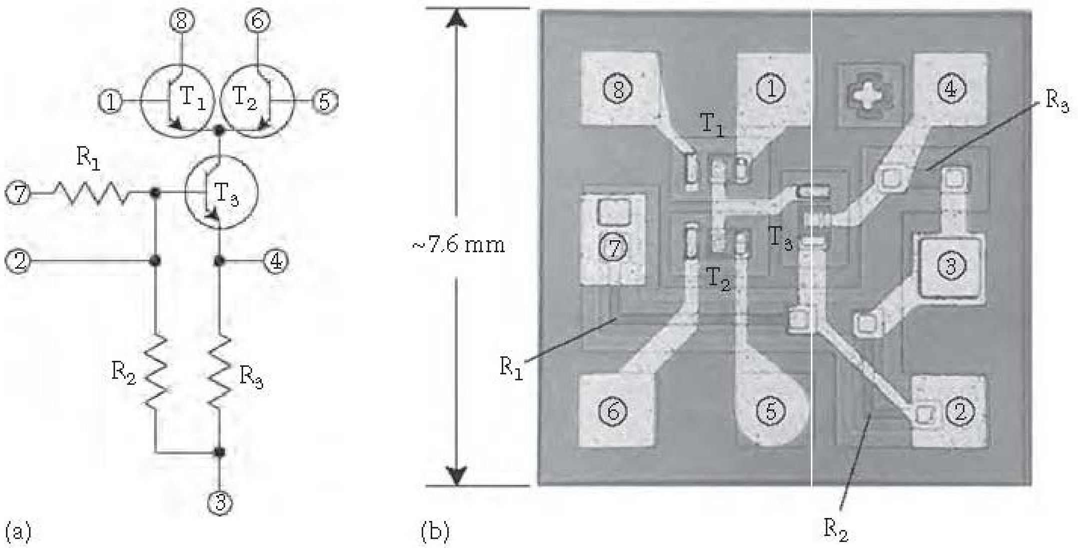


Figure 5.18 Design of an IC having three transistors (T_1, T_2, T_3), three resistors (R_1, R_2, R_3) and contact pads (1–8). (a) The layout diagram is shown on the left, and (b) the top view of its architecture that has been fabricated on a silicon chip is shown on the right. The estimated chip size is ~7.6 mm square. [Courtesy of Hagley Museum and Library, Wilmington,

2) Moore’s law

- Increase of the bit storage capacity and the speed in computers: increase of the transistor density (number of transistors per chip area)

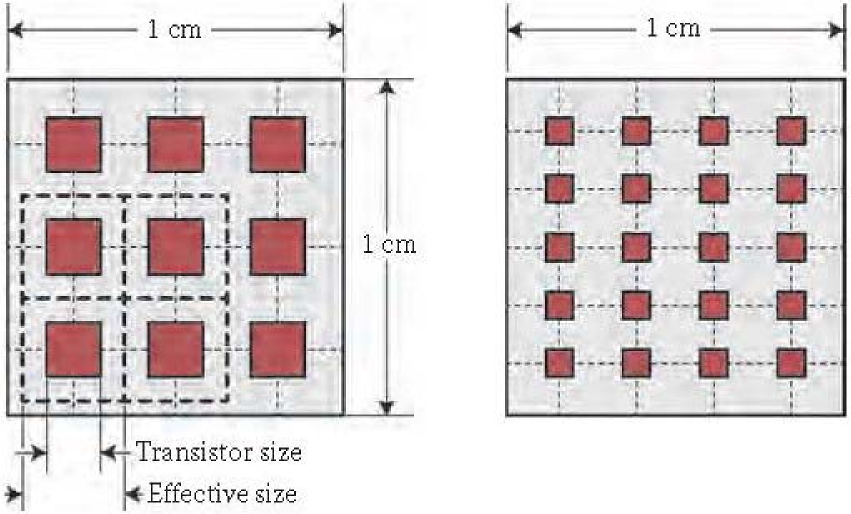


Figure 5.19 Illustration of approximately doubling the number of transistors (red squares) per cm^2 on chip from 9 to 20. (The units of “cm” were traditionally used in Moore’s law.) The effective transistor size is indicated by the bold squares. The effective size takes into account the other chip components that support the transistors, that is, interconnections, capacitors, and resistors on the same real estate.

$N \sim (5 \times 10^{13})\ S^{-2.80}$ with S = transistor size in units of nm.

5.3 Computer Applications

5.3.1 Bits and Bytes

- BIT: Binary digIT (0 or 1)
  *Bits are the language of computers and their sizes come in bytes (8 bit chunks).
  Letter “a” can be represented by the 8 bit code of 01100001.

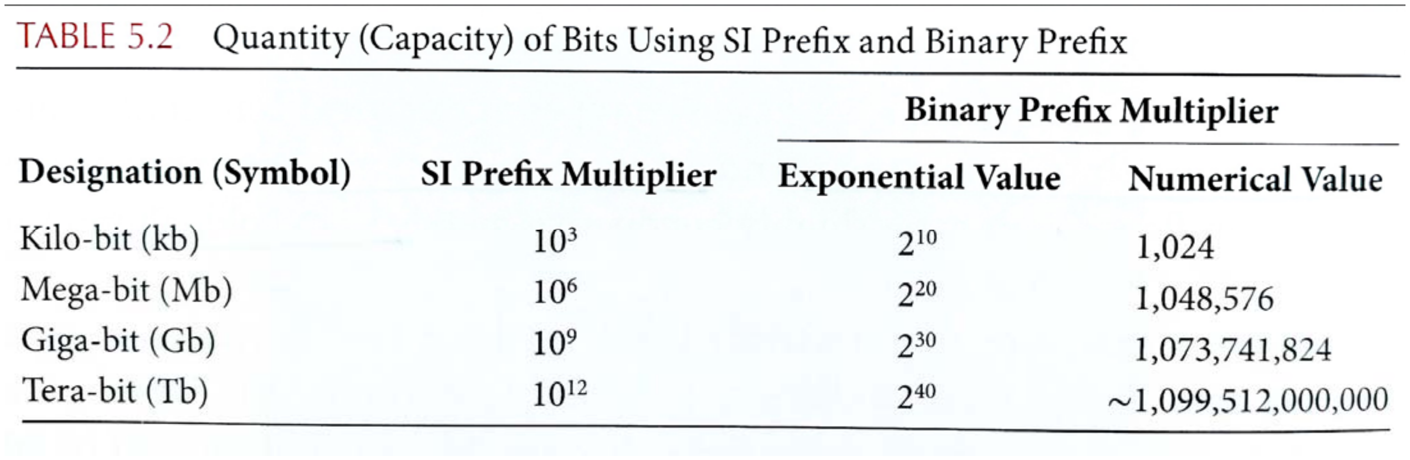


TABLE 5.2 Quantity (Capacity) of Bits Using SI Prefix and Binary Prefix

		Binary Prefix Multiplier	
Designation (Symbol)	**SI Prefix Multiplier**	**Exponential Value**	**Numerical Value**
Kilo-bit (kb)	10^3	2^{10}	1,024
Mega-bit (Mb)	10^6	2^{20}	1,048,576
Giga-bit (Gb)	10^9	2^{30}	1,073,741,824
Tera-bit (Tb)	10^{12}	2^{40}	~1,099,512,000,000

5.3.2 Electrical Storage

- Dynamic RAM (volatile memory) and static RAM (nonvolatile or flash memory)

5.3.3 Magnetic Storage

- Magnetization: magnetic domains and grains,