

A HISTORY OF ELECTRONIC DEVICES

FROM STORED CHARGE AND VACUUM TUBES TO CHIPS, SENSORS, AND SMART SYSTEMS



A CLASSROOM REFERENCE AND VISUAL TIMELINE

This textbook traces the ideas, materials, components, systems, and social choices that turned electricity into modern electronics. It emphasizes how each device solved a control problem - switching, amplification, detection, computation, information storage, and power conversion.

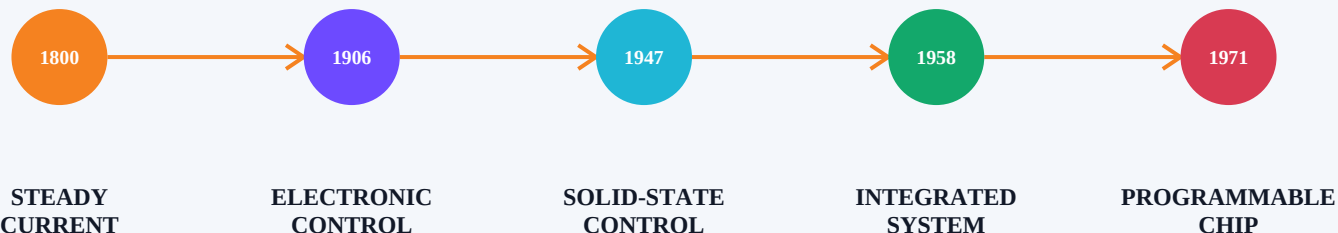
FREE MATH TUTOR EDITION

Definitions • Timelines • Diagrams • Equations • Review Questions • Sources

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HOW TO USE THIS BOOK

READING HISTORY AS A CHAIN OF SOLVED PROBLEMS



THE BIG QUESTION

- How did people learn to control electric charge accurately enough to carry voices, make images, store facts, calculate, sense the environment, and command machines?
- For every invention, identify four things: input, control process, output, and energy source.
- Then ask what earlier technologies were necessary and what limitation the new device overcame.
- History becomes clearer when devices are treated as connected systems rather than isolated objects.

CORE THEMES

- **Control:** small signals govern larger flows of charge or energy.
- **Representation:** physical states stand for sound, pictures, numbers, instructions, or decisions.
- **Integration:** more functions occupy less space with fewer connections.
- **Conversion:** devices translate among chemical, electrical, magnetic, mechanical, optical, thermal, and informational forms.
- **Networks:** standards and infrastructure turn individual devices into social systems.

HISTORICAL CAUTION

- Invention dates can refer to a theory, experiment, patent, prototype, demonstration, commercial product, or mass adoption. These are not the same milestone.
- Many devices have multiple contributors working independently or competitively. Credit should reflect evidence and context rather than a single-name myth.
- Electrical history and electronic history overlap. This book includes earlier electrical foundations but marks the rise of active electronic control.
- Dates are presented as guideposts, not as claims that change happened everywhere at once.

STUDY ROUTINE

1. Read the diagram before the text. Explain the direction of energy and information.
2. Underline the limitation that motivated the next technology.
3. Compare a device with its predecessor using size, power, speed, reliability, cost, and manufacturability.
4. Complete the end-of-book timeline and review questions without looking back.
5. Choose a modern product and trace at least five historical device families inside it.

CONTENTS AND MASTER TIMELINE

A MAP OF THE ELECTRONIC AGE

1	Before Electronics Ancient observations-1800	11	Memory and Storage 1940s-present
2	Electromagnetism and Signals 1820s-1870s	12	Optoelectronics 1960s-present
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MASTER TURNING POINTS

1800 battery • 1830s relay/telegraph • 1876 telephone • 1897 electron and CRT • 1904 diode • 1906 triode • 1920s broadcasting • 1940 radar and electronic computing • 1947 transistor • 1958 integrated circuit • 1959 MOSFET • 1960 laser • 1962 visible LED • 1969 CCD • 1971 microprocessor • 1990s web/mobile/blue LED • 2000s smartphone convergence • today: chiplets, AI accelerators, 3D integration

1. BEFORE ELECTRONICS: ELECTRICITY BECOMES A SCIENCE

ANCIENT OBSERVATIONS TO 1800

THE VOLTAIC PILE: CHEMICAL ENERGY BECOMES STEADY CURRENT



CELL VOLTAGES ADD IN SERIES

$$V(\text{total}) = V_1 + V_2 + \dots + V_n$$

CURRENT NEEDS A CLOSED PATH

$$\text{POWER: } P = VI$$

FIGURE 1. The battery changed electricity from a brief spark into a sustained current that could do work.

Electricity Before the Electron

- Ancient observers knew rubbed amber could attract light objects. The Greek word *elektron* later supplied the name electricity.
- William Gilbert's *De Magnete* (1600) separated magnetic effects from the static attraction produced by rubbing certain materials.
- Early machines accumulated charge, but the effects were brief. They could make sparks; they could not yet power continuous operation.
- The Leyden jar, developed in the 1740s, stored separated charge. It was an early capacitor and made repeatable experiments possible.

The Voltaic Pile, 1800

- Alessandro Volta stacked unlike metals separated by electrolyte-soaked material, producing a continuous source of electric potential.
- A cell converts chemical energy to electrical energy. A battery is one or more cells arranged to provide useful voltage and current.
- Series cells add voltage: $V(\text{total}) = V_1 + V_2 + \dots + V_n$.
- Steady current allowed electrochemistry, electromagnets, telegraphy, motors, and later electronic circuits to develop.

Electrical vs. Electronic

- An electrical device mainly converts or transports electrical energy: heater, lamp, generator, motor, or transformer.
- An electronic device controls charge carriers to switch, amplify, detect, compute, communicate, sense, display, or store information.
- The boundary is not absolute. A modern motor is electrical, while its speed controller is electronic; together they form one system.
- This book includes enabling electrical inventions because electronics grew directly from batteries, magnetism, circuits, and communication networks.

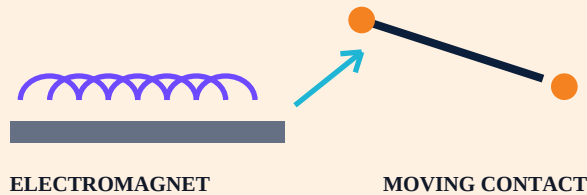
Foundation Quantities

- Charge Q is measured in coulombs. Current $I = Q/t$ is charge flow per unit time, measured in amperes.
- Voltage V is electric potential difference. Resistance R opposes current; Ohm's law is $V = IR$.
- Power is the rate of energy transfer: $P = VI = I^2R = V^2/R$ for a resistive element.
- Capacitance describes stored charge: $Q = CV$. Inductance describes voltage produced by changing current: $V = L(di/dt)$.

2. ELECTROMAGNETISM, THE RELAY, AND DISTANT SIGNALS

1820S-1870S

RELAY: A SMALL CURRENT CONTROLS A SECOND CIRCUIT



SIGNAL -> SWITCH

FIGURE 2. A relay joins communication and control: one circuit magnetically opens or closes another.

A Unified Physical Story

- In 1820 Hans Christian Ørsted showed that current deflects a compass needle: current produces a magnetic field.
- Ampère developed mathematical descriptions of current and magnetism. Faraday's 1831 induction experiments showed that changing magnetic flux can produce voltage.
- James Clerk Maxwell later organized electricity, magnetism, and light into a unified electromagnetic theory.
- The result was both scientific and practical: fields could generate, transmit, detect, and control energy and information.

The Electromagnetic Relay

- A relay uses current in a coil to magnetize an iron core and move a contact. The contact opens or closes a separate circuit.
- The device provides control, isolation, and signal restoration. A weak signal can command a stronger local circuit.
- Relays made long telegraph lines and automatic switching systems possible, and later formed logic in early calculators and computers.
- Their moving parts made them slower and less durable than vacuum tubes and transistors, but the control principle survived.

Telegraph: Encoded Current

- The electric telegraph used timed current pulses to represent symbols. Samuel Morse and Alfred Vail developed a widely adopted system and code.
- In 1844, a public demonstration linked Washington and Baltimore, showing that information could move much faster than people or objects.
- Telegraph networks required batteries, keys, line wires, relays, sounders, insulation, standards, trained operators, and business organization.
- Electronic communication is never only a device; it is a device plus an agreed code plus a network.

Telephone: Current Carries Sound

- Telephone pioneers converted air-pressure variations into changing electrical signals, transmitted them, and converted them back into sound.
- Alexander Graham Bell received a major U.S. telephone patent in 1876, amid work by several inventors including Antonio Meucci and Elisha Gray.
- Unlike telegraph symbols, the telephone carried an analog waveform that continuously followed speech.
- Microphones and receivers established a lasting pattern: physical input -> transducer -> signal -> transducer -> physical output.

SOURCE NOTES: [S1] [S2] [S3]

3. ELECTRONS AND VACUUM TUBES

1883-1915

VACUUM TUBE: CONTROLLED ELECTRON FLOW THROUGH EMPTY SPACE



CATHODE: EMITS ELECTRONS

GRID: CONTROLS THE STREAM

PLATE: COLLECTS ELECTRONS

TRIODE = AMPLIFIER + SWITCH

FIGURE 3. The triode's grid controls electron flow, enabling amplification and fast switching without moving contacts.

The Edison Effect

- In 1883 Thomas Edison observed that current could pass through the evacuated space of a lamp from a hot filament to a separate plate.
- Heating frees electrons from a material by thermionic emission. In a vacuum, those electrons can travel toward a positively charged electrode.
- This one-way conduction was initially a lamp observation, but it revealed a method for controlling current without mechanical contacts.
- The discovery became a bridge between nineteenth-century electrical technology and twentieth-century electronics.

The Electron, 1897

- J. J. Thomson's cathode-ray experiments showed that the rays consisted of negatively charged particles much smaller than atoms: electrons.
- Electronics now had a physical carrier. Current in metals could be understood as charge motion; vacuum devices could direct electron beams.
- The electron has charge magnitude approximately $e = 1.602 \times 10^{-19}$ C.
- A current of one ampere corresponds to roughly 6.24×10^{18} elementary charges passing a point each second.

Diode and Triode

- John Ambrose Fleming patented a two-electrode thermionic valve in 1904. The diode rectified alternating radio signals into one-way current.
- Lee de Forest added a control grid to form the three-electrode Audion/triode in 1906-1907.
- A small grid-voltage change could control a larger plate current. The triode therefore amplified weak signals and acted as an electronic switch.
- Later tube families included tetrodes, pentodes, rectifiers, oscillators, display tubes, microwave tubes, and phototubes.

Why Tubes Mattered - and Failed

- Advantages: high gain, fast response compared with relays, operation at high voltages, and the ability to generate or detect radio-frequency signals.
- Costs: hot filaments, high power use, bulky glass envelopes, fragile construction, limited lifetime, and many failure points in large systems.
- Tube equipment transformed broadcasting, telephone repeaters, radar, television, audio, instruments, and computers.
- The search for a cooler, smaller, sturdier amplifier led researchers back to semiconducting solids.

SOURCE NOTES: [S4] [S5] [B2]

4. RADIO: ELECTRONICS LEAVES THE WIRE

1890S-1940S

RADIO SYSTEM: INFORMATION RIDES ON AN ELECTROMAGNETIC WAVE

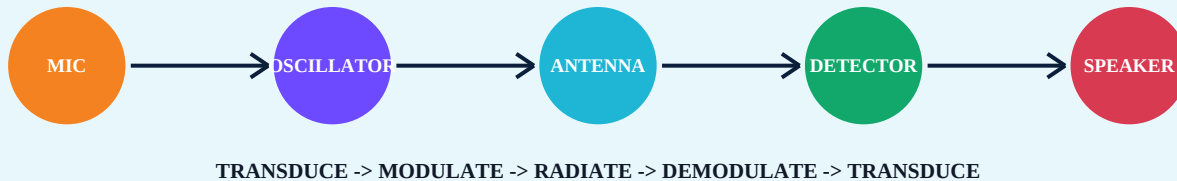


FIGURE 4. A radio chain converts sound to electricity, places it on a carrier wave, then recovers the information remotely.

From Waves to Wireless

- Maxwell's theory predicted electromagnetic waves; Heinrich Hertz experimentally produced and detected them in the late 1880s.
- Guglielmo Marconi and other experimenters developed practical wireless telegraph systems in the 1890s and early 1900s.
- Early spark transmitters sent pulses. Continuous-wave oscillators and tube amplifiers later made stable voice and music broadcasting possible.
- An antenna converts alternating current into radiated electromagnetic fields and performs the reverse process when receiving.

Modulation and Tuning

- A high-frequency carrier transports information efficiently. Modulation changes carrier amplitude, frequency, or phase according to the message.
- A tuned circuit selects a band of frequencies. Its ideal resonance is $f_{\text{res}} = 1/(2\pi\sqrt{LC})$.
- A detector or demodulator recovers the original message. Amplifiers raise the signal to a usable level.
- These functions survive in modern radios, though software and integrated circuits now perform many of them digitally.

Broadcasting and Mass Culture

- Radio linked transmitters to large audiences at once, changing news, music, advertising, politics, emergency warnings, and entertainment.
- Household receivers helped turn electronics from specialized infrastructure into consumer products.
- Standards and spectrum regulation became necessary because many transmitters share the same electromagnetic environment.
- Radio also drove advances in microphones, loudspeakers, recording, antennas, frequency control, and low-noise amplification.

Radar and Microwaves

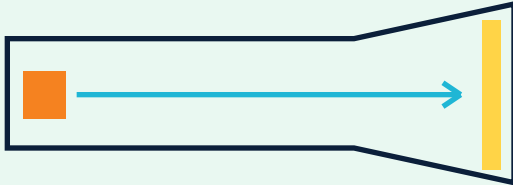
- Radar transmits radio energy and analyzes echoes. Distance follows from round-trip time: $d = ct/2$.
- The cavity magnetron, greatly improved in 1940, produced strong microwave signals suitable for compact wartime radar.
- Radar accelerated microwave engineering, displays, pulse timing, antennas, signal processing, and navigation.
- Later descendants include weather radar, air-traffic control, vehicle sensing, speed measurement, and planetary observation.

SOURCE NOTES: [S5] [S13] [B2]

5. ELECTRON BEAMS, IMAGES, AND TELEVISION

1897-1960S

CATHODE-RAY TUBE: ELECTRONS ARE AIMED TO MAKE LIGHT



1. ELECTRON GUN
2. DEFLECTION / SCANNING
3. PHOSPHOR SCREEN
4. LIGHTED IMAGE

FIGURE 5. A CRT steers an electron beam across phosphor, translating an electrical signal into a visible image.

Cathode-Ray Tube

- Karl Ferdinand Braun demonstrated an early cathode-ray tube in 1897. Electron beams could be focused, deflected, and made visible on phosphor.
- Oscilloscopes used the beam to draw voltage against time, allowing engineers to see rapidly changing signals.
- Television and computer displays scanned beams line by line to build images from varying brightness and, later, color components.
- The CRT joined three functions: electron source, beam-control system, and light-emitting screen.

Mechanical to Electronic Television

- Early television experiments used spinning disks to scan scenes. Limited resolution and mechanical speed constrained the picture.
- Electronic camera tubes and CRT receivers replaced moving scanning disks with controlled electron beams.
- Philo Farnsworth demonstrated an all-electronic television system in 1927; Vladimir Zworykin and RCA developed competing camera and receiver systems.
- Television combined imaging, broadcasting, timing, synchronization, amplification, and mass manufacturing.

From CRT to Flat Panel

- Liquid-crystal displays control light passing through pixels; plasma displays use ionized gas cells; OLEDs emit light from organic layers.
- Thin-film transistors placed at pixels allow active-matrix addressing and faster, sharper flat-panel images.
- Flat panels reduced depth and mass while enabling portable computers, digital cameras, phones, and wall-mounted screens.
- Display history shows a recurring pattern: new materials replace bulky control mechanisms while preserving the information function.

Pixels and Color

- A digital image is sampled into pixels. Each pixel stores or receives intensity information, commonly for red, green, and blue subpixels.
- For an uncompressed image, rough storage is width $\times$ height $\times$ bits per pixel.
- Resolution describes the sampling grid, not picture quality alone; optics, contrast, color accuracy, refresh rate, and viewing distance also matter.
- Modern displays depend on electronics for addressing, timing, conversion, correction, and power control.

SOURCE NOTES: [S1] [B3]

6. THE FIRST LARGE ELECTRONIC COMPUTERS

1930S-1950S

ELECTRONIC COMPUTER: SWITCHES REPRESENT AND TRANSFORM BITS



0 AND 1 ARE PHYSICAL STATES: LOW/HIGH VOLTAGE, OFF/ON, UNCHARGED/CHARGED

FIGURE 6. A computer maps mathematical logic onto physical switching states and repeats operations under control.

From Calculation to Stored Procedure

- Mechanical calculators automated arithmetic; punched-card machines sorted and counted records; relay machines automated sequences of logic.
- Vacuum tubes increased switching speed dramatically. Electronic machines could perform thousands of operations each second.
- ENIAC, completed in 1945 and publicly unveiled in 1946, used about 18,000 tubes for general numerical work.
- Stored-program architectures placed instructions and data in memory, making computers easier to reconfigure through software.

Switching Becomes Logic

- A switch can represent a bit: 0 or 1. Networks of switches implement Boolean operations such as NOT, AND, OR, XOR, and memory.
- For AND, output is 1 only when both inputs are 1. For OR, output is 1 when either or both inputs are 1.
- Arithmetic circuits build from logic gates: half adders, full adders, registers, counters, and arithmetic-logic units.
- Digital reliability comes from assigning ranges of voltage to discrete states rather than requiring every exact analog value to be preserved.

Memory Before Chips

- Early systems used delay lines, electrostatic storage tubes, rotating magnetic drums, relays, and later magnetic cores.
- Memory must support address selection, writing, retention, and reading. Each technology balances speed, density, cost, and reliability.
- Magnetic-core memory became dominant in the 1950s and 1960s because it was durable, random-access, and nonvolatile.
- The processor-memory relationship became central: computation is fast only if instructions and data arrive when needed.

Lessons of the Tube Era

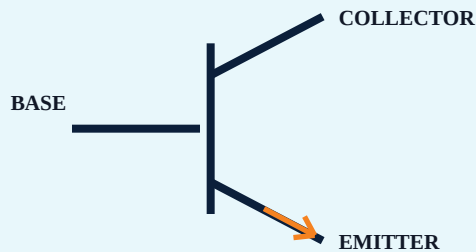
- Large tube counts meant heat, electrical demand, cooling equipment, frequent maintenance, and expensive assembly.
- Yet these machines proved that electronic switching could automate science, engineering, cryptanalysis, logistics, and administration.
- Engineers learned modular design, fault diagnosis, timing discipline, power distribution, and the importance of reliable components.
- The computer created a powerful demand for a solid-state switch that could be manufactured in enormous quantities.

SOURCE NOTES: [S7] [B4]

7. SEMICONDUCTORS AND THE TRANSISTOR REVOLUTION

1833-1954, WITH THE TURNING POINT IN 1947

TRANSISTOR: A SMALL INPUT CONTROLS A LARGER ELECTRICAL PATH



TWO CORE JOBS
AMPLIFY ANALOG SIGNALS
SWITCH DIGITAL STATES

FIGURE 7. The transistor performs the tube's key jobs inside a solid: signal amplification and switching.

What Is a Semiconductor?

- A semiconductor has electrical behavior between that of a strong conductor and an insulator, and its conductivity can be deliberately controlled.
- Adding selected impurities is doping. Donor atoms produce n-type material with abundant electrons; acceptors produce p-type material with mobile holes.
- A p-n junction permits strongly asymmetric current flow and forms the basis of diodes, transistors, solar cells, LEDs, and detectors.
- Temperature, light, electric fields, magnetic fields, and mechanical strain can change semiconductor behavior, making the materials useful for sensing.

December 1947

- At Bell Laboratories, John Bardeen and Walter Brattain demonstrated point-contact transistor action in germanium in December 1947.
- William Shockley developed the junction-transistor concept and a broader theoretical explanation of semiconductor devices.
- Shockley, Bardeen, and Brattain shared the 1956 Nobel Prize in Physics for semiconductor research and discovery of the transistor effect.
- The invention emerged from team science: quantum theory, pure materials, surface studies, precision measurement, and communications needs.

How a Transistor Helps

- In an amplifier, a small input variation controls a larger output variation while an external power source supplies energy.
- In a switch, the device is driven between low-conduction and high-conduction states to represent logic values.
- A bipolar transistor is current-controlled in a simplified circuit model; a field-effect transistor uses an electric field to control a channel.
- Transistors were smaller, cooler, more rugged, and potentially longer-lived than vacuum tubes.

From Laboratory to Product

- Reliable production required better crystal growth, purification, doping, contacts, packaging, testing, and circuit design.
- Early transistors were expensive and inconsistent, but military, telephone, hearing-aid, and computer applications accelerated improvement.
- The 1954 Regency TR-1 became the first widely marketed pocket transistor radio in the United States.
- Portability became a defining electronic value: lower power allowed smaller batteries, and smaller devices enabled new markets.

SOURCE NOTES: [S7] [S8] [S11]

8. THE INTEGRATED CIRCUIT

1958-1960S

INTEGRATED CIRCUIT: MANY COMPONENTS FORMED TOGETHER ON ONE CHIP



SHORTER CONNECTIONS -> HIGHER SPEED

BATCH FABRICATION -> LOWER COST

FEWER JOINTS -> HIGHER RELIABILITY

SCALING -> MORE FUNCTIONS PER AREA

FIGURE 8. Integration replaces hand-wired assemblies with complete circuits created together on a semiconductor substrate.

The Interconnection Problem

- As circuits gained transistors, the number of solder joints and wires grew rapidly. Assembly cost and failure risk threatened further complexity.
- The solution was integration: form transistors, resistors, capacitors, and their connections as parts of one manufactured structure.
- Integration changes economics as much as physics. Many microscopic devices can be produced together through repeated batch-processing steps.
- Short internal connections reduce delay and parasitic effects while standardized packages simplify system assembly.

Kilby and Noyce

- On September 12, 1958, Jack Kilby at Texas Instruments demonstrated a working solid circuit formed on germanium.
- In 1959, Robert Noyce at Fairchild described a practical monolithic silicon integrated circuit using planar processing and metal interconnections.
- Their approaches addressed complementary parts of the problem: integration as a concept and manufacturable silicon construction.
- Kilby shared the 2000 Nobel Prize in Physics for his part in inventing the integrated circuit.

Scale of Integration

- Small-scale integration placed tens of devices on a chip; medium-scale and large-scale integration brought hundreds, then thousands and more.
- Very-large-scale integration allowed processors, memories, communication systems, and mixed analog-digital functions to fit on chips.
- A chip is commonly called a die; many dies are patterned on a wafer, separated, tested, packaged, and connected to circuit boards.
- Yield - the fraction of usable dies - strongly affects cost. Defects matter more as dies become larger or processes become less mature.

Why Integration Won

- Cost per function fell because photolithography reproduced patterns at scale.
- Reliability increased because many fragile hand-made connections disappeared inside the chip.
- Speed increased because signals traveled shorter distances through smaller capacitances.
- Integration created feedback: cheaper electronics expanded demand, demand funded better factories, and better factories enabled greater integration.

SOURCE NOTES: [S9] [S12]

9. THE MOSFET AND THE SCALING AGE

1959-PRESENT

MOSFET: AN ELECTRIC FIELD OPENS OR CLOSES A CONDUCTING CHANNEL



INSULATED GATE: VERY LOW INPUT CURRENT

TINY SIZE: IDEAL FOR DENSE DIGITAL LOGIC

CMOS: LOW STATIC POWER IN LOGIC CIRCUITS

TODAY'S CHIPS USE BILLIONS OF MOSFETS

FIGURE 9. An insulated gate controls the channel electrostatically, making MOS technology highly scalable.

A Field-Controlled Switch

- Mohamed Atalla and Dawon Kahng demonstrated the metal-oxide-semiconductor field-effect transistor at Bell Labs in 1959.
- Its gate is insulated from the semiconductor by a thin dielectric. Gate voltage changes the carrier population in a channel between source and drain.
- Because the gate ideally draws very little steady current, many MOSFETs can be used in dense low-power logic.
- Modern terminology also covers polysilicon gates, high-k dielectrics, and new geometries even when the historical metal-oxide stack changes.

CMOS Logic

- Complementary MOS pairs n-channel and p-channel devices so that one network is mostly off while the other establishes the output state.
- Ideal CMOS uses little static power; most energy is consumed during switching, leakage, and supporting analog functions.
- Dynamic switching power is often approximated by $P \approx \alpha CV^2f$, where α is activity, C capacitance, V voltage, and f frequency.
- Reducing voltage saves power strongly, but lower voltage can reduce noise margin and performance.

Moore's Observation

- In 1965 Gordon Moore described the rapid growth in components per integrated circuit and predicted continued economic scaling.
- The later phrase Moore's law names an industry trend, not a physical law. Its pace and measurement have changed over time.
- Scaling required progress in lithography, materials, transistor structure, design software, contamination control, packaging, and factory precision.
- Performance no longer comes from simple shrinking alone; architecture, specialization, stacking, and parallelism now matter greatly.

Transistor Geometry Evolves

- Planar transistors placed the gate over a flat channel. FinFETs wrap the gate around raised fins for stronger electrostatic control.
- Gate-all-around devices surround thin channels more completely and help control leakage at very small dimensions.
- Shrinking introduces quantum tunneling, resistance, variability, heat density, and immense manufacturing cost.
- The device remains a switch, but every generation demands new materials and three-dimensional engineering.

SOURCE NOTES: [S7] [S12] [B5]

10. THE MICROPROCESSOR PUTS A CPU ON A CHIP

1971-1980S

MICROPROCESSOR: A PROGRAMMABLE CENTRAL PROCESSOR ON ONE CHIP



FETCH INSTRUCTION -> DECODE -> EXECUTE -> STORE RESULT -> REPEAT

FIGURE 10. A microprocessor repeatedly fetches, decodes, and executes stored instructions.

Intel 4004, 1971

- The Intel 4004 integrated the main functions of a four-bit central processor on one chip as part of the MCS-4 chipset.
- Federico Faggin, Ted Hoff, Stanley Mazor, and Masatoshi Shima made key design and implementation contributions.
- The 4004 contained about 2,300 transistors. Its importance was programmability: one manufactured device could perform many tasks under software control.
- Microprocessors shifted complexity from custom wiring toward stored instructions and reusable hardware platforms.

CPU Building Blocks

- The control unit sequences operations. Registers hold immediate values. The arithmetic-logic unit performs arithmetic and Boolean operations.
- Buses move data, addresses, and control signals among processor, memory, and input/output devices.
- A clock coordinates many operations, although modern processors use multiple clock regions, asynchronous boundaries, and sophisticated timing control.
- An instruction-set architecture defines the programmer-visible contract between software and hardware.

From Controllers to Personal Computers

- Early microprocessors served calculators and embedded control. Eight-bit processors such as the Intel 8080 and MOS 6502 supported early personal computers.
- Sixteen- and thirty-two-bit designs expanded address spaces and performance. Single-chip microcontrollers combined CPU, memory, timers, and input/output.
- Home and office computers made programming, word processing, games, spreadsheets, and digital media widely accessible.
- The same technology entered appliances, vehicles, instruments, toys, industrial machines, and medical equipment.

Architecture Becomes the Battleground

- Pipelining overlaps instruction stages. Caches keep recently used data near the processor. Branch prediction guesses future control flow.
- Multiple cores and vector units perform operations in parallel. GPUs apply massive parallelism to graphics and general computation.
- Specialized accelerators improve efficiency for video, cryptography, neural networks, and signal processing.
- Modern performance depends on hardware-software co-design, memory movement, energy limits, and packaging - not clock speed alone.

SOURCE NOTES: [S10] [S7] [S15]

11. ELECTRONIC MEMORY AND STORAGE

1940S-PRESENT

MEMORY: INFORMATION STORED AS PHYSICAL STATE



EVERY MEMORY TECHNOLOGY TRADES SPEED, DENSITY, ENERGY, COST, AND RETENTION

FIGURE 11. Memory technologies differ in the physical state used to represent information.

Volatile Semiconductor Memory

- Static RAM stores a bit in a bistable transistor circuit. It is fast but uses more area per bit and loses data without power.
- Dynamic RAM stores charge on a tiny capacitor and must be refreshed because charge leaks away.
- The Intel 1103, introduced in 1970, helped semiconductor DRAM begin replacing magnetic-core memory in computers.
- Caches favor speed; main memory balances speed and density. The hierarchy hides the large gap between processor and storage speeds.

Read-Only and Flash Memory

- ROM stores fixed patterns. PROM can be programmed once; EPROM can be erased with ultraviolet light; EEPROM can be electrically erased.
- Flash memory stores charge in floating-gate or charge-trap structures and erases blocks efficiently.
- Solid-state drives combine many flash dies with controllers that correct errors, distribute wear, map addresses, and manage failed cells.
- Nonvolatile memory retains data without continuous power, but write endurance and retention remain design concerns.

Magnetic and Optical Storage

- Magnetic tape and disks encode data in magnetized regions. Mechanical motion adds delay but provides economical high capacity.
- Optical discs use laser light to read physical or optical differences along a track.
- Storage technologies persist when they occupy different cost-performance roles; new forms do not instantly erase older ones.
- Archives value durability and low cost, while interactive systems value low latency and fast random access.

A Universal Tradeoff Table

- Latency: how long before requested data arrives. Bandwidth: how much data moves per second.
- Density: bits per area or volume. Energy: power used to read, write, refresh, or retain.
- Endurance: how many writes a cell tolerates. Retention: how long information remains readable.
- No memory is best at every measure; successful systems arrange several technologies into a hierarchy.

SOURCE NOTES: [S14] [B4]

12. LIGHT-EMITTING AND LIGHT-SENSING ELECTRONICS

1960S-PRESENT

OPTOELECTRONICS: DEVICES CONVERT BETWEEN ELECTRONS AND PHOTONS

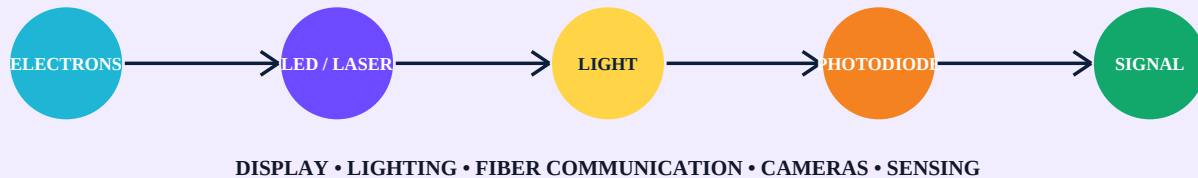


FIGURE 12. Optoelectronic devices connect electrical circuits to light for display, communication, energy, and measurement.

LEDs

- A light-emitting diode releases photons when electrons and holes recombine across a forward-biased semiconductor junction.
- Practical visible LEDs appeared in the early 1960s. Different semiconductor band gaps produce different photon energies and colors.
- Efficient blue LEDs developed in the early 1990s enabled white solid-state lighting by exciting phosphors or combining colors.
- Akasaki, Amano, and Nakamura received the 2014 Nobel Prize in Physics for efficient blue light-emitting diodes.

Lasers and Fiber

- A laser uses stimulated emission and optical feedback to produce coherent, narrow, directed light. Theodore Maiman demonstrated the first working laser in 1960.
- Semiconductor laser diodes can be tiny, efficient, and rapidly modulated.
- Optical fibers guide light with low loss. Laser transmitters and photodiode receivers form high-capacity communication links.
- The same platform supports scanners, rangefinding, surgery, manufacturing, sensing, optical storage, and spectroscopy.

Electronic Imaging

- Charge-coupled devices, invented in 1969, move photo-generated charge through a sensor array for readout.
- CMOS image sensors place active electronics within or beside pixels and integrate well with standard chip fabrication.
- A camera includes lenses, sensor, timing, analog amplification, analog-to-digital conversion, image processing, storage, and display.
- Digital photography became possible not from one component, but from the convergence of sensors, processors, memory, displays, and batteries.

Solar Cells and Detectors

- A photovoltaic junction converts photon energy into electrical power; a photodiode measures light as current or voltage.
- Quantum efficiency measures the fraction of incident photons producing useful carriers; spectral response shows sensitivity versus wavelength.
- Detectors extend human vision into infrared, ultraviolet, X-rays, and other spectral regions when paired with suitable materials and conversion layers.
- Optoelectronics makes the boundary between communication, sensing, power, and display increasingly fluid.

SOURCE NOTES: [S13] [B6]

13. POWER ELECTRONICS

1900S-PRESENT

POWER ELECTRONICS: SWITCHING DEVICES SHAPE AND CONTROL ENERGY



POWER SUPPLIES • MOTOR DRIVES • SOLAR INVERTERS • VEHICLES • GRID CONTROL

FIGURE 13. Power electronics uses controlled switching to convert electrical energy efficiently.

From Rectifiers to Thyristors

- Rectifiers convert alternating current to direct current. Early forms included vacuum, mercury-arc, copper-oxide, and selenium devices.
- Semiconductor power diodes improved efficiency and reliability. The silicon controlled rectifier, commercialized in the late 1950s, enabled controlled high-power switching.
- Thyristors transformed motor drives, industrial control, lighting, transmission, and large power supplies.
- Unlike signal electronics, power devices must safely manage substantial voltage, current, heat, and switching stress.

MOSFETs and IGBTs

- Power MOSFETs switch rapidly and are common at lower to medium voltages. Insulated-gate bipolar transistors combine gate control with high-current capability.
- Switch-mode converters reduce wasted energy by spending little time in partially conducting states.
- Inductors, capacitors, transformers, diodes, and controllers shape pulses into the required voltage and current.
- Wide-band-gap materials such as silicon carbide and gallium nitride support higher fields, temperatures, or switching speeds in suitable applications.

Conversion Families

- AC to DC: rectifier. DC to AC: inverter. DC to DC: chopper/converter. AC to AC: regulator or frequency converter.
- Conversion is never perfectly lossless. Efficiency is $\eta = P(\text{out})/P(\text{in}) \times 100\%$.
- Thermal design protects semiconductor junctions; filters limit ripple and electromagnetic interference.
- Control loops measure output and adjust switching to keep voltage, current, speed, or torque near a target.

Why It Matters Now

- Power electronics connects renewable sources, batteries, motors, vehicles, data centers, factories, household appliances, and the electrical grid.
- Efficient conversion saves energy across billions of devices, often producing greater system impact than a single spectacular invention.
- Electrification makes the control electronics as important as the energy source itself.
- The design goal is not merely power; it is controlled, efficient, safe, and reliable power.

SOURCE NOTES: [B7]

14. DIGITAL COMMUNICATION AND NETWORKED DEVICES

1948-PRESENT

NETWORKED ELECTRONICS: SIGNALS BECOME PACKETS, THEN ROUTES

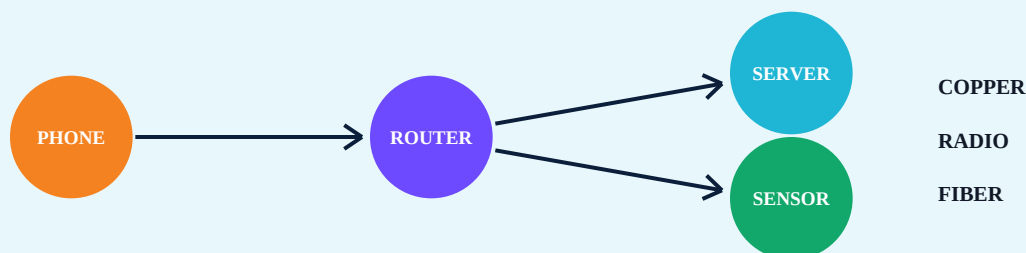


FIGURE 14. Modern communication divides information into encoded units that can be stored, corrected, routed, and copied.

Information Becomes Quantitative

- Claude Shannon's 1948 work established a mathematical theory of communication built around information, channel capacity, coding, and noise.
- A bit resolves one binary choice. Digital systems encode text, sound, images, and control data into bit sequences.
- Sampling converts a continuous signal into measurements. The sampling rate must be high enough to represent the signal band without aliasing.
- Error-detecting and error-correcting codes add controlled redundancy so a receiver can identify or repair corrupted data.

Transistors Transform Networks

- Transistor amplifiers and switches replaced many tube circuits in telephone exchanges, radios, repeaters, modems, and satellites.
- Integrated circuits placed modulation, coding, filtering, timing, and control into compact systems.
- Packet switching divides messages into addressed units that may share links and take different routes.
- Routers, switches, servers, and end devices cooperate through layered protocols rather than one giant central machine.

Copper, Radio, and Fiber

- Copper guides electrical signals but suffers resistance, capacitance, interference, and frequency-dependent loss.
- Radio provides mobility and broadcast reach but must share spectrum and manage fading, obstruction, and interference.
- Fiber guides light with low attenuation and enormous bandwidth, but requires optical transmitters, receivers, splices, and precise interfaces.
- Networks mix media: a phone may use radio locally, fiber through the backbone, and electronics at every conversion point.

The Internet of Devices

- Embedded processors give everyday objects computation. Network interfaces add communication; sensors add observation; actuators add physical action.
- A networked device creates security and privacy responsibilities because it can receive commands and disclose data.
- Reliability requires updates, authentication, encryption, fault handling, and safe behavior when the network fails.
- Connectivity magnifies both usefulness and risk: a defect can spread from one product to an entire installed population.

SOURCE NOTES: [S16] [B8]

15. PERSONAL ELECTRONICS AND THE SMARTPHONE

1970S-PRESENT

SMARTPHONE: MANY HISTORIC DEVICES CONVERGE IN ONE POCKET



TELEPHONE

RADIO

CAMERA

COMPUTER

GPS

RECORDER

CLOCK

SENSORS

FIGURE 15. The smartphone is a convergence device: centuries of separate inventions share one compact platform.

Consumer Miniaturization

- Transistor radios, calculators, digital watches, cassette players, game systems, and personal computers made electronics intimate and portable.
- Integrated circuits reduced component count; printed circuit boards automated interconnection; plastics and standardized batteries reduced product cost.
- Human-interface design became central: buttons, screens, pointing devices, menus, sound, vibration, and accessibility features.
- Electronics moved from shared household appliance to personal tool and eventually to continuously carried companion.

Mobile Telephone to Smartphone

- Cellular networks divide territory into reusable radio cells and hand calls from one base station to another.
- Digital cellular systems improved capacity, security, messaging, and data services. Smaller chips and lithium-ion batteries enabled lighter handsets.
- IBM's Simon, sold in 1994, combined mobile telephony with touchscreen organizer functions; later platforms expanded web, camera, media, and apps.
- The 2007 iPhone helped popularize a large multi-touch screen, desktop-class browsing, and an application-centered smartphone model.

What Is Inside

- A system-on-chip may combine CPU cores, graphics, neural processing, memory controllers, radio support, image processing, and security functions.
- Other devices include flash memory, display drivers, microphones, speakers, cameras, accelerometers, gyroscopes, magnetometers, GPS, and power management.
- Antennas connect to cellular, Wi-Fi, Bluetooth, and satellite systems across different frequency bands.
- Software coordinates the hardware, but each digital action ultimately becomes voltages, currents, stored charge, photons, or radio waves.

The Social Device

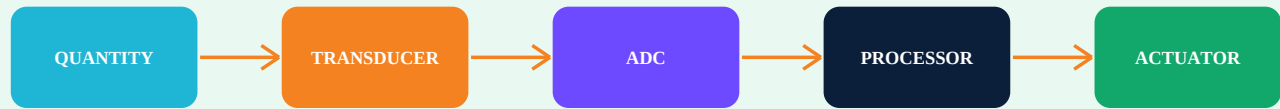
- Smartphones concentrate communication, photography, mapping, banking, entertainment, work, education, identity, and surveillance potential.
- Design choices affect attention, access, labor, repair, accessibility, misinformation, privacy, and environmental impact.
- A complete history must include users and institutions, not only inventors and components.
- The device's power comes from a global system of satellites, towers, cables, data centers, factories, software, standards, and human labor.

SOURCE NOTES: [S6] [S17] [B9]

16. SENSORS, MEMS, AND EMBEDDED CONTROL

1960S-PRESENT

SENSOR CHAIN: PHYSICAL WORLD -> ELECTRICAL SIGNAL -> DECISION -> ACTION



TEMPERATURE • PRESSURE • LIGHT • MOTION • SOUND • CHEMISTRY • MAGNETIC FIELD

FIGURE 16. A sensor system converts a physical quantity into data, processes it, and may act on the world.

Transduction

- A sensor is a device whose output changes with a measured quantity. It may use resistance, capacitance, voltage, current, frequency, light, or resonance.
- Thermistors respond to temperature; photodiodes to light; strain gauges to deformation; Hall sensors to magnetic fields; electrodes to chemical conditions.
- Calibration connects electrical output to a reference value. Sensitivity is output change per unit input.
- Accuracy, precision, range, resolution, drift, hysteresis, response time, selectivity, and noise describe different aspects of performance.

MEMS

- Microelectromechanical systems form microscopic mechanical structures using fabrication methods related to semiconductor processing.
- MEMS accelerometers detect motion through tiny proof masses; gyroscopes detect rotation through vibrating structures.
- Pressure sensors, microphones, mirrors, inkjet nozzles, resonators, and lab-on-chip devices also use microscale structures.
- MEMS bridges mechanical and electronic history: movement occurs physically, while integrated circuits sense, interpret, and control it.

Embedded Systems

- An embedded system is a computer built into a larger product to perform a focused function, often under timing, power, or safety constraints.
- Microcontrollers integrate processor, memory, timers, communication ports, and analog interfaces.
- Real-time systems must respond within defined deadlines. A correct result delivered too late may be a system failure.
- Firmware is software closely tied to hardware. Updates can repair flaws but can also introduce compatibility, security, and longevity problems.

Feedback and Automation

- A feedback controller measures output, compares it with a setpoint, and adjusts an actuator to reduce error.
- Thermostats, cruise control, wastewater processes, robotics, medical pumps, aircraft, and power converters all use feedback.
- Stability matters: too much delay or gain can produce overshoot or oscillation.
- Modern control combines sensors, signal conditioning, conversion, algorithms, actuators, and safeguards into a closed loop.

SOURCE NOTES: [B10]

17. HOW MODERN CHIPS ARE MADE

FROM PURIFIED SILICON TO PACKAGED SYSTEM

CHIP FABRICATION: REPEATED PATTERNING BUILDS DEVICES LAYER BY LAYER

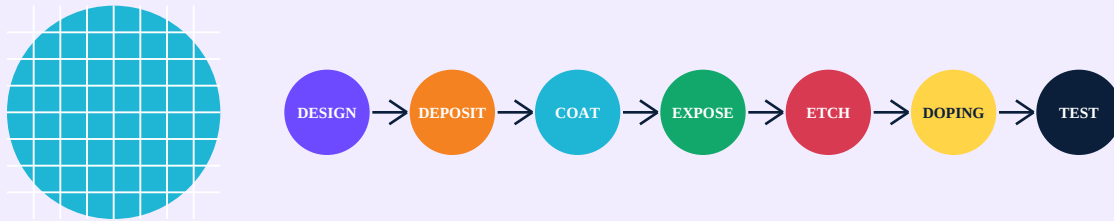


FIGURE 17. Fabrication repeatedly adds, patterns, removes, and modifies microscopic layers across an entire wafer.

From Sand to Crystal

- Silicon is refined to extreme purity, melted, and grown into a single-crystal ingot. The ingot is sliced into wafers and polished.
- Crystal quality matters because electronic behavior depends on controlled atomic structure and extremely low contamination.
- Wafers provide a common surface on which many copies of a circuit are produced at once.
- Fabs use filtered cleanrooms, chemical controls, ultrapure water, vibration isolation, and precise temperature management.

Patterning the Layers

- Deposition adds thin films. Oxidation grows insulating layers. Photoresist records projected patterns. Etching removes exposed material.
- Ion implantation or diffusion introduces dopants. Annealing repairs crystal damage and activates dopant atoms.
- Lithography repeats aligned patterns at successively smaller scales. Modern processes may use deep-ultraviolet or extreme-ultraviolet light.
- Hundreds or thousands of tightly controlled operations may be required to create transistors and many levels of interconnection.

Test, Dice, Package

- Wafer probing checks dies before separation. A diamond saw or laser divides the wafer into individual chips.
- Packaging protects the die, removes heat, and provides electrical and mechanical connections to the larger system.
- Wire bonds, flip-chip bumps, interposers, through-silicon vias, and chiplets provide different connection strategies.
- Final tests screen defects and verify performance across temperature, voltage, and speed grades.

A Global Production System

- Electronic products may involve design software, intellectual property blocks, equipment, chemicals, wafers, packaging, assembly, and testing from many regions.
- Factories cost billions of dollars and depend on specialized suppliers and highly trained workers.
- Supply disruptions reveal that a tiny component can halt production of vehicles, instruments, appliances, and communication systems.
- Chip history is therefore also a history of trade, standardization, infrastructure, education, and geopolitical strategy.

SOURCE NOTES: [S7] [B5]

18. PRESENT DIRECTIONS AND RESPONSIBLE DESIGN

2020S AND BEYOND

THE NEXT ERA: SPECIALIZED, THREE-DIMENSIONAL, LOW-ENERGY, AND QUANTUM-AWARE

CHIPLETS

3D STACKS

AI ENGINES

QUANTUM

FLEXIBLE

FUTURE PROGRESS MUST INCLUDE REPAIRABILITY, SECURITY, ENERGY EFFICIENCY, AND RESPONSIBLE MATERIAL USE

FIGURE 18. Progress is shifting from simple transistor shrinkage toward specialization, packaging, new structures, and system-level efficiency.

New Computing Structures

- Chiplets divide a large system into smaller dies connected in one package. This can improve reuse, yield, technology matching, and modularity.
- Three-dimensional stacking shortens some connections and increases density, but intensifies heat-removal and manufacturing challenges.
- AI accelerators emphasize matrix operations, local memory, and parallel dataflow to reduce costly data movement.
- Neuromorphic devices explore brain-inspired signaling; quantum devices manipulate quantum states for specialized algorithms and experiments.

Materials Beyond Conventional Silicon

- Silicon remains dominant because of manufacturing maturity, oxide quality, cost, and enormous design infrastructure.
- Gallium nitride and silicon carbide are important for certain power and radio-frequency uses.
- Two-dimensional materials, spintronic devices, phase-change materials, photonic circuits, and superconducting devices remain active research areas.
- A laboratory advantage becomes a practical technology only when materials, fabrication, reliability, interfaces, cost, and system value align.

Environmental Cost

- Electronics require mined materials, chemical processing, large factories, water, electricity, transport, and packaging.
- Short product life and difficult repair increase electronic waste. Batteries and circuit boards require responsible collection and processing.
- Efficiency during use matters, but embodied energy and manufacturing impacts must also be counted.
- Better design includes longevity, repair access, replaceable parts where practical, material disclosure, recycling pathways, and energy-aware software.

A Responsible History

- Invention is rarely a single heroic moment. It is cumulative work involving scientists, technicians, factory workers, users, funders, standards bodies, and public institutions.
- Patents record claims, not the whole social history. Commercial success may occur years after discovery and may depend on manufacturing breakthroughs.
- Technology can expand human capability while also concentrating power or creating new risks.
- The best question is not only 'Can this device be built?' but also 'Who benefits, who bears the cost, and how can the design improve?'

SOURCE NOTES: [B5] [B11]

19. MASTER REFERENCE: DEVICE FAMILIES

WHAT EACH DEVICE CONTROLS AND WHY IT MATTERED

DEVICE	CONTROLLED QUANTITY	CORE FUNCTION	HISTORICAL ADVANTAGE
Relay	Mechanical contact moved by magnetic field	Switch / isolation	Remote control and restored telegraph signals
Vacuum triode	Electron stream controlled by grid voltage	Amplify / switch / oscillate	Fast electronic control with no moving contact
Junction diode	Carrier flow across p-n junction	Rectify / detect	Compact one-way conduction
Bipolar transistor	Carrier injection controlled by input current	Amplify / switch	Small, rugged, low-power replacement for many tubes
MOSFET	Channel conductivity controlled by gate field	Switch / amplify	Very high integration density
Integrated circuit	Many patterned devices and connections	Complete circuit function	Low cost, speed, reliability, miniaturization
Microprocessor	Instruction-controlled data operations	General computation	Reusable programmable hardware
DRAM / flash	Stored electric charge	Working memory / storage	High density and digital portability
LED / laser	Electron-hole recombination	Emit light	Efficient display, lighting, and optical communication
Photodiode / image sensor	Photon-generated carriers	Detect light / form images	Electronic vision and optical links
Power transistor	High-current path controlled by gate/base	Energy conversion	Efficient motors, supplies, vehicles, and grid systems
MEMS sensor	Microscopic mechanical displacement	Measure motion / pressure / sound	Tiny low-cost physical sensing

THE REPEATING PATTERN

New electronic devices repeatedly replace a bulky, hot, slow, fragile, expensive, or specialized control method with one that is smaller, cooler, faster, more reliable, cheaper per function, easier to manufacture, or programmable. No invention wins on every measure; systems combine old and new technologies according to purpose.

20. ESSENTIAL VOCABULARY

A COMPACT GLOSSARY FOR REVIEW

ACTIVE DEVICE

A component capable of controlling or amplifying a signal using supplied energy.

AMPLIFICATION

Increasing signal magnitude or power while preserving useful information.

ANALOG

Representing information by continuously variable quantities.

BANDWIDTH

The usable frequency range or data-carrying capacity of a system.

CAPACITOR

A component that stores separated electric charge and energy in an electric field.

CARRIER

A high-frequency wave varied to transport information; also an electron or hole in a semiconductor.

DIODE

A two-terminal device with strongly directional current behavior.

DIGITAL

Representing information with discrete states, commonly binary 0 and 1.

DOPING

Adding controlled impurities to adjust semiconductor carrier concentration.

EMBEDDED SYSTEM

A computer built into a larger product for a focused purpose.

FEEDBACK

Returning part of a system's output to influence its input or control.

FREQUENCY

Cycles per second, measured in hertz.

INTEGRATED CIRCUIT

Multiple components and interconnections fabricated together on a substrate.

MODULATION

Varying a carrier to encode information.

OSCILLATOR

A circuit that generates a repeating signal.

PHOTOLITHOGRAPHY

Pattern transfer using light-sensitive material during chip fabrication.

RECTIFICATION

Converting alternating current into predominantly one-direction current.

SEMICONDUCTOR

A material whose conductivity can be engineered and controlled.

SIGNAL

A changing physical quantity used to represent or communicate information.

TRANSDUCER

A device that converts one physical form or quantity into another.

TRANSISTOR

A solid-state device used primarily for switching or amplification.

VACUUM TUBE

A device that controls electron motion through evacuated space.

WORD-BUILDING CLUE

electro- = electricity • photo- = light • thermo- = heat • magneto- = magnetism • micro- = small • opto- = light/vision

21. MASTER CHRONOLOGY

MILESTONES, CONTEXT, AND WHAT CHANGED

1740s	Leyden jar stores separated charge Repeatable electrostatic experiments	1945-1946	ENIAC completed and unveiled Large-scale electronic computation
1800	Voltaic pile provides steady current Continuous electrical work	1947	Point-contact transistor demonstrated Solid-state amplification
1820-1831	Electromagnetism and induction established Relays, motors, generators, transformers	1954	TR-1 pocket radio marketed Consumer transistor portability
1830s-1844	Relay and practical telegraph systems Long-distance coded electrical messages	1958-1959	Kilby and Noyce integrated circuits Circuits manufactured as unified structures
1876	Bell's major U.S. telephone patent and first call Electrical transmission of speech	1959	Atalla and Kahng MOSFET Scalable field-effect switching
1877	Edison's phonograph Recorded sound becomes reproducible	1960	First working laser Coherent electronic light source
1883	Edison effect observed Thermionic path to vacuum electronics	1962	Early practical visible LEDs Solid-state visual indicators
1897	Electron identified; Braun CRT demonstrated Charge carrier and controlled electron beam	1969	CCD invented Electronic image sensing
1904	Fleming thermionic diode Electronic rectification/detection	1970	Intel 1103 DRAM introduced Semiconductor main memory growth
1906-1907	De Forest Audion/triode Electronic amplification and oscillation	1971	Intel 4004 microprocessor Programmable CPU on a chip
1920s	Broadcast radio expands Mass electronic communication	1990s	Web, digital cellular, efficient blue LED Global digital access and solid-state white light
1940	Improved cavity magnetron Compact powerful microwave radar	2000s	Smartphone convergence Computer, camera, radio, sensors, and network in one device

TIMELINE PRACTICE: Select any three adjacent milestones. Write a causal explanation showing how the first enabled or motivated the second and how the second enabled or motivated the third. Do not merely repeat the dates.

22. REVIEW, ANALYSIS, AND DESIGN CHALLENGES

USE EVIDENCE, DIAGRAMS, AND COMPLETE EXPLANATIONS

1. Explain the difference between an electrical device and an electronic device. Give one borderline example.

2. Why was the continuous current of the voltaic pile historically different from a static-electric spark?

3. Describe how a relay permits one circuit to control another. Name one advantage and one limitation.

4. Trace speech through a telephone or radio system using input, transduction, signal, transmission, and output.

5. What did the control grid add to a vacuum tube? Why did that change communication and computing?

6. Compare vacuum tubes and transistors using size, heat, power, ruggedness, speed, and manufacturing.

7. Why did the integrated circuit solve an interconnection problem as well as a size problem?

8. Explain the MOSFET as a field-controlled channel. Why is low gate current valuable for integration?

9. Why is Moore's law better described as an industry observation than a law of nature?

10. Draw the fetch-decode-execute cycle and identify the roles of registers, ALU, control unit, memory, and buses.

11. Compare SRAM, DRAM, flash, magnetic disk, and tape using latency, density, volatility, endurance, and cost.

12. Show how an LED and a photodiode perform opposite energy conversions.

13. Calculate radar distance if an echo returns after 200 microseconds. Use $d = ct/2$ and $c \approx 3.00 \times 10^8$ m/s.

14. A converter accepts 120 W and delivers 108 W. Calculate efficiency and power lost as heat.

15. Select a smartphone function and trace at least five earlier device families necessary for it.

16. Explain why calibration, accuracy, resolution, drift, and response time are different sensor properties.

17. Why do chip fabrication and global supply chains belong in a history of devices?

18. Propose a repairability improvement for a modern electronic product and identify one engineering tradeoff.

DESIGN CHALLENGE

Design a portable emergency communicator using any historical era's technology. State the era, power source, switching or amplification device, transmission medium, user interface, expected limitations, and one improvement borrowed from a later era.

23. SOURCES AND FURTHER READING

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SOURCE PRACTICE

Institutional collection pages establish dates, artifacts, and documented milestones. They should be paired with scholarly books for wider social and technical interpretation. Online access dates change; URLs were checked during preparation in September 2026.

24. SELECTED BOOKS, INDEX, AND CLASSROOM LICENSE

CONTINUE THE INVESTIGATION

SELECTED SCHOLARLY READING

- B1** Bernal, John D. *Science in History*. Broad history of scientific and technical development.
- B2** Aitken, Hugh G. J. *The Continuous Wave*. Technology and the rise of American radio.
- B3** Abramson, Albert. *The History of Television, 1880 to 1941*. Early television systems and inventors.
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amplifier 6, 7, 10 • analog 5, 15, 16 • battery 1, 15 • Boolean logic 6 • capacitor 1, 4, 11 • chiplets 18 • CMOS 9, 15 • computer 6, 10 • CRT 5 • diode 3, 7, 12, 13 • display 5, 12 • DRAM 11 • electron 3 • embedded system 16 • feedback 13, 16 • flash 11 • integrated circuit 8 • laser 12 • LED 12 • memory 6, 11 • MEMS 16 • microprocessor 10 • modulation 4, 14 • MOSFET 9, 13 • network 14 • photodiode 12 • power electronics 13 • radio 4 • radar 4 • relay 2 • semiconductor 7 • sensor 12, 16 • smartphone 15 • telegraph 2 • telephone 2, 15 • transistor 7 • vacuum tube 3

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History is the story of controlled energy becoming controlled information.