CHAPTER 1

Electrical Engineering

1.1 ELECTRICAL CONDUCTION

1.1.1 Solids

Electricity is conducted by some solids, including metals and carbon. Their resistivity is independent of current density or direction but is dependent on temperature.

Metal conductors are used in magnetizing coils, capacitor plates, resistors and heaters and as contacts, conductors, arc quenchers, mechanisms, and structures. Examples include contactors and circuit breakers [Chapter 9], [A9]. Magnetic metals are discussed below. In some relays, magnetic metals carry both magnetic flux and electric current.

Some solids are superconducting at cryogenic temperatures; that is, their resistivity is truly zero, so there is no heating from conducted current. Some recently developed ceramics are superconducting at higher temperatures and show promise for economical devices. This effect is extremely useful for electro-magnet coils carrying high current densities to generate intense magnetic fields. An example is the levitation systems in experimental high-speed trains, which, of course, are large EMDs.

Some solids are non-linear conductors in a variety of ways. The most important are doped semiconductors, such as silicon and germanium, used in transistors, diodes, light-emitting diodes (LEDs), photodiodes, and solid-state lasers. All these are used in EMDs. Silicon wafers are made into one-piece strain gauges and accelerometers. The conductors are built onto the surface and the entire disc serves as a diaphragm or proof mass, respectively. Silicon wafers are etched into parts for microminiature motors. Doped silicon is light sensitive and is the base of most photovoltaic cells.

Selenium is a semiconductor whose resistivity is sensitive to light and to current direction. In the *xerography* process, a uniform electro-static charge is deposited on the selenium surface of a rotating drum; an image is imposed, either by optical projection or by laser scanning; the charge is conducted away where light reaches the surface; powdered ink *(toner)* is applied to the surface and adheres to the remaining charged areas; the surface is pressed against paper and the ink is transferred; finally, heat melts the ink to form a permanent image [Chapter 11]. Xerography is used in photoprinters, computer laser printers, and some computer plotters. Selenium has also long been used in photoelectric cells and in rectifiers.

The resistivity of solids varies with temperature; in most metals, it increases almost linearly with absolute temperature. This is the basis for resistance thermometer temperature transducers, which measure temperature by measuring resistance [A18], [Chapter 7]. A few materials, such as carbon, have resistivities that decrease with increased temperature.

The volume of solids, liquids, and gases (at constant pressure) increases with temperature. This effect is used in a variety of devices including bimetal elements and other temperature-sensitive devices [Chapter 7].

Mechanical tensile and compressive stresses change the resistance of metal conductors. This effect has been of extreme value as the basis of the EM strain gauge [Chapter 7].

Carbon has unique properties of great value in EMDs. It does not melt, evaporate, or weld under ordinary conditions; thus it is valuable for electrodes and contacts. It is chemically almost inert except for oxidizing at high temperatures, and its oxides are gases that blow away, so its surface remains uncontaminated. (Once oxidized, carbon becomes the basic element of all organic compounds, of course.) [Chapters 3, 4, and 9].

Mercury is unique in being a metal that is liquid at room temperature; it melts at $-39°C$. Mercury has enabled the construction of contact makers that would otherwise not be possible [Chapter 9].

Properties of materials are tabulated in the handbooks listed in the References and Bibliography Group [B].

1.1.2 Liquids

Liquid conductors include molten metals such as mercury, aluminum, and iron. Mercury is particularly useful in switching devices in which liquid mercury is made to flow instead of solid objects being made to move. Silent wall switches in the home are a common example [Chapter 9].

Molten iron is agitated by induced eddy currents during steelmaking.

Molten bauxite (aluminum oxide aluminum ore) conducts electricity during the electrolytic extraction of aluminum.

Another large class of liquid conductors is ionized solutions, such as salt water, in which conduction is by physical motion of the electrolyte's ions. In electrolytic conduction, the H^+ ions release hydrogen gas at the negative electrode. The gas may coat that electrode with fine bubbles that obstruct current flow; this effect is called *polarization*. Positive ions of metal may deposit as a metal film on the negative electrode; this is *electroplating*.

1.1.3 Gases

Ionized gases conduct electricity, with positive ions moving one way and free negative electrons moving the other way. This is what happens in neon signs, fluorescent lamps, and certain lasers. An ionized gas is called a *plasma*. Evaporated mercury is a gas much used as an electrical conductor, for example in fluorescent lamps.

In a sense, vacuum is a superconductor since it allows electrons to move through it with no voltage drop other than that used to accelerate the electrons. This occurs in television and other cathode-ray tubes and in other vacuum tubes. The motion of the electrons is accelerated by electric and magnetic fields and obeys the same Newtonian laws as do the motion of baseballs. (Gravity fields also accelerate the electrons but the effect is negligible in practical electron devices.) When electron speed approaches the speed of light, relativistic effects also occur.

In mass spectrographs, ions move through a vacuum, electro-statically accelerated and magnetically deflected. (Is a mass spectrograph a kind of curvilinear motor and therefore an EMD? If it is, so is every cathode-ray and other vacuum tube! Does it matter? "A rose by any other name would smell as sweet.")

Conduction in metals is by free electrons moving in the metal; conduction in an electrolyte is by ions moving in the solution; but conduction in a vacuum requires a separate source of electrons, such as a hot filament, or a separate source of ions.

1.1.4 Contacts

Conductor surfaces that touch one another conduct electricity from one to the other, depending on the conditions of the surfaces; the principal obstacles are the oxide and dirt layers that may be on the surfaces. Silver, gold, platinum, palladium, and rhodium—are called *noble metals* because they resist chemical attack such as oxidation in air. Therefore, they make good contact materials in switching devices even though their resistivities (other than silver's), and costs, are higher than those of copper or aluminum alloys [Chapter 9].

Carbon is also noble (although not usually called so), but its resistivity is high and it is difficult to make a low-resistance connection to it. (One way is to electro-plate the carbon with tin and then solder to the tin surface.) Carbon has the useful property that the resistance between carbon parts in contact with one another or with metal parts varies inversely with the force pressing the parts together. This is the basis for the following devices:

- The carbon granule microphone [Sections 7.4.1 and 12.2]
- A rheostat in which a stack of carbon plates is compressed by an adjusting screw
- A spot heater [Chapter 13]

Carbon does not melt, so it cannot be welded, intentionally or otherwise, and its oxides are gases that dissipate. These properties make it a valuable contact material in relays and circuit breakers [Chapter 9].

Silver is a special case. In air, it develops a sulfide coating (tarnish), but the coating is conductive. Since silver is cheap, it is a very common electrical contact material. A limitation of silver is its tendency to migrate over plastic surfaces and cause electrical leakage and short circuits.

In many switching devices, the contact surfaces are made to rub against each other *(wipe)* when they are brought together to scrape away dirt and chemical contaminants. This is particularly important for inexpensive switches and connectors whose contact surfaces are bronze or other non-noble metals [Chapter 9].

Many switching devices are enclosed in a vacuum or an inert gas to prevent atmospheric chemical or dirt contamination. Motion is transmitted to them via flexible diaphragms, bellows, magnetic fields, or gravity. Examples are reed switches, mercury switches, and vacuum circuit breakers [Chapter 9]. A vacuum or an inert gas also reduces arcing.

A solid conductor in contact with a liquid or gas is called an *electrode.* (Welding, medical, and chemical electrodes may also contact solids.) There is little problem with inadequate conductivity, but there may be severe problems with corrosion. In some instruments, the electro-chemical voltage between electrode and liquid would cause errors, so platinum electrodes may be used. In batteries, of course, these electro-chemical voltages provide electric power.

This *electrolytic corrosion* is sometimes combated by providing *sacrificial electrodes,* usually of zinc, which corrode, instead of the metal of the device to be protected, which is typically steel. Large devices, such as steel pipelines, are sometimes protected by electric voltages applied between the device and the earth. Even nominally dry contact between dissimilar metals can produce corroding voltages and currents if a return path exists. Corrosion of iron pipe in contact with copper tubing is a common example.

Electrolytic removal and deposition of metal are not always bad; this is the basis of electro-plating and electro-polishing and of a technique of metal purification. The original ampere-hour meter electro-plated silver from an anode to a cathode; weighing the electrodes gave an accurate measure of ampere-seconds, or coulombs. Another useful device is a running time meter comprising a small, sealed, glass tube with electrodes at each end and with a slug of metal at one electrode. A fixed current is sent through the device whenever the associated equipment is on. Transfer of metal to the other electrode is read on a scale calibrated in hours.

1.2 ELECTRICAL INSULATION

Insulation is as important as conduction; you must not only get electricity from here to there, but you must also prevent it from leaking out and spreading to where you do not want it.

The important electrical properties of insulating materials are dielectric strength, dielectric constant, dielectric loss, and arc and tracking resistance. For circuit breaker arc quenching, high thermal capacitance is of great value; hydrogen and sulfur hexafluoride are of particular value, as are solids that outgas *(ablate)* when heated by an arc [Chapter 9].

Dielectric loss is useful when it allows heating insulating material with high-frequency electric fields.

Insulating materials include solids, liquids, and gases. Most organic and inorganic compounds and non-metallic elements are insulators.

1.2.1 Solids

Many solid insulating materials are plastic laminates; and many others are polymers or mixtures, such as molding compounds with and without fillers. Coils are sometimes molded into solid plastic insulators, usually after being outgassed in a vacuum to allow the uncured plastic to penetrate the windings. Voids in electrical assemblies are sometimes filled with liquid *potting compounds* that harden in place. Solid insulation is fabricated by molding, machining, and laminating.

Organic solid insulators include molded thermoplastic and thermoset plastics, laminated plastic, wood, paper, cloth, and fiber.

Inorganic solid insulators include glasses, ceramics, mica, and glass filled with mica particles. Silicones are organic or inorganic, depending on one's chemistry semantics. They resemble organic compounds in many ways and make excellent insulation, particularly in place of other organics at high temperatures.

The important non-electrical properties of solid insulating materials are strength, stiffness, creep, brittleness, temperature resistance, moisture, chemical and fungus resistance, toxicity, fabrication properties, and aesthetic attractiveness [Group B].

1.2.2 Liquids

Liquid insulating materials are used to immerse and impregnate many transformers, capacitors, high-voltage cables, and high-voltage switches.

Long after they started to be used as insulators or manufacturing solvents, it was discovered that some materials were carcinogens, were poisons, damaged the ozone layer, or otherwise polluted the environment. Most of these materials were liquids, such as polychlorinated biphenyls (PCBs) and chlorofluorocarbons (CFCs), that spread easily or were volatile. Asbestos, a solid, was long used as an excellent heat-resistant insulation before it was discovered to be a carcinogen. (The fine strands of asbestos float through the air and hook into lung tissue.) [Chapter 27].

1.2.3 Gases

Gases, usually under pressure, are used instead of air as insulating materials in some devices such as large circuit breakers and high-voltage cables. Sulfur hexafluoride is a particularly good insulator. Hydrogen is an excellent electrical insulator and heat conductor, but it is a dangerous explosive.

Vacuum is an excellent insulator provided there is no source of either free electrons, such as a hot filament, or of ions; both can pass freely through it.

The properties of insulating materials are tabulated in the handbooks in [Group B].

1.3 ELECTRO-MAGNETISM

1.3.1 Magnetism

Many *electro-magnetic* devices are EMDs, but since the word *electro-magnetic* occurs in this book less frequently than *electro-mechanical,* it is spelled out each time. Alphabet soup is not a worthy end in itself.

A magnetic field is produced by every electric current. In most electro-magnetic devices, a current flows through a coil of many turns, N, the field of each turn adding to the fields of the other turns. The total magnetizing effect of a coil, *magnetomotive force,* (MMF), is measured as *ampere turns,* NI.

Magnetic material atoms have what amounts to electric currents in superconducting short-circuited rings. These may be thought of as aligned electron spins and orbits, although a physicist would call this description a rough approximation of quantum mechanical phenomena. In both soft magnetic materials, such as pure iron, and hard (permanent) magnetic materials, such as Alnico, MMF is required to change the directions of atom alignments from random to parallel and from parallel alignments in one direction to parallel alignments in the opposite direction. (It is as if there were friction among the atoms). The tendency for the alignments to remain in the same direction until forced to change by an MMF is called *hysteresis.* The difference between soft and hard *(permanent)* magnetic materials is the difference between low and high hysteresis. This difference is many orders of magnitude beween the least and the greatest.

Most materials have no effect on magnetic fields, which pass right through them, but some materials provide easier paths than air, that is, they have *permeability* greater than air. Principal among these are iron and nickel and their alloys. Parts made of these materials reduce the ampere turns necessary to produce a desired magnetic field. As moveable parts, they help convert electrical energy to mechanical work, as described later.

These *ferromagnetic* materials *saturate* at some level of magnetic field density. Therefore, they are not helpful for fields much above saturation density. Some iron-nickel alloys have very high permeability and very low hysteresis but saturate at a low magnetic field density. These alloys are useful in sensitive relays, certain transformers, and sensors for weak fields.

Some materials, such as bismuth, have permeability slightly *less* than that of air. They are *diamagnetic;* iron is *paramagnetic* or *ferromagnetic.*

Magnetic materials have *hysteresis;* their state of magnetization remains until reverse ampere turns demagnetize them. These reverse ampere turns may come from current in a coil or from an air gap. An air gap requires continual ampere turns to maintain continual flux and thus acts as such a current in a coil. Energy is dissipated as heat with each cycle of magnetizing and demagnetizing. Most AC devices use an alloy of iron and silicon, *silicon steel,* which has low hysteresis and high electrical resistivity, the latter reducing power dissipation from eddy currents. Materials with extremely high hysteresis become *permanent magnets* when magnetizing MMF is removed.

Another class of magnetic material is ferrite ceramics. They can be made with either very low or very high hysteresis, and they are insulators.

An extremely valuable use of magnetic hysteresis is in digital and analog memories. If you magnetize a piece of magnetic material having hysteresis, and then go away, and then return and examine the hysteresis state of the piece, and find that it is magnetized, you may say that the piece has *remembered* that you magnetized it. This is digital memory, which is used in digital computers [Chapter 10].

If you magnetize high-hysteresis material to less than saturation and later measure how much it was magnetized, this is analog memory, which is used in tape recorders for sound [Chapter 12]. (Sound can also be periodically sampled, the samples measured and the measurements digitized, and the digital measurements recorded or transmitted. This is what compact disc (CD) recording is and what modern telephone systems do for long-distance telephony.)

Since magnetic metals are electrically conductive, AC magnetic fields induce *eddy currents* in them that dissipate power in addition to the power dissipated by hysteresis. Therefore, the iron cores of motors, generators, and transformers are stacks of thin sheets *(laminations)* of magnetic steel. The laminations have insulation between them, typically an iron oxide layer on the lamination surfaces. The thinner the laminations, the less the eddy current loss. Hysteresis loss is unaffected by laminating. The magnetic steel used in most AC cores is an alloy of iron and silicon. It has less *core loss* (total eddy current and hysteresis loss) than other alloys or than pure iron. Ferrites are non-conducting and need no laminating but saturate at lower flux densities than do iron alloys.

Core-loss heating is used to heat iron parts for forging.

The force between permanent magnets is the reaction of their internal electric currents with the magnetic fields those currents generate. Electro-magnetic force is described below.

The properties of magnetic materials are tabulated in handbooks [B6, B9, B11, B13, B16].

1.3.2 Flux Linkage

To understand electro-magnetic force one must first understand *flux linkage.* Consider Fig. 1-1. Magnetic fields are represented by *lines of force* 1. The density of the field is represented by lines per unit area, and the direction of the field is represented by the direction of the lines. It works out that each line is an endless loop, so the total number of lines through any cross section of the entire field is the same. A bundle of lines is called a *magnetic flux.* The closed-loop path of a bundle of lines is called a *magnetic circuit.* (The array of all flux lines and the magnetic parts through which some pass is also called the magnetic circuit.) Where there is an iron core, as in a transformer or an electro-magnet 2,3 most of the lines 4 pass through the iron path. However some lines extend out and back through the envelope of the iron and are called *leakage flux* 5a, 5b.

There exist both approximate and rigorous mathematics and also finite element analysis for magnetic fields. The fields in both the iron and the leakage flux paths in devices made of iron 2,3 with air gaps 6a, 6b can

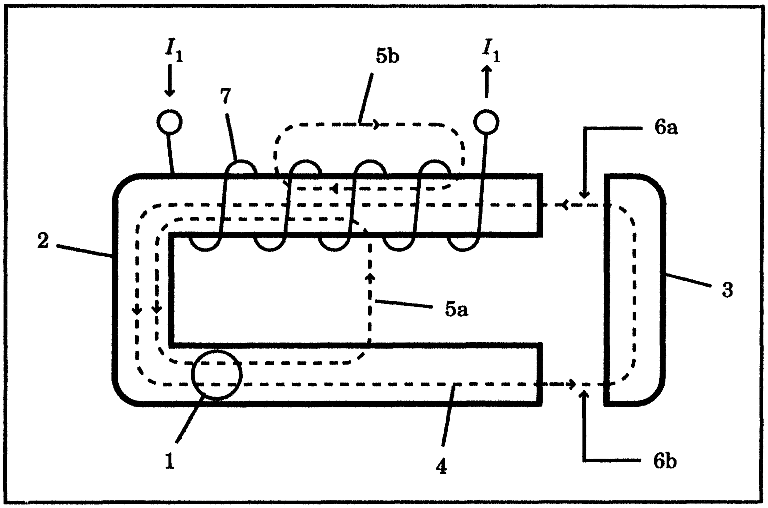

Figure 1-1 Flux Linkage

be calculated. However for our purposes we do not need the mathematics [A10].

An electric current flows in a closed loop in an electric circuit. An electric circuit is usually confined to the shape of the circuit conductors, and the conductors often include a coil of wire 7.

It has not been useful to coil magnetic circuits although there is no law of physics that says they cannot be coiled. An exception is the transformer core that is a spiral of magnetic strip instead of stacks of flat laminations. The flux crosses from turn to adjacent turn and the net effect is beneficial magnetically and economically.

A bundle of magnetic lines of force passing through—linking—coil turns of an electric circuit constitutes flux linkage. Flux linkage is an essential concept in understanding electrical and EM engineering.

One magnetic line linking a two-turn coil is equivalent in flux linkage to two magnetic lines linking a one-turn coil. Usually, some flux links some turns and some flux does not, as shown in Fig. 1-1. The total flux linkage is the sum, over all the turns, of the lines linking each turn. This is equivalent to saying that the flux linkage is the sum, over all the magnetic lines of force, of the number of turns linking each line.

There are few devices in which all the magnetic lines link all the circuit turns. Even in an iron-core transformer with no air gap, and certainly when there is an air gap 6a, 6b, there is some *leakage flux* 5a, 5b part of whose path is through the air. This leakage flux does not link all the turns. A perfectly made toroid, however, would have no leakage flux [Section 18.3].

In solenoids with large air gaps, it is the change of flux linkage with mechanical position that makes the device work, as we shall see.

In motors and generators, the flux crosses the air gap between stator and rotor, from tooth to tooth, with fringing around the edges of the teeth [Fig. 3-2]. Before finite element analysis (FEA) by computer, enormous amounts of effort were expended on approximate calculations of magnetic field shape. Reference [A10] describes the FEA approach and contains software to do it. New computer programs continually appear.

1.3.3 Induced Voltage

Voltage is induced in a coil by the rate of change of its flux linkage. This is equally true for huge turboalternators and for tiny instruments. The linking flux may come from any of the following:

1. An outside source, such as a permanent magnet moving relative to the coil
2. Electric current in another coil, such as in a transformer or a motor
3. Electric current in the coil itself, such as in an inductance

In each case, induced voltage is proportional to the rate of change of flux linkage.

If the flux comes from a permanent magnet or electro-magnet, we have either a *motor* or a *generator,* depending on which way power flows [Chapter 3].

If the flux comes from current in another coil, we have a *transformer* and the two coils have *mutual inductance.*

If the flux comes from current in the coil itself, we have an *induction coil* (or *inductor* or *choke*) with *self-inductance.*

If there is a movable piece of magnetic iron in the magnetic circuit, as in Fig. 1-1, when it moves it changes the shape and reluctance of the magnetic circuit. This changes the amount and shape of the magnetic flux and thus the flux linkage [Chapter 6].

In each case, voltage is *induced* by time varying flux linkage.

In AC devices, the flux linkage reverses cyclically, producing a reversing voltage, but the effect of geometry change is the same as for DC devices.

Flux cannot increase to infinity, so in DC motors and generators flux linkage is made to reverse; it is really AC. However, the coil connections are also reversed when the flux linkage starts to reverse, so the reversing voltage appears on the terminals as DC. Sliding brush *commutators* are EM switches for this purpose [Fig. 9-13]. *Commutation* is also done electronically: in generators by rectifiers and in motors by transistor switching circuits.

1.3.4 Electro-magnetic Force

In Fig. 1-1, if current I_1 is caused to flow in coil 7, flux 4, 5a, 5b is produced. Armature 3 is pulled toward core 2, the magnetic circuit reluctance is reduced, the flux linkage increases, and energy is drawn from the current source. *Motion in the direction of the force increases the total flux linkage of the system,* and the mechanical power comes from electric power to the coil. *The instantaneous electric power converted to mechanical power is current times the voltage induced by the increase in flux linkage. This is what happens in all electric motors and in all other electric actuators.*

We have assumed that current I is constant, which it is if a DC coil is exerting a force on either a stationary second DC coil or a stationary piece of iron. This is not the case while the device is in motion doing its work. While the system is in motion, changing flux linkage induces voltage that causes current change; thus the instantaneous force varies with time.

If DC voltage is suddenly applied to the coil, flux linkage builds up in the usual way for an inductance. If the rising force starts motion before steady-state current is reached, that motion begins with less force than if steady-state current were reached before the parts were released.

If AC voltage is applied to the coil, the action is more complicated. First, the current-time relationship depends on the electrical transient determined by the phase of the voltage when the switch is closed. Second, in an AC device, the current is affected only slightly by the coil resistance. It is the amount needed to generate such AC flux as will induce a back electro-motive force (EMF) equal to the applied EMF. As the iron moves, the time-varying magnetic circuit reluctance changes the amount of current needed.

There are three configurations in which electro-magnetic force occurs:

1. A single coil and iron. In Fig. 1-1, assume that the position of iron part 2 is mechanically fixed relative to the coil. A force appears between the two pieces of iron 2,3 that is proportional to I_1^2. If part 2 were not present, there would still be a force between iron part 3 and the coil that would be proportional to I_1^2, although much weaker.

2. Two coils, with or without iron cores. In Fig. 1-2 there are two coils 8,9 carrying I_2 and I_3, respectively. Some of the flux generated by each coil links the other coil. A force appears between the coils proportional to $I_1 \times I_2$. If one or both coils have iron cores to which they are mechanically bound, a larger force appears, but it still is proportional to $I_2 \times I_3$. If the two coils are connected in series so they carry the same current I_2, then the force is proportional to I_2^2.

3. A single coil and a permanent magnet: In Fig. 1-3 coil 10 carries current I_4 and is linked by flux from permanent magnet 11. A force proportional to I_4 appears between the coil and the magnet. Permanent mag-

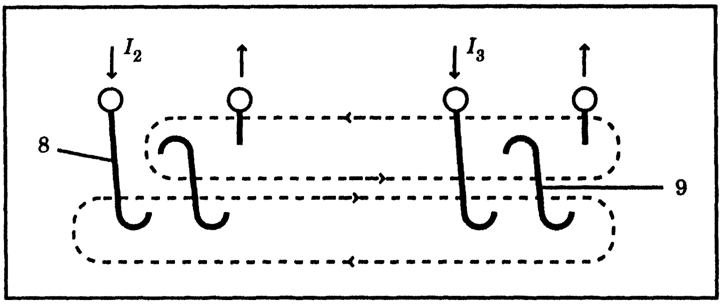

Figure 1-2 Force between Two Coils

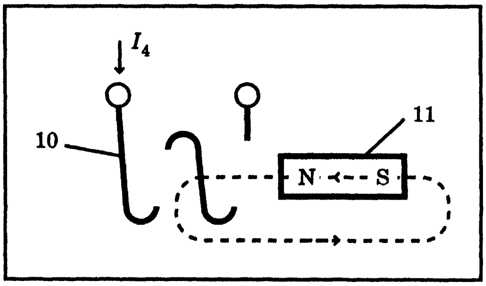

Figure 1-3 Force between Coil and Magnet

net 11 acts like a coil with a constant current, as explained in the next section.

The structure of Fig. 1-1 is used in the electro-magnets of most relays and in lifting electro-magnets. The structure of Fig. 1-2, each coil having an iron core, appears in DC shunt motors. The structure of Fig. 1-3 appears in loudspeaker voice coils, d'Arsonval galvanometers, and some electric motors.

Please note that in all cases *the force is proportional to the product of two currents.* In case 1, both currents are the same, and the "product" is a "square." In case 2, there are two distinct currents, although in the series case, there is again a single current that appears twice. In case 3, the permanent magnet produces a flux just as if it were a coil carrying a current—which it really is, the current being electron spins and orbits. In each case, the presence of soft iron changes the shape and increases the magnitude of the magnetic field but does not change the "product of two currents" law [Chapter 6].

1.3.5 Permanent Magnets

To repeat: Permanent magnets are pieces of matter in which many electron spins and electron orbits have parallel axes so their individual magnetic fields add up. The permanent magnet acts like a superconducting coil needing no external source of power to keep its electrons moving.

The force causing iron particles to attract each other in a magnetic field is the force on those electron currents. The attraction of particles to each other is the basis of the magnetic particle clutch and brake [Section 4.4.2].

1.3.6 Electric Power

If induced voltage causes current to flow in the same direction as the induced voltage, then electric power flows *out* of the coil, proportional to induced voltage times current, there is a generator. The amount of current depends on the impedance of the coil's circuit. The power is consumed by a load, for example, a utility customer's motor. The power may also be consumed by the resistance losses in the coil itself if it is short-circuited, which it is in some EMDs.

If *external* voltage causes current to flow in *its* direction, *opposite* to induced voltage, then electric power flows *into* the coil, proportional to external voltage times current; there is a motor or actuator. The law of the conservation of energy applies. Generator power comes from external mechanical force moving against $I \times I$ force, and motor power comes from $I \times I$ force moving against external mechanical force.

In most EMDs, there is energy transfer from electrical mode to mechanical mode or vice versa. In power devices, the power may be megawatts; in information devices, it may be microwatts.

More complete and mathematical explanations of electricity and magnetism are given in many textbooks, including references [A10, A11].

1.4 ELECTRO-MAGNETIC RADIATION

Electro-magnetic radiation extends in a continuous spectrum from extremely short gamma-ray waves to extremely long radio waves. Regardless of their wavelengths, all are combinations of interacting AC electric and magnetic fields.

The AC electric field induces the AC magnetic field that induces the AC electric field. The combination of fields, independent of the wavelength, moves forward in empty space at the speed of light. If this action is new to you and this description is hard to believe, you have my sympathy. The best I can do for you is to refer you to any formal textbook on electricity and magnetism, but it will say the same things much more rigorously, at much greater length, and with differential equations, wave diagrams, words like *displacement current, Poynting vector*, and *Maxwell's equations.*

To add to your troubles, the radiation always exists in discrete units called *quanta* or *photons,* each having a fixed amount of energy that varies inversely with its wavelength. There are sensors that can detect a single photon.

The good news is that, to understand the remainder of this book, you do not have to understand the last two paragraphs!

The spectrum of electro-magnetic radiation is usually divided into *frequency bands* named:

1. Gamma rays (shortest wavelength, highest frequency, greatest energy per photon)
2. X-rays
3. Visible light. (The longest wavelength is approximately twice the shortest wavelength. In musical terms, visible light spans approximately only one octave of the hundreds of octaves of known radiation.)
4. Infrared (IR) rays
5. Microwaves
6. Short radio waves
7. Long radio waves

Many of these bands have subbands with corresponding names.

In each band, EMDs are used for a variety of purposes, for example:

1.4.1 Gamma Rays

Gamma rays are used in inspection systems. Either a test body or a set of sensors is manipulated by an EMD with respect to a stationary beam of radiation. (A radioactive gamma-ray source, with its necessary shielding, is too heavy to move easily.)

1.4.2 X-Rays

X-ray tubes, film cassettes, objects being studied, and medical patients are all manipulated by EMDs.

1.4.3 Visible Light

Visible light is associated with a large number of EMDs. Light is *produced* by arcs (some controlled by EMDs), hot bodies (including incandescent lamps, fires, and the sun), lasers, fluorescent surfaces impacted by electrons or other invisible radiation, and phosphorescent surfaces energized by radiation.

Light is *directed and modified* by lenses, mirrors, prisms, shutters, and filters, all manipulated by EMDs.

Light *passes through* vacuum, most gases, many liquids, and some solids. Optical fibers are glass fibers, usually with glasses of different refractive index at different radii. They carry light signals for extremely wideband communication and are displacing plain wires and coaxial cables for long-distance communication.

Light is *sensed* by chemical deposits on photographic film, by photovoltaic and photoresistive cells, by emission of electrons from atoms impacted by photons in photomultipliers, and by silicon solid-state–charge coupled devices (CCD's). Examples include photoelectric cells of all kinds and cameras of all kinds, from vest pocket to the Hubble space telescope. All are manipulated by EMDs. Similar effects occur in video cameras that use CCD's as image sensors. Light is generated and used as a sensing and control medium in a variety of EMDs.

Light sources and sensors, such as searchlights, telescopes, and video cameras are aimed by EMDs [Section 8.1]. Many have photoelectric sensors in their control systems.

1.4.4 Infrared Rays

IR sources and mirrors are manipulated by EMDs. For example, the Sidewinder missile uses a spinning mirror in its IR target tracking system.

1.4.5 Microwaves

Microwave systems use an EM slotted line with a mechanically positioned sensor as an accurate measuring device for standing wave ratio. They use accurately manufactured waveguides, cavities, and antennas. Radar uses microwaves whose steerable antennas have diameters from a few inches to over one hundred feet [Section 8.1]. (But a *phased-array* antenna has no moving parts. It steers its beam by combining the radiation of many small, fixed antennas whose time phases are electronically varied.)

1.4.6 Radio Waves

Short- and long-wave radio transmitters use mechanically adjustable inductors and capacitors, some of quite large physical size. Some communication antennas for satellites and deep-space probes resemble large radar antennas. Some satellite and probe antennas are themselves EM unfurled and aimed.

1.5 NUCLEAR RADIATION

Radiation from nuclear fission comprises electro-magnetic radiation, electrons, and isotope particles (both ionized and non-ionized.)

Many EMDs are used with nuclear radiation, for example:

1. Control rod positioners and the *scram* electro-magnets that release control rods in nuclear reactors
2. Remote manipulators in *hot* rooms
3. Conveyors for mail or luggage in detectors for terrorist bombs and for foods being sterilized by nuclear radiation
4. Experimental portable detectors for land mines

Magnetic resonance imaging (MRI) medical diagnostic imaging uses no nuclear radiation at all but depends on the resonant frequencies of hydrogen nucleii (protons) oscillating in the patient's body. Large electro-magnets and EM patient manipulators are parts of the system. (MRI, Magnetic Resonance Imaging, used to be called Nuclear Magnetic Resonance Imaging, NMRI. Medical terminology now omits the word *nuclear* because, after the Three Mile Island accident, many patients fear anything involving nuclear phenomena. The *nuclear medicine* profession suffered a major reduction in its practice.)

1.6 PIEZOELECTRIC AND MAGNETOSTRICTIVE EFFECTS

Another kind of electric voltage generation and force generation by electricity is *piezoelectric.* Certain crystals and ceramics, when stressed mechanically in certain directions, generate electric voltage between certain surfaces. Conversely, when electric voltage is applied to those surfaces, mechanical stresses and corresponding strains (displacements) are produced in the crystals and ceramics.

One of the most useful of these materials is quartz. When electro-plated surfaces of a quartz crystal are connected to an appropriate electronic circuit, the crystal oscillates *mechanically* and establishes an extremely stable natural frequency for the circuit. Wristwatches, computers, and radios use such oscillators [Section 7.7.2].

Another particularly useful piezoelectric material is the ceramic, barium titanate. It is used in ultrasonic devices ranging from sonar to welders for plastics.

Magnetostriction is a magnetic dual of piezoelectricity. It is the shortening of certain materials in a magnetic field. Nickel is such a material. The effect has been used to adjust, with fine resolution, a massive center-less grinder [A34].

1.7 ELECTRO-STATIC EFFECTS

Electric charge can be stored without current flowing. The ability to store a charge is called *capacitance* and the devices to do so are *capacitors* [Section 18.2]. When charge is stored in a capacitor, electric voltage appears between its terminals.

Electro-static voltages are produced by friction between dissimilar insulating materials, by moving a body close to an existing electric charge *(electro-static induction),* and by connection to an electro-dynamic voltage source such as the generators described above that comprise AC voltage, a high-voltage transformer, and a rectifier.

Extremely high voltages are produced by mechanically spreading apart positive and negative charges. This occurs in nature when air currents charge clouds that then discharge as lightning; it occurs in the laboratory in EM machines such as the Van de Graff generator [Chapter 3] that uses a moving belt to spread apart charge, and it is produced by turning rotors of insulating material.

Electro-static voltage is used in EM dust precipitators, in xerographic photocopiers and laser printers, and for accelerating and steering electron beams in cathode-ray tubes and other vacuum tubes.

Electro-static motors can be made by applying voltage to electro-static generators. An electro-static motor has been made on a microminiature scale by etching shapes in semiconductor material. No coil winding is needed.

1.8 ELECTRO-EXPLOSIVE EFFECTS

Electric currents are used to ignite explosions by sparks in internal combustion engines and by hot wires in other explosives.

There is a large class of *powder-operated devices* in which a small explosive charge does useful work. Among such tasks are breaking a bolt in which the charge is embedded and moving a piston to drive a cable cutter. Many such devices are electrically detonated from a remote control or from an automatic circuit. Such devices are widely used to deploy parts of a satellite after its launch.

In industry, blasting explosives are detonated by a hand-powered generator to prevent accidental connection to a continuing electrical power source such as a battery.

The energy in an electrical discharge from a large capacitor is itself a kind of explosion. Lightning is one example, and the electric rail gun and the electro-magnetic forming machine are others [Chapters 13, 15]. Electro-magnetic pulses (EMP) from nuclear explosions are duplicated by such discharges to test the effects on electronic circuits.

Many EMDs are used in military safing, arming, and fusing devices [Chapter 15].

1.9 ELECTRO-THERMAL EFFECTS

Electric current generates heat in solids, liquids, and gases. The heating current may enter by conduction, or be driven by induction, or be displacement current between capacitor plates. Electric heating is produced by:

1. Current through resistance (solid, liquid, or gas)
2. Bombardment of arc electrodes by electrons or ions
3. Hysteresis in magnetic materials
4. Induced eddy currents in conducting materials
5. Dielectric loss in insulating materials

Heat from these effects is transferred to other bodies by conduction, convection, and radiation.

Electric ovens, spot and arc welders, electric furnaces, induction heaters, plastic welders, medical diathermy machines, and incandescent lamps use these effects.

Electric current also *extracts* heat in certain material junctions, providing a kind of refrigeration.

Conversely, heat generates electric voltage in junctions between different metals; such *thermocouples* are used as thermometers, measuring temperature indirectly by measuring voltage. Stacks of such junctions *(thermopiles)* are used as electric power generators.

Temperature affects electrical resistivity. This effect is used in resistance thermometers.

1.10 ELECTRO-CHEMICAL EFFECTS

EMDs, particularly sensors and sensor-controlled systems, use a variety of electro-chemical effects. The most commonly used sensor is the *pH electrode* that is measuring the acidity of a solution, but there are many other electrodes sensitized to other parameters.

Primary and secondary batteries power EMDs. Today's big hunt is for electric car batteries, primary or secondary, that are small, lightweight, capable of widely variable discharge rates, easily and quickly recharged with either electricity or fuel, non-polluting, safe, and cheap. The present art of electronic motor control makes the remainder of the electric car problem easy.

Electricity and chemistry are teamed in many processes including electro-plating and metal refining. Chemical plants use electrical transducers, control circuits, switchgear, and electrically powered pumps. Electrically powered proportional valves have not yet overcome the competition from pneumatically powered proportional valves, so many control systems are electro-pneumatic.

1.11 ELECTRO-BIOLOGICAL EFFECTS

Our bodies generate voltages which are sensed, recorded, and used by EMDs. For example, the *electro-cardiograph* is an EM recorder of the voltages that control the heart; the *electro-encephalograph* records brain activity; and the *electro-myograph* measures voltage signals in nerves.

Electric voltages applied to the body affect its processes in a variety of ways. For example:

1. The *cardiac pacemaker* generates voltages that control the heart. (Nominally, pacemakers have no moving parts, but the flexible conductors extending to the heart have severe EM problems.)
2. Electric voltages are used in pain-reduction therapy.
3. High frequency voltage produces *diathermy* (internal heating).
4. Electric current accelerates fracture healing.
5. Electric current cauterizes a cut blood vessel in surgery.
6. Shock: Some electric shocks *defibrillate* heart muscles, and others cure certain mental illnesses. Accidental electric shock, for example lightening, can kill. Dictators use electricity to torture their victims. You already know about the electric chair. Slaughterhouses electrocute incoming animals for painless death. Low-level shocks were once used as a mode of entertainment.

The patent office records many, many efforts to help the human body by applying voltage to it.

Lasers are used in diagnosis and surgery; EMDs manipulate lasers and their radiation.

X-rays are used for both diagnosis and therapy. EMDs are used to manipulate the X-ray tube, the film, the fluoroscope, and the patient.

Electric currents induced in the body by the magnetic fields from power lines and transformers are suspected of being carcinogenic. Designing these devices to minimize their external fields is an EM problem. Similar effects are suspected from the Navy's ELF (Extra-Low-Frequency) high power radio transmitter for communicating with submarines; its very long antenna is buried just below the surface of the ground.

Nerve voltages command EM prostheses.

Biological and medical laboratory instrumentation uses many kinds of EMD, such as automatic sample manipulators in analysis machines [Chapter 16].

1.12 ELECTRICAL-MECHANICAL ANALOGS AND ANALOG COMPUTING

Many electrical and mechanical equations are mathematically identical. For example, the current produced by a constant voltage applied to an inductance has the same linear rise with time as the speed produced by a constant force applied to a mass. The two cases are *analogs.* A pair of analogs is sometimes called a pair of *duals;* inductance and inertia are duals. An internal combustion engine fueled by gasoline is a dual of an electric motor powered by a storage battery. A set of analogous parameters is as follows:

ELECTRICAL	MECHANICAL
Voltage	Force
Current	Speed
Charge	Displacement
Inductance	Inertia
Capacitance	Elasticity
Resistance	Viscosity (also friction, but friction is non-linear)
Time	Time
Power	Power
Energy	Energy
Frequency	Frequency
Strength (Dielectric)	Strength (tensile, compressive, shear)
Natural Frequency	Natural Frequency

Hysteresis exists in both fields. In electricity, it appears in magnetism; in mechanics, it appears in backlash and stiction.

An electric circuit can be designed to behave as an analog of a mechanical device, using the proper conversion constants and scaled with respect to time and magnitude. Thus a small, fast, electric circuit can quickly *simulate* the behavior of a large, slow, mechanical or thermal system. Such a circuit is a *direct analog computer.* The technique was once used but was replaced, first, by other forms of analog computer (below) and then by digital computers.

It is often useful to make a sketch or mental image of a direct analog computer to aid in thinking about a mechanism.

A more sophisticated form of electronic analog computer uses *operational amplifiers* to add, differentiate, and integrate. It uses EM servomultipliers and EM sine/cosine generators for trigonometric functions. Using the computer starts with writing the differential equations of the system to be simulated and continues with hooking up computing components to match the equations.

In the servo multiplier of Fig. 1-4, potentiometer 1 has brush 3 driven by servo 2. Output voltage X is proportional to input voltage Y times servo command voltage Z; $X = Y \times Z$.

In the sin/cos generator of Fig. 1-5, a special potentiometer comprises a square card 1 on which is a uniform resistance winding 2. Voltage V is applied to the winding. A set of four brushes is rotated by a servo whose input voltage is proportional to θ. The output voltage between brushes S1 and S2 is proportional to $V \sin \theta$, and the output voltage between brushes C1 and C2 is proportional to $V \cos \theta$. A two-phase synchro does the same thing with AC voltages.

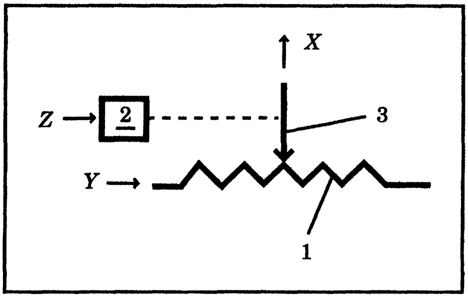

Figure 1-4 Servo Multiplier

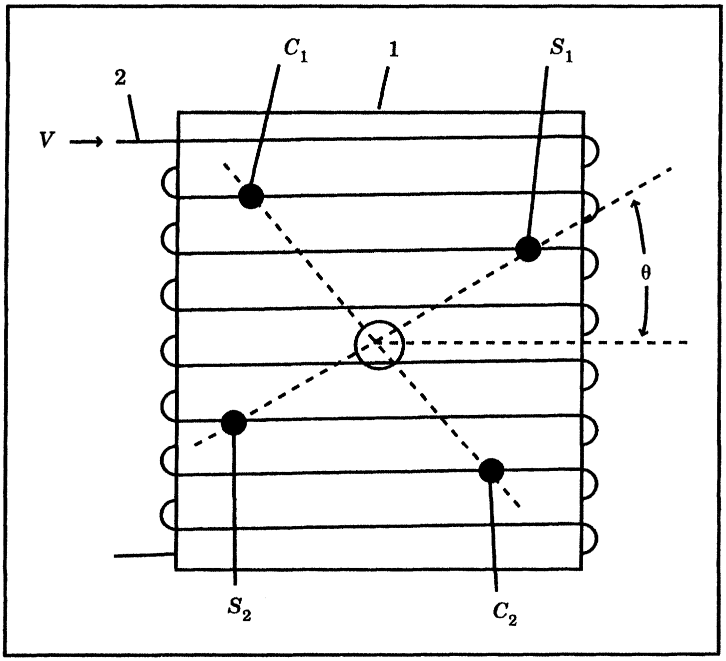

Figure 1-5 Sin/Cos Generator

Before electronic operational amplifiers were available, EM analog computers used integrating discs, Fig. 1-6. Disc 1 is driven by servo 2 at a speed commanded by input voltage Z. Disc 3 is driven by friction by disc 1 and is positioned radially by command input voltage Y, servo 9, lead screw 8, nut 7, and yoke 6. Disc 3 slides along output shaft 4 and is keyed to it so that shaft 4 rotates with disc 3. Shaft 4 turns transducer 5 that generates output voltage X.

$$X = \int Y\,dZ$$

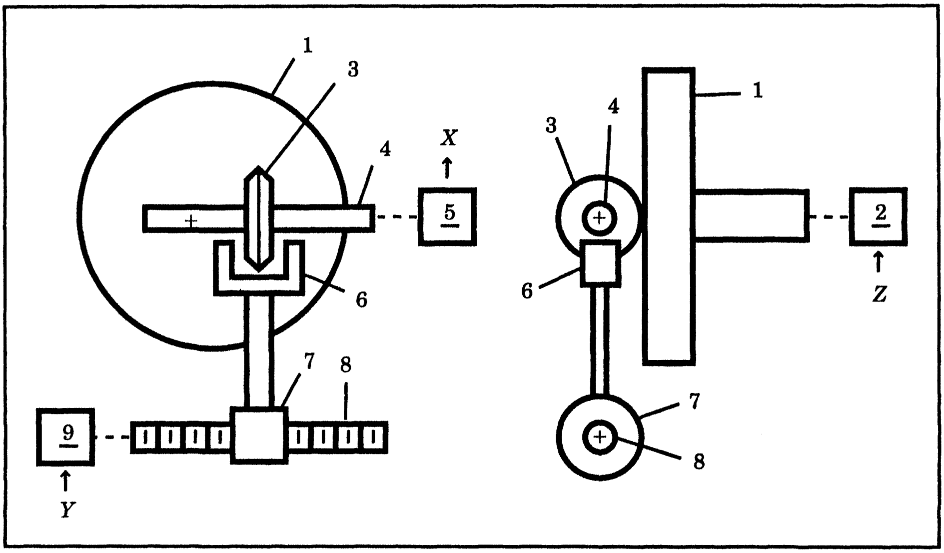

Figure 1-6 Integrating Disc

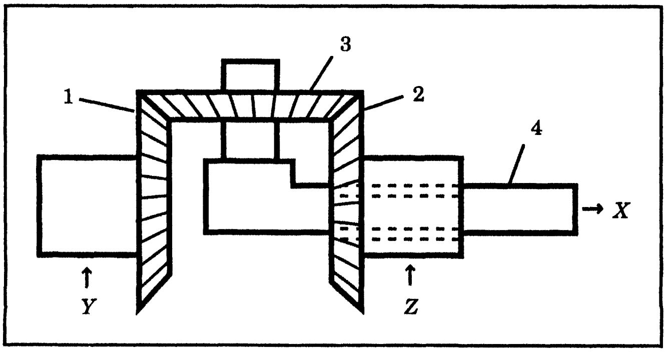

Figure 1-7 Differential

Addition and subtraction were done with gear differentials, Fig. 1-7, similar to a car differential. Output gear 3 is turned by a combination of input gears 1 and 2 and delivers its motion by shaft 4 extending through the hollow shaft of gear 2. Inspection of the figure will show that $X = ½ (Y + Z)$.

Non-analytic functions were stored on two- and three-dimensional cams or as relay-switched voltages.

There are pneumatic analog computers still used in industrial control systems in which air pressure and flow are used instead of electric voltage and current. They have the unique advantages that air pressure on a large diaphragm provides a cheap and reliable means to operate a control valve, and that pneumatic systems cannot trigger explosions in explosive environments.

Digital technology has replaced most analog computing with digital computing, so most EM computing devices are now obsolete. They are described here because the principles are interesting and may be revived, perhaps by yourself, in some new device.

1.13 DIGITAL COMPUTERS

There is a proliferation of databases, computing programs, and computer hardware useful in EM engineering. The programs include *finite element analysis* (FEA) programs for magnetic and electric fields [A10], heat flow and fluid flow fields, and mechanical stress fields. Formerly, except for simple cases, these were only roughly approximated, or subjected to very difficult mathematical analysis, or left to judgment and test.

Computer-aided drafting (CAD) is now commonplace. Many CAD programs include some mathematical calculations, justifying the translation of CAD to *computer-aided design* and the abbreviation CAE for *computer-aided engineering* [A36, A37].

Many EMDs are used in digital computers and are described later in this book. These include:

- Magnetic cards and readers
- Hard disk drives
- Floppy disk drives
- Tape drives
- Keyboards
- Switches
- Cables and connectors
- Printers
- Plotters

- Drawing digitizers
- Mouses (Mice?)
- Fans

Literally, "digital computers" include the ancient abacus (still used) and mechanical adding machines (obsolete). The first programmed digital computer was entirely mechanical, built in England in the nineteenth century by Professor Charles Babbage but not finished until recently [A21]. Experimental pneumatic digital computers with no moving parts have been built but have not been commercially successful. Pneumatic digital logic devices with moving part valves have some commercial success where their high temperature and radiation resistance and their safety in explosive environments give advantage over electrical systems. Pneumatically and hydraulically operated power valves provide logic control in fluid power systems. In present usage, *digital computers* means only electronic machines [Chapter 10].

1.14 COMMUNICATIONS

For many generations of development, until modern digital electronics came to the fore, all telegraphy and telephony were entirely EM. Even now, much EM engineering is used in the most modern communication systems.

Before Samuel F. B. Morse's invention of the telegraph in the 1840s, communication at a distance, *telecommunication*, used the following techniques, that need no detailed explanation here:

1. Human messengers, including postal systems
2. Carrier pigeons and dogs
3. Visuals (the first digital technology):
   - Semaphores [A52]
   - Smoke signals
   - Fires ("One if by land, two if by sea")
   - Rockets (one or more; different colors; still used with Very pistols)
   - Coded flags (still used by navies)
   - Hand signals (still used by infantries and by baseball catchers)
   - Heliographs
   - Blinking lights (still used by the Navy)
   - Others (for example, at Waterloo, Wellington galloped back and forth waving his hat to order the counterattack)
4. Sounds:
   - Bells, whistles, horns, sirens, buzzers, gunshots

- Speech via shouts, megaphones (now EM bullhorns), speaking tubes

5. Mechanisms:
   - Ropes, chains, shafts, push/pull rods, linkages. All are used to this day in railroad yards to move semaphores and rail switches from levers in control towers.
6. Hydraulics:
   - Analog displacement in hydraulic tubing
7. Pneumatics:
   - Message conveyor carriers and tubes
   - Analog pressure transmitted through tubing (still used in chemical plants and in some commercial building thermostats)

Morse's telegraph introduced instant long-distance electrical communication using digital codes. Early transmitters, relays, receivers, and printers were entirely EM. Most have gradually been superseded by electronics. The final receiver is now either a cathode-ray tube or an EM printer, and the initial device is an EM keyboard.

Telegraphy extended communication from the original person-to-person to include:

- Person-to-person *(telegraphy):*
  - E-mail consists of telegrams from personal computer to personal computer. It is much less expensive than earlier telegraph communication.
  - Facsimile (FAX) is telegraphy by raster scan instead of alphanumeric codes.
- Machine-to-person *(telemetry)*
- Person-to-machine *(remote control)*
- Machine-to-machine *(automation)*

Alexander Graham Bell, in the 1870s, extended digital telegraphy to analog telephony. Transmission of speech was then extended to transmission, first, of still pictures and then of moving pictures, *television.*

Telegraph and telephone signals were conducted first by electric current in open or twisted pair wire, then by coaxial cable or radio (some radio is via satellite and some is on microwave links), and now by light in optical fibers. For short distances, for example, amplifiers for theatergoers and for TV controllers, IR radiation is used.

The telephone originally used sound-modulated electric current. Now that analog technology has been replaced for long distances by digital technology, sound is sampled, digitized, and transmitted by what is essentially high-speed digital telegraphy [A22].

1.15 SOLID-STATE DEVICES

The first solid-state devices were rectifiers and photoelectric cells, with selenium as a principal material. (Photoelectric selenium is still the key material in photocopiers and laser printers.)

Marconi used a *coherer,* in which particles moved under the influence of radio frequency (RF) voltage, as his detector.

A galena crystal (lead sulfide) with a *cat's whisker* electrode was the detector diode in early radios.

The triode vacuum tube started the avalanche of electronic technology.

When the three-terminal transistor was invented, modern electronics exploded. Plates of pure silicon, *substrates,* have transistors, diodes, photodiodes, lasers, light emitting diodes, and integrated circuits built on them in two or more layers, using advanced photolithography. The manufacturing technology for solid-state devices is surveyed in [Sections 2.11.1 and 2.11.2].

Mechanically flexible solid-state devices are used as transducers [Chapter 7].

1.16 CIRCUITS, FIELDS, AND NON-LINEARITY

Many mechanical phenomena are much more complex and non-linear than most electrical phenomena. Many are three-dimensional *field effects,* such as the stress distribution in a non-uniform part, rather than two-dimensional *circuit effects.* Others, such as friction, are fundamentally complex. Therefore, many are described with only approximate mathematics and much pragmatism, while many electrical phenomena, being physically simpler, can be described by exact equations. Magnetic fields, particularly with portions in iron, electro-static fields, and electric current fields in conductors of complex shape, share the complexity of mechanical fields.

Fields bounded by certain geometric shapes are analytical. Among these are the electrical and magnetic fields around parallel cylindrical conductors, inside coaxial cables, and inside rectangular waveguides. Accurate mathematical descriptions of many mechanical, thermal, electric, and magnetic fields exist but are too complex, and therefore too expensive, for most engineering work. We have become fortunate in that computer programs now attack many such problems both by finite element analysis and by solving complex mathematical equations.

We have seen the distinction between electrical and mechanical phenomena begin to blur. Now we go on to primarily mechanical phenomena.