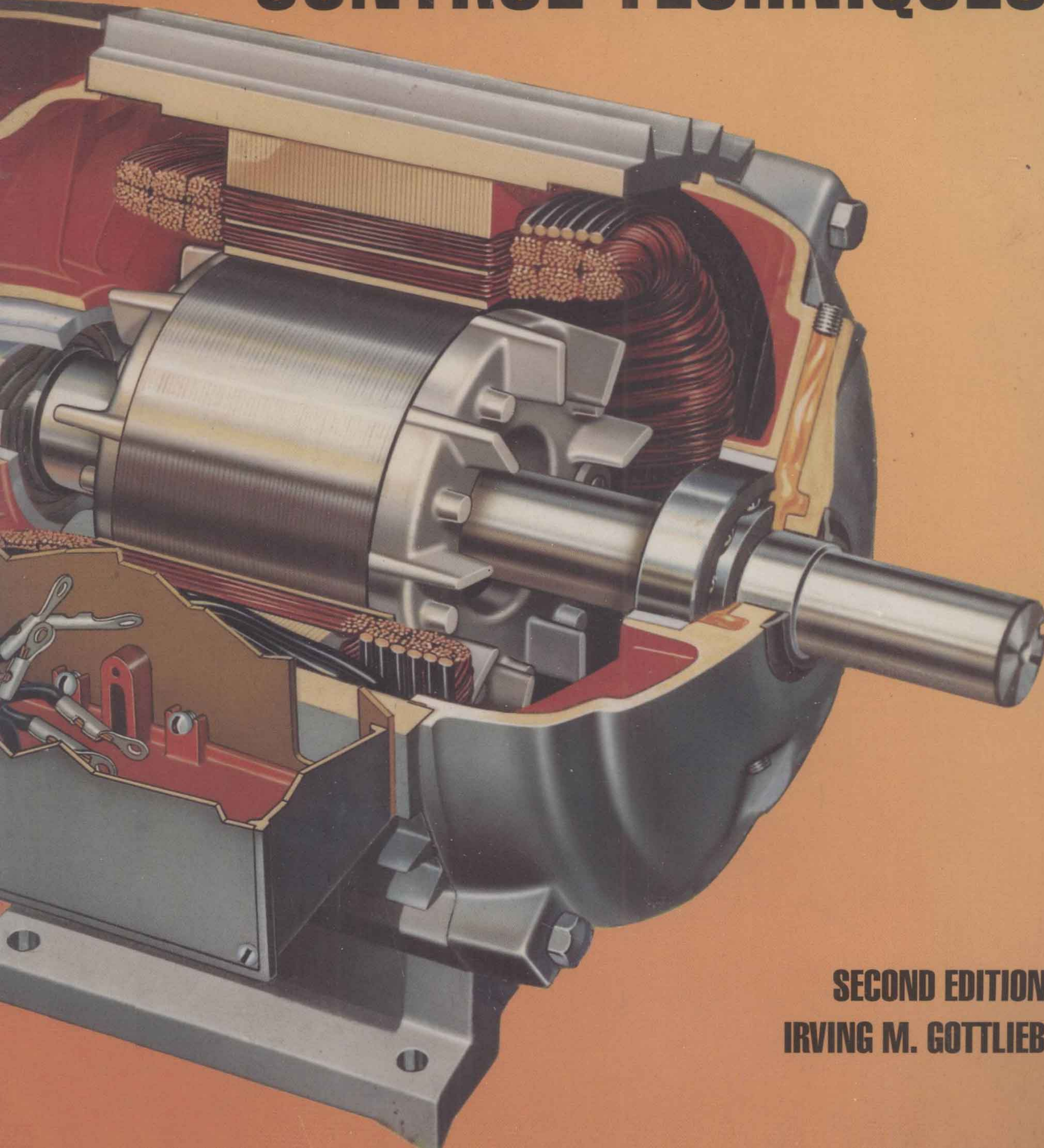
ELECTRIC MOTORS AND CONTROL TECHNIQUES



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IRVING M. GOTTLIEB

Electric Motors & Control Techniques

2nd Edition

Irving M. Gottlieb

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Introduction

FROM SHIPS TO TOYS, FROM STEEL MILLS TO PHONOGRAPHS, AND WHEREVER ELECTRICAL energy has teamed with mechanical motion, the impact of solid-state electronic control of electric motors has made itself felt. It is true that antennas were rotated, tools were driven, and vehicles were electrically powered prior to the advent of thyristors, power transistors, and sophisticated integrated-circuit modules. However, the improvements in precision, flexibility, reliability, and controllability have been so great with the new devices and techniques, that we find ourselves involved with a new and fascinating aspect of technology.

Electric motors, generators, and alternators (the so-called "dynamos" of yesteryear) assumed their roles as industrial "workhorses" during the latter portion of the previous century and the early part of this century. Surprisingly, a perusal of texts dating that far back can still yield useful information about starting, stopping, reversing, and stabilizing such machines. But continued reliance on these venerable methods can only lead to technical obsolescence of machines and techniques. A new era of motor control exerts new demands and, at the same time, stimulates new challenges and provides new opportunities.

When both power engineering and electronics were still in their early stages, those with bold imaginations perceived the potential benefits that might result from a merger of the two arts. A formidable deterrent to such mutuality between these two electrical disciplines was the unreliability of then-available electronic devices and components. During the 1930 to 1950 interim, the electronic control of motors did make some headway as better tubes and components became available for such applications. In particular, *thyratrons* and *ignitrons* attained popularity. It became feasible to electronically control the speed of fractional-horsepower machines and, to some extent, larger integral-horsepower machines. Significantly, some of these circuit techniques are clearly recognizable as the predecessors of present-day solid-state controllers.

This obviously brings us to the solid-state chapter of electronic evolution. Initially, the invention of the transistor sparked a number of application efforts. With the soon-to-follow development of power transistors, the direct control of larger electromagnetic devices became possible. Also, the introduction and quick commercialization of *thyristors* enabled the precise and efficient control of very large motors. Now, a plethora of solid-state devices have become available for arriving a wide range of motor types and sizes; these include silicon NPN and PNP power transistors, N and P channel power MOSFETs, power Darlingtons, germanium power transistors, IGBTs, GTOs, MCTs, and power op amps.

So much for the muscles for motor-control systems. Fortunately, technological-evolution has also provided us with the brains to actuate these muscles in coordinated precision. No end of dedicated ICs have been developed to time, automate, manipulate, and protect these motor-control systems. Both analog and digital techniques are used; excellent control and regulation of motor operational-parameters can be realized without extensive development-projects, or wasteful cut-and-try activities.

The motors, too, have participated in this evolution. The traditional motor-formats, although remaining useful, have to a considerable extent given way to types relying less upon mechanical commutation or conventional single or polyphase power, but much more upon timed-pulses from the alluded "brainy" control-ICs. Such motors exhibit attributes of the long-enduring dc and ac motors, but also possess unique advantages of cost, reliability, and controllability.

The foregoing matters lead very naturally to the final chapter of the treatise dealing with electrically-powered automobiles. Therein, I endeavor to resolve some of the controversies that have long plagued this area of electric-motor application. Interestingly, all of the preceding chapters bear relevancy. The propulsion of the electric auto can be provided by dc or ac motors, and by traditional or new-age motor formats. This stems from the versatility of the aforementioned dedicated control-ICs.

Regardless of specific areas of interest, if you are technically-inclined, you should find useful guidance to practical implementations of electric motors and their control, but I hope that this book will also stimulate rewarding, experimentation and creativity.

The following individuals and firms deserve thanks for their assistance and for their contributions of electronic-control circuits and systems for electric motors: Michael Apcar, President, Randtronics, Inc.; Michael P. Brown, President, ELECTRO AUTOMOTIVE; W.C. Caldwell, Distributor Sales Administrator, Delco Electronics; Walter B. Dennen, Manager, News and Information, RCA; Robert C. Dobkins, Manager of Advanced Circuit Development, National Semiconductor Corp.; Norbert J. Ertel, Marketing Analyst, Bodine Electric Co.; Forest B. Golden, Consulting Application Engineer, General Electric Co.; Alan B. Grebene, Vice President, Exar Integrated Systems, Inc.; Frank A. Leachman, Media Manager, Superior Electric Co.; Larry Steckler, Editor-in-Chief & Publisher, Gernsback Publications, Inc.; Lothar Stern, Manager, Technical Information Center, Motorola Semiconductor Products, Inc.

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1 Reconsiderations of basic motor and generator action

THE APPLICATION OF ELECTRONIC CONTROLS TO ELECTRIC MOTORS AND GENERATORS has the appearance of a mere merger of two somewhat divergent practices of a common engineering discipline. It is, however, much more than this! It taxes the ingenuity of the practical man and challenges the imagination of the theorist. Indeed, such a merger has evolved as an excellent illustration of applied science. For instance, one might consider such recent innovations as motors with superconducting field magnets, homopolar machines with liquid-metal contacts, magnetohydrodynamic generators, commutatorless dc motors, printed-circuit motors, levitated induction drives for transport vehicles and, of course, the application of solid-state devices to all types of electric machines.

The nature of the new control techniques

As the author, I assume in this book that you have at least a basic knowledge of electrical and electronic devices. Accordingly, I will not attempt to duplicate the contents of the other books already available on electricity, magnetism, and electronics.

This chapter explores the known, with deliberate intent to invoke the unknown. It touches on elemental notions to show how accepted principles band together to produce useful hardware. Basic questions are raised, but the very contemplation thereby initiated will, in *itself*, constitute my objective. From this study, I hope you will realize that electric machine technology, though rooted in the past, is destined for a profuse blossoming in the future.

Let us commence with a discussion of a feature *common to all motors that convert electrical to mechanical energy*—the phenomenon of action at a distance.

Action at a distance

One example of this phenomenon, which greatly perplexed yesterday's scientists, is that of a ferromagnetic object being physically acted upon by magnetic force. Forces other than the magnetic kind also act upon objects or entities separated by a distance. Here, I can think of electrostatic, gravitational, molecular, and nuclear forces. Electromagnetic waves, such as radiant light, might well be included, and there are undoubtably others. For example, those versed in parapsychology often allege that physical objects can, under some circumstances, be acted upon by force fields emanating from the mind. Although the manifestations mentioned are apparently diverse, they incorporate a common feature—*action at a distance without need for an intervening medium.* It was this latter aspect that inspired the postulate of the "ether." Supposedly, the ether was everywhere but it was elusive because of its tenuous nature—it had a viscosity of zero! Although endowed with the properties of "nothingness," it served as the medium of transmission for light and other electromagnetic radiation; that is, it supported wave motion. The static forces exerted by magnets, by charged bodies, and by gravitation were not so glibly explained. Then, and now, such forces were simply ascribed to "fields" and the role of the ether was somewhat more nebulous.

The mathematicians next extended the concept of the field and endowed it with properties of *self-propagation*, which eliminated the need for the ether. This new concept came at a favorable time, because experiments carried out to detect the presence of the ether were not successful. Besides, whether one comprehended the mathematics or not, the notion of radiant energy traversing the vacuum of space did not stretch the imagination any farther than the elder hypothesis. Fortunately, the mathematical descriptions provided by Maxwell's equations and by other theories dealing with fields, harmonized with experimental investigations and facilitated the development of practical devices. Nonetheless, the imaginative mind remains undecided over the part played by the intervening space when any type of force exerts influence over a distance. If the influence manifests itself over a gap of true "nothingness," does this imply the propagation of particles of some sort between the source of the action and that which is acted upon? This, too, was given much thought by many brilliant minds. And, like the ether, we find that the emitted particles are still with us, but dressed in a new style. For example, the prevailing concept of the *photon*, the elemental carrier of radiant energy, postulates a rest mass of zero. Thus, the ghost of the extinct ether returns to haunt us!

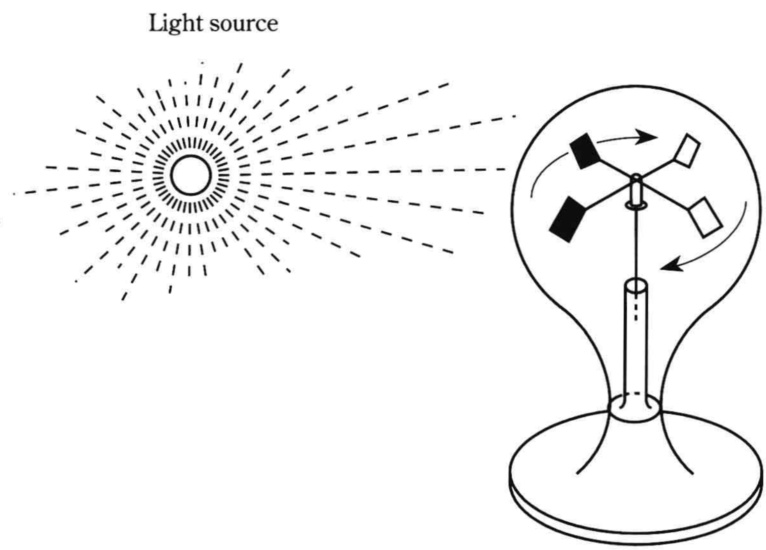
There is considerable scientific speculation that gravity, magnetism, and the electric field are somewhat different manifestations of a *universal* law of nature. The coupling between magnetism and moving electric charges is evidenced by electric motors and generators and by the myriad devices that exploit the phenomenon of electromagnetic induction. It is easy to assume a matter-of-fact attitude regarding the relationships between electricity and magnetism. However, it is instructive to reflect that these "simple" facts of technological life eluded the scientists of the nineteenth century until they were experimentally observed and interpreted. In one case, Hans Christian Oerstead recognized the significance of the deflection of a compass needle by a current-carrying wire. In the other case, Michael Faraday was seeking a relationship between *steady* magnetic fields and electric currents in stationary conductors. Although he found none, he recognized the significance of currents induced in certain situations where relative motion existed between the magnetic field and the conductor.

In our era, the assumed relationship of gravity to electricity and magnetism has thus far been quite elusive. Despite the powerful concepts of *relativity* and *quantum physics*, the relationship between gravity and other forces does not appear to be strong. But perhaps history will repeat itself—a surprise observation might one day be made of an unsuspected cause-and-effect relationship that will shed a new light on the nature of gravitational force. Actual experiments are already being carried out to detect and explain "gravity waves." It is known that gravitational force does not communicate its influence instantaneously. Like the forces of magnetic and electric fields, gravitational influence cannot propagate through space faster than the speed of light. And the force associated with the gravitational field, like that of the magnetic and electric fields, diminishes inversely in proportion to the square of the distance between two bodies, poles, or charges. Unlike the force fields of magnetism and electricity, gravitational force produces only attraction, never repulsion between bodies! Although this subject has been a favorite for science-fiction writers, the quest for a method of reversing, or neutralizing, gravity is by no means the exclusive indulgence of those who deal in fantasy.

Just as practical motors and generators have been profoundly influenced by research in cryogenics and superconductivity, solid-state theory, plasma physics, and materials technology, subsequent progress in the development of a unified field theory can be expected to manifest itself in improved hardware and new control techniques. Surely, the harnessing of basic forces is what motors and generators are all about!

Electrostatic force

Pretend that our electrical technology exists and that you have a good grasp of it but that, somehow, electric motors have not yet been developed. Given the assignment to create such a device, how might you proceed? A reasonable way would probably be to investigate forces capable of acting on physical materials of some kind. Then, you would think of some way to produce *torque*, or a *turning motion*. This would be an encouraging step, but the torque would also have to be continuous, so that a constant rotation would ensue. However, the mere attainment of this objective might not result in a practical motor. For example, the well-known novelty item, the *radiometer* (Fig. 1-1), converts the energy of incident light photons to kinetic energy

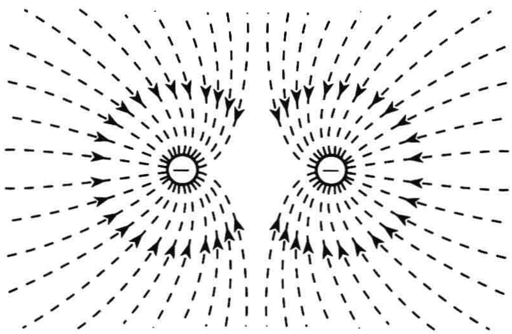


1-1 The radiometer.

by the rotation of its windmill-like blades. But only a feeble torque is developed in such a device. It would be futile to provide the radiometer with a shaft so that work could be performed. Perhaps such an approach might be put aside reluctantly because certain instrumental applications could be visualized. But for use in the environment, this type of "motor action" does not appear promising.

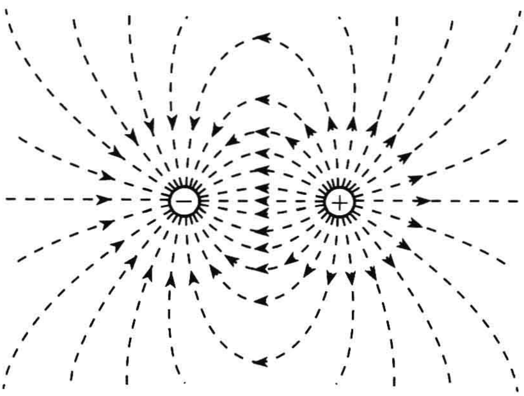
You might next consider electrostatic force. Figure 1-2 displays the field patterns of point charges. Figure 1-3 shows an *electrostatic voltmeter*. Here, the at-

A. A single point charge.

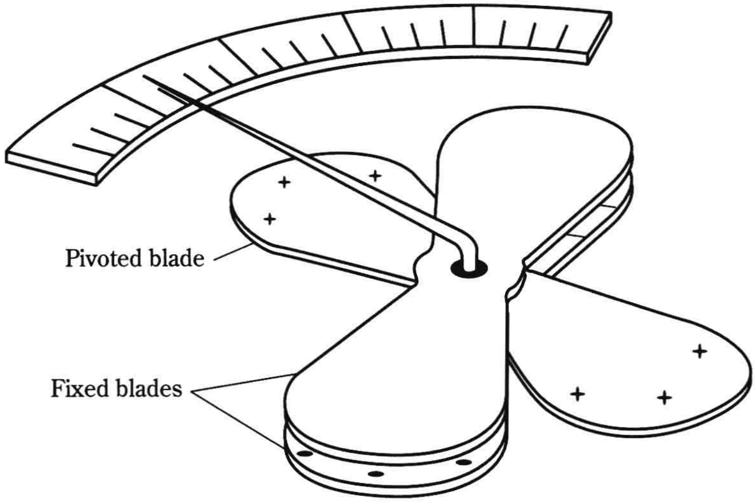


B. Repulsion between similar charges.

1-2 The field pattern associated with electrostatic lines of force.



C. Attraction between dissimilar charges.



1-3 The electrostatic voltmeter.

traction of unlike charges is evidenced as usable "motor action" in this device. To be sure, the rotation of the electrostatic voltmeter is not continuous, but perhaps this can be arranged. Of course, the torque developed by this meter movement is still woefully inadequate for the needs of industrial motive power. Maybe you would ponder whether an electrostatic motor could be devised to develop the turning power needed.

Consider a current of *one ampere*. Such a current is readily produced by small batteries and is safely carried by ordinary 18-gauge hookup wire. Now, one ampere represents the flow past a point of approximately 3×10^9 electrostatic units of charge per second. Because the charge of the electron is $4.8 \times 10_{-10}$ electrostatic units, it follows that one ampere corresponds also to 6.25×10^{18} electrons per second. This number of electrons is defined as the *coulomb*, so finally we say that one ampere of current flows in a circuit when the rate of charge is one coulomb per second. Apparently, the coulomb is *not* a wild concept described by fantastic numbers. In many ordinary electrical and electronic devices, you can expect to deal with currents ranging from several tenths to several tens of coulombs per second.

Using Coulomb's law, it is easy to show that if two metallic spheres, one centimeter in diameter and separated by one meter, center to center, could somehow be oppositely charged with one coulomb of electricity, they would develop the fantastic attractive force of approximately *one million tons*. The conditional "somehow" is well used, for the potential difference developed by such an electrified system would be in the hundreds of teravolts. Long before such an astronomically high voltage could be brought into existence between the spheres, a cataclysmic lightning flash would have disintegrated the apparatus. If you scale down the charges and alter the geometrical configuration of the spheres, or plates, the best that can be accomplished falls miserably short of what is easily, compactly, and economically achieved when the basic motive force is derived from the interaction of magnetic fields. Fractional-horsepower motors using electrostatic forces have been experimented with, but they require many tens of thousands of volts, involve critical insulation techniques, and show little indication of practicality.[1]

Although the idea of electrostatic force as the torque-producing source for motors was dispensed, there are many who remain intrigued with the fantastically powerful force fields of electrons. Among these people, the feeling prevails that perhaps a radically different technique might yet be found to use this elemental force of nature to directly produce mechanical rotation at power levels suitable for industry.

A possible spur to the development of electrostatic motors is the great stride that has been made in the transmission of very high dc voltage. Also, there are whole new families of insulating materials that were nonexistent some years ago when interest declined in electrostatic motive power. Of considerable relevance, also, is the recently attained state of vacuum technology. The future might hold some interesting surprises for those who view electrostatic motive power as a dead issue.

Consideration of the use of magnets to achieve motor action

The general practical aspects of magnets are now well known; the considerable forces of attraction and repulsion evident between the poles of strong magnets naturally suggest the possibilities of motor action. Not only do ferromagnetic materials have force fields available with reasonable shapes, they have *permanent* magnetization as an added dividend. However, if you did not know otherwise, it would be easy to cite reasons why the magnetization of magnets should be "used up" under certain circumstances.

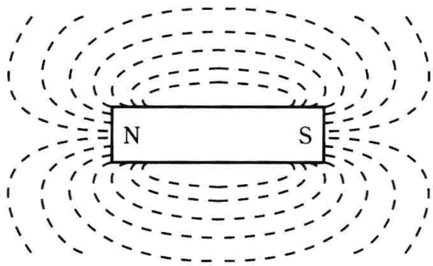
Magnetic lines of force surrounding bar magnets are shown in Fig. 1-4. The magnets behave as if such field lines had the following characteristics:

- Like poles repel; unlike poles attract.
- The forces of attraction and repulsion are the same when pole strengths, distances, and arrangements are the same.
- Pole pairs always exist in a magnet in such a way that one might say that the lines leave from a north pole and enter at a south pole. *There are no unipoles in practical magnets.*
- Lines of force *never cross*. In a space subjected to fields from more than one source, a *resultant field* is produced, having a density and direction determined by the directions and strengths of the contributing fields.
- In the case of repulsion, it is more correct to speak of field deflection than of neutralization. In other words, lines of force have their paths altered, but they are not destroyed.

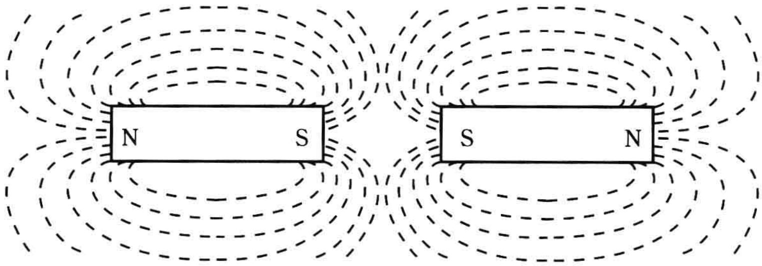
[1]Benjamin Franklin actually made an electrostatic motor! It produced rotation from the stored electrostatic energy in a Leyden jar. A modernized version of this machine developed one-tenth horsepower when powered from a 30,000-volt electrostatic generator. Electrostatic motors must also consume current to produce useful torque. The situation remains, as in Franklin's day, tantalizingly suggestive, but generally impractical.

- The lines of force surrounding a magnet mutually repel one another.
- Lines of force have been likened to rubber bands in that they seek the shortest path. A somewhat better statement would be that they seek the easiest magnetic path.
- Forces arising from magnetism obey the inverse square law.

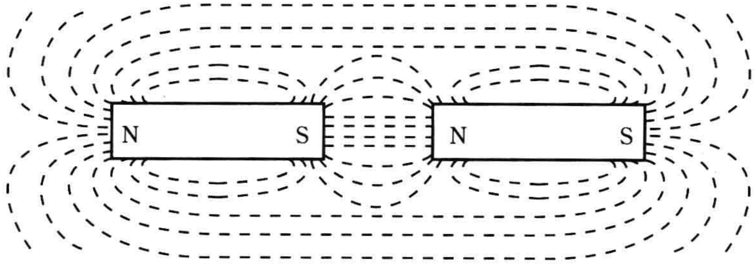
Interestingly, there have been reports of discoveries that the magnetic field has a *particle* nature. The search for the elusive *magnetic monopole* has apparently been rewarded with success. Although this can have tremendous ramifications for motor technology, the nature of practical implementations is not yet discernible.



A. A single bar magnet.



B. Repulsion of similar poles.



C. Attraction of dissimilar poles.

1-4 The field patterns associated with magnetic lines of force.