The Davenport Electric Motor: A look at how the First Electric Motor Can Teach the Fundamentals of Magnetism and Motion

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0.0 Introduction

Today, with the growing drive to move away from internal combustion technology and fossil fuels, the electric motor has become a focal point of modern science and technology. The electric motor is common in a wide variety of applications; from trains to cars to your smartphone; an electric motor can be found just about everywhere (Source). The growing use of electric motors in society has placed a great deal of emphasis on the education on its operating principles to both students and adults.

A great way to understand the fundamentals of the electric motor is to take a trip back to its beginnings, and its inventor, Thomas Davenport. Thomas Davenport was an early 19th century inventor located in central Vermont. He is credited with patenting the first practical direct current electric motor. Looking into Davenport's story can not only provide the reader with insight into the motors first days of infancy, but a basic understanding of a motor's fundamentals.

This paper is organized into three distinct sections to better explain DC electric motors. The first describes the historical context for the electric motor and Thomas Davenport. The second section elaborates on the physics of the motor: why does the motor rotate when connected to power? The final section of the paper describes the efforts taken to recreate the Davenport Patent Model Electric Motor and permanent magnets.

1.0 History:

1.1 Joseph Henry

Figure 1: Joseph Henry

1.1.1 Overview

Joseph Henry was an American scientist born December 17, 1797, in Albany, New York. From an early age he tinkered in engineering and science. At 13 he worked as an apprentice watchmaker and silversmith. With an initial dream to pursue theater, Henry was quickly convinced to pursue a more academic career after discovering a book of lectures on scientific topics titles "Popular Lectures on Experimental Philosophy." In 1819 he was persuaded by influential friends and enrolled at Albany Academy. Henry originally intended to go into the field of medicine but was recruited as an assistant engineer for the survey of state road being constructed between the Hudson River and Lake Erie. From then on, he remained in the engineering field. (Source).

In 1832, after some of Henry's discoveries in magnetism, he was hired as a professor of mathematics at Princeton University. He remained at Princeton until 1846. During his time at Princeton, he continued his research into magnetism and electricity making many discoveries relevant to most technology today. In 1846, Henry became the first secretary of the Smithsonian Institution in Washington, DC. During his time at the Smithsonian, he organized and supported a group of weather observers which would eventually lead to the creation of the U.S. Weather Bureau. In 1893, his name was given to the electrical unit of inductive resistance, the henry. (Source)

1.1.2 Key Scientific Discoveries

During his time at Albany Academy, Henry excelled at his studies. He often assisted his professors at teaching science. By 1826, he was appointed professor of mathematics at the academy. Henry grew interested in the concept of terrestrial magnetism. He quickly began experimenting with magnetism in general. Henry would eventually discover the phenomena of self-inductance.

Key inventions/discoveries:

- The Henry Electromagnet: Henry was the first scientist to wrap a large amount of insulated wire around an iron core forming powerful electromagnets. Others had experiments with magnetic effects from electric currents, but Henry was the first to apply the discovery. He built a number of electromagnets with his most famous being the Yale magnet. The Yale magnet was able to lift upwards of 2300 pounds, the largest at the time. Eventually, one of his magnets would be purchased by inventor and blacksmith Thomas Davenport. While experimenting with the electromagnet, Henry noticed a large spark when disconnecting the battery. This would lead to his next discovery
- Self-Inductance: While experimenting with electromagnets, Henry was the first to discover the idea of self-inductance. Self-inductance is the inertial characteristics of an electric current. Self-inductance tends to prevent the current from changing – if current is flowing, self-inductance tends to keep it flowing hence the spark when the circuit is broken.
- The "Telegraph:" as a demonstration to students, using an electromagnet, a high voltage battery, Henry was able to ring a bell from over one thousand feet away. The electric current from the battery caused the magnet to swing a bell. With improvements, Henry was eventually able to ring the bell from multiple miles away. The demonstration would become the precursor to the telegram and doorbell and lead to his next invention
- The Relay: When challenged with sending electronic signals over long distances for the "telegraph," Henry created a device which when activated would activate another circuit. The device allowed the electric signal to be sent over long distances in smaller manageable sections. He never published any formal details, but his idea would be passed to Samuel Morse who would eventually create the first practical communication system (the morse telegraph)
- Electric Motion Devices: Henry produced a simple device which can be noted as the predecessor to the modern direct current motor. The novelty contraption did not produce any useful work. It did contain all of the modern components of a DC motor but produced a simple harmonic rocking motion as opposed to rotational motion.

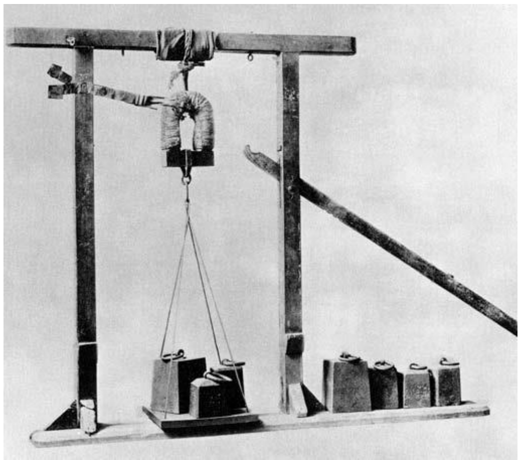


Figure 2: Henry's Electromagnet supporting various weights.

Henry as contributed to many more discoveries (weather/atmosphere and solar/astronomy) outside the scope of this paper. Further information on Henry and his discoveries can be found on the Princeton University Joseph Henry biography page here.

1.2 Davenport

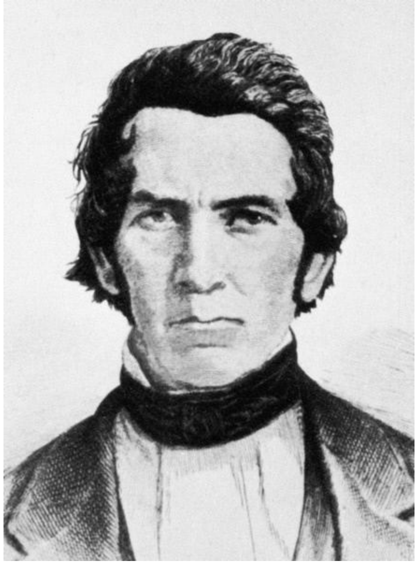


Figure 3: Thomas Davenport

Overview

Thomas Davenport was born in the year 1802 in the small town of Williamstown Vermont. His father passed soon after his birth which left him, along with the rest of his brothers and sister, to care for the family farm alongside his widowed mother. As a result, Davenport received little formal education, in fact, by Davenports own account he predicted less than two total years of schooling from birth to the age of 21. Davenport's career would begin at the age of 14 when he apprenticed for a local blacksmith.

Davenport would spend the next 7 years working as an apprentice for Enoch Howe in his blacksmith firm. During his time in the shop Davenport was exposed to the wonders of modern machinery. He witnessed "nature doing one's work for him." Additionally, while completing the daily tasks given to him, Davenport would spend his time reading and studying any book he could find. Thomas Davenport was a very imaginative person. He would spend his time thinking and exploring the objects around him. It was clear to see the beginnings of an inventor.

After completing his apprenticeship, Davenport settled on opening his own blacksmith practice in the town of Brandon, Vermont. With no money to his name, he made the 50-mile trek from Williamstown to Brandon and purchased the shop "on tick." The fact Davenport achieved this shows how independent the young inventor was. Davenport soon met his wife, Emily Goss, who would accompany and encourage his many experiments. For 10 years Davenport and Emily would live a typical life to support and pay for the shop. It wasn't until 1833 when Davenports great discoveries began.

During his time as inventor, Davenport would make a number of pivotal inventions in the use of electricity and magnetism including the first Direct Current motor, electric railway and many more. His inventions would draw the attention of many notable figures in science at the time as well as secure him a patent for his device.

Davenport would unfortunately die in 1851, at the age of 49 years, at his home in Salisbury Vermont. He leaves behind a legacy which powers the modern world.

Initial discoveries and the Henry Electromagnet

In 1833, Davenport quickly learned of a “galvanic battery” as he described, what he had discovered was the famed Joseph Henry electromagnet. Davenport was drawn by the claim the magnet could lift a blacksmiths anvil. Davenport, along with his brother Oliver made the journey to crown point and purchased the device with everything they had. Upon the return home, Davenport stripped the magnet down with his wife Emily documenting every step. Davenport was determined to recreate the device and to learn from it. It’s at this point we begin to see the level of curiosity and imagination from the inventor. Davenport quickly remade the device with a larger piece of Iron and more windings of wire. He used the silk from his wife’s wedding dress as insulation for the wires. The new magnet as described by his brother could “lift a ton a minute.” The statement is possibly an overexaggerating but none the less the new magnet was more powerful than the original. At this point davenport quickly began to realize the power at his control. He claimed, “If three pounds of copper and iron could suspend in the air 150 pounds, what would 300 pounds suspend?” At this point he even predicted the now “power” would one day propel steamboats. This revelation marked another key point in Davenport’s life.

Invention of the Electric Motor

With his new electromagnet and the premise of electric transportation, Davenport set out with his mission of putting the electric power to work. While experimenting with the magnet discovered one of the first key principles behind a direct current motor: power switching. Davenport noticed when he would hold the wires together with his fingers the magnet would work and when separated the magnet would not. Davenport discovered the very concept we rely on today to work our lights. At this time, Davenport made the acquaintance of fellow blacksmith Orange Smalley; a man interested in the electromagnet almost as much as Davenport.

Davenport and Smalley began to experiment with the magnet. Davenport had the idea of attempting to spin a wheel with the magnet. Davenport easily made the wheel spin with the magnet but found it impossible to turn the magnet off as the completion of a revolution. When about to give up, Emily came up with the idea of a conductor made up of “quicksilver” (mercury), to switch the current more rapidly. The idea had worked, as the wheel would spin, Davenport would energize the magnet at a specific time to keep the wheel spinning. Davenport demonstrated the basic principle behind the electric motor.

Following his initial test, Davenport created another iteration of the design. The new design featured four electromagnets on a common shaft – two of which were fixed. As the two free magnets rotated, the connections with the battery would be reversed causing the polarity of the magnet to switch. Davenport invented the first known “commutator” to be used in a motor. The commutator is at the heart of every brushed DC motor. The motor only held one drawback: cost. The primitive battery of the time consumed large quantities of zinc which was costly. Despite the drawback, Davenport realized it would be a long journey to reach the same level of practicality as say the steam engine.

Patent Application and Further Design

Davenport continued to refine his design from 1834 to 1836. Facing criticism from those around him for creating a “perpetual motion machine,” Davenport continued his research and make a number of discoveries along the way.

Realizing the potential for greater power out of the device, Davenport began testing by adding more magnets to the rotating components. Additionally, Davenport substituted the stationary electromagnets with permanent magnets to reduce power consumption. Had he the necessary resources, one can imagine the size of the device Davenport would have constructed. It was at this time Davenport began to seek out the advice and praise of scholars. He visited Middlebury college where the device received high praise from the professors. Davenport was advised to quickly file for a patent. Shortly after, Davenport while on his way to Washington D.C to file the first patent became acquainted with Professor Eaton of Rensselaer and Professor Henry, then working at Princeton University.

Each of the professors provided Davenport with important information regarding his device to which Davenport was grateful for. While Davenport was not a formally educated man himself, he grew very appreciative of a formal education. Following his meetings with each professor, Davenport continued on to Washington. Davenport was quickly turned away. His lack of plans and specifications resulted in the patent not being secured. Discouraged Davenport returned home to Vermont.

Discouraged, Davenport soon received a letter from Professor Eaton, Davenport was to bring his device to Troy and demonstrate it for a crowd of people. In exchange Eaton would give Davenport a small sum. With the encouragement of his wife and brother, Davenport set out to build the most refined version of his machine yet. His demonstration went exactly to plan, the motor had performed perfectly, and Davenport secured s strong relationship with Professor Eaton. In this time Davenport also fabricated his first practical device – a small model railway which would be powered by one of his motors. Despite the functionality of the device, it again received further criticism from his peers.

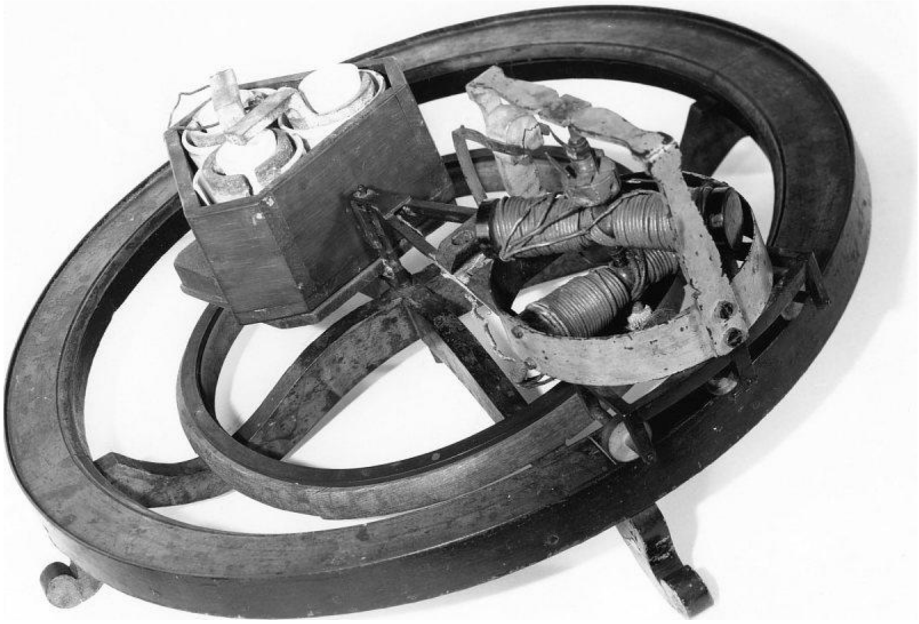


Figure 4: Image of the Davenport Model Railway. The little cart would be propelled around the circular track at “great speed” by the motor.

Despite the success in Troy NY with his motor, Davenport was met with much criticism from demonstrations of his railway in Dedham and Boston and soon returned to his home in Vermont, very little better off than before. He remained at home for a long while, in an attempt to rebuild some of the capitol he had lost over his recent adventures and to tend to the needs of his family. As put by his nephew in the biography of Davenport: “inventors have to eat too.” For the next few months Davenport would remain dormant.

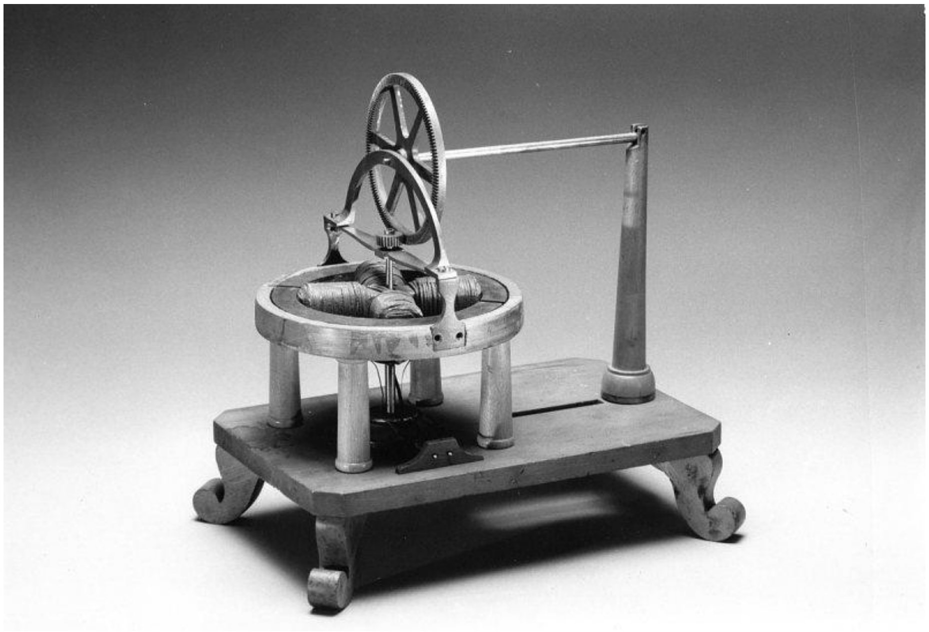


Figure 5: Davenport's patented electric motor model. This model was submitted along with Davenport's patent application. It now resides in the Smithsonian.

After a short while, in 1836 Davenport became acquainted with the entrepreneur Ransom Cook. The two quickly connected over the usefulness of such an invention. Cook while seeing its importance as a scientific discovery likely saw the financial opportunities as well. Following a fire at the Patent Office in Washington, DC, the two set out on the journey to rebuild a model and re-apply for the patent. Davenport filed his patent on January 7, 1837, and only 32 days later the patent was approved. Thomas Davenport had successfully filed the first patent for an electric motion machine in the United States.

End Of life

Following the successful filing of his patent, Davenport embarked with Cook to commercialize the motor. The endeavor failed to yield any tangible results due to mismanagement by their associated responsible for selling stock in the company. The duo was left with little money despite being promised "a large sum" from investors. Despite the loss and separation from cook, Davenport continued his studies with the little money he had left.

At this point Davenport was working in a small shop in New York. He was continuing to receive a fair number of visitors to see his inventions. One of his more notable visitors being Samuel Morse future inventor of the telegraph. Morse would receive great help from Davenport in regard to the device for Davenport had already been experimenting with the idea of sending messages over wires for some while. In fact, at the time of their meeting, Davenport had already figured a code for letters so only one conductor needed to be used to transmit messages. It can be said that Davenport invented the telegraph despite not receiving the patent.

Additionally at the time, Davenport sought to further spread information about his devices. His desire led to his next invention – an electric printing press. His papers quickly failed, as Davenport was an inventor - not a writer. Despite their failure, his papers still demonstrated the use of an electric printing machine, a machine still used today.

Thomas Davenport was a pioneer. From his initial curiosity with the electromagnet to his various inventions later in life Davenport always sought find new ways of achieving tasks and employ new powers to help him along the way. He achieved a respectable number of firsts – First to produce rotary motion from magnetism, first to demonstrate a working DC motor, first to receive a patent for the first motor. Thomas Davenport was the first in so many aspects it is impractical to list them all here. This fact makes his death more peculiar. Davenport was born a poor man and died a poor man. If his inventions were as monumental as described, why would he have no money to his name? Two main factors play into his poverty: at the time the world was not ready for his inventions. The cost to manufacture a device was to great and it did not yield much value to the industrial society. Secondly, Davenport failed to realize his device could be operated in reverse – generating electricity rather than consuming it. The legacy of Davenport continues on today and can be seen in nearly all electric powered devices in some fashion.

Figure 6: One of Davenport's original motors. Likely an early version based on the use of his Mercury cup commutator in at the base of the armature shaft. Not seen are the permanent field magnets which would rest on the supporting posts. For nearly 200 years old, the motor is in excellent shape. It is one of a handful known to currently exist and is currently part of a private collection.

For further reading on Davenport consider reading his biography, written by his nephew Walter Rice Davenport: Biography of Thomas Davenport, The Brandon Blacksmith: Inventor of the Electric Motor

1.3 Beyond the Davenport Motor – Electric Motors Today

Electric motors today play a super-critical role in society. Motors are everywhere – from cars to cellphones and everything in between – electric motors are at the heart of many objects we use. Notably, like Davenport predicted, electric motors quickly found their way into transportation and manufacturing technologies.

Throughout the late 19th and early 20th centuries, many mills switched from their conventional belt driven machines to ones powered by electricity. Electric motors quickly became the driving force of pumps, blowers, tools – nearly all machines in most factories (Source).

Figure 7: An advertisement to the “all-new” electric Sewing Machine. The electric sewing machine was much easier to operate and didn’t require a human for power. It is a great example of the introduction of electric motors into home devices.

Additionally, home appliances, such as food processors, vacuums, fans, etc. saw the introduction of electric motors. At the same time, electric motors found their way into transportation technology.

Streetcars, Subways, and long-distance trains began to use electric motors as their driving force to replace steam. A great example is the Northeast corridor – A section of rail which connects Washington DC to Boston. At the turn of the 20th century, the section between New Haven, CT and New York City was electrified. This section of track featured overhead “catenary” wires which would provide power to the electric motors in the trains. As of today, the entire Northeast Corridor is electrified. Fully electric trains run between Boston, MA, and Washington DC. The electric train was a key prediction of Davenport.

Figure 8: A New Haven EP-5 “Jet”. These electric locomotives would operate between New York and New Haven from the early 1950s through the 1970’s. At the time, the electrified line was revolutionary, and the New Haven was one of the first in its development. https://www.american-rails.com/ep5s.html

Many of Davenports early predictions and ideas for the motor have become a reality. The electric motor plays a critical role in our society and Davenport’s contributions to its construction and development cannot be dismissed.

2.0 Fundamentals of Operation:

Figure 9: An Amtrak AEM-7 Pulling four cars. The AEM-7 is an electric locomotive featuring a 7000hp drivetrain with a top speed of around 125mph. The electric train was one of Davenports imagined applications of his electric motor. (https://history.amtrak.com/blogs/blog/digging-into-the-archives-the-aem-7-locomotive)

2.1 Types and Basic operation:

At its most basic, an electric motor simply converts electrical energy into mechanical motion through magnetic fields. There are many types of motors today which achieve this task including: Permanent magnet DC, Brushless DC, Series Wound DC, AC induction, etc. Each type of motor possesses its own set of unique benefits, making one type more ideal for specific situations. This paper will focus one of the more basic designs, the Permanent Magnet DC Motor (PMDC) – the same type as the motor invented by Davenport.

2.2 Basic Components

To help with understanding the function of a PMDC motor, some basic components must be defined. A basic Permanent Magnet motor is comprised of six basic parts:

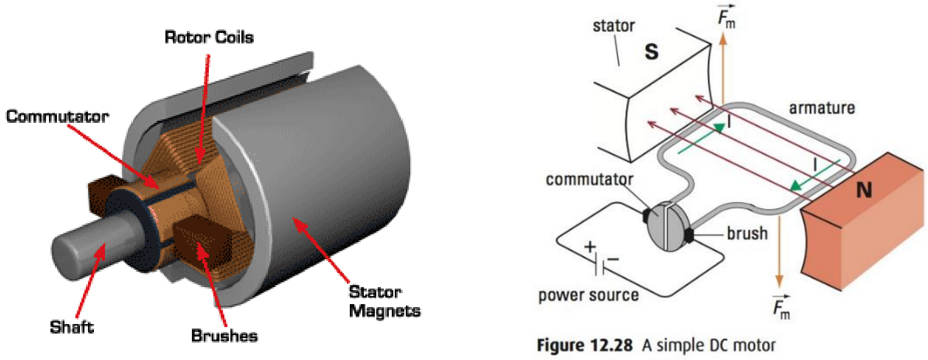


Figure 10: Basic Cutaway view of an PMDC motor (left) and a simple DC motor (right). (https://www.electrical4u.com/permanent-magnet-dc-motor-or-

1. Rotor: the rotating part of the motor
2. Stator: The stationary part of the motor

3. Field System: The part of the motor which provides the needed magnetic flux needed for creating torque – In the case of a PMDC motor, the field system consists of permanent magnets inside a fixed housing
4. Armature: The part of the motor which carries the current that interacts with the field flux to create torque.
5. Brushes: part of the circuit which electric current is supplied to the armature from power supply.
6. Commutator: The part of the motor which is contact with the brushes. Receives the current from the brushes to pass on to the armature.

Together, these parts form the basis of a functioning PMDC motor regardless of configurating or size. These are the same parts which Thomas Davenport used in his model. The following sections will explain these components in further detail.

2.3 Magnetic Fields and Forces

2.3.1 Magnetic Fields

Figure 11: A piece of lodestone with staples attached. Lodestone (magnetite) has a naturally occurring magnetic field due to its high concentration of iron oxides.

The earliest historical accounts of magnetism date back to earlier than 600 b.c. with the ancient Greeks and lodestones. Lodestone, a natural formation of the mineral magnetite, have natural magnetic abilities due to their high concentration of iron oxide. Humanity however would not truly understand the full effects of magnetism until the 19th and 20th centuries.

Magnets are present in a large number of products we use today. From computers to compasses, magnets - and more specifically - magnetic fields are a fundamental part of our world. So, what are magnetic fields?

To start, experimentation shows all magnets have both a North (N) and a South (S) pole - you cannot make a magnet with only one of the poles. Additionally, opposite poles will attract to each other while like poles will repel.

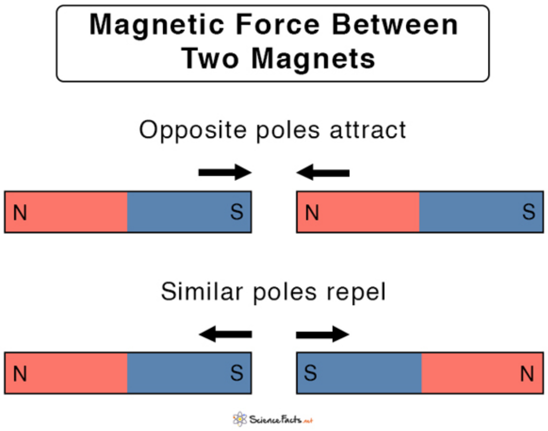


Figure 12: Magnetic attraction between two bar magnets. The opposite poles attract to each other while the similar poles repel.

A permanent magnet or constant current carrying wire produces a magnetostatic field. In other words, a permanent magnet produces a stationary magnetic field. At any given point in the field, the strength and direction does not change with respect to time.

The actual "magnetic field" of these sources can be defined by the Lorentz force law:

$$(1)\ \ \vec{F} = q\vec{E} + q\vec{v} \times \vec{B}$$

Where F is the force the particle experiences, q is the charge on the particle, E is the electric field vector, v is the velocity of the particle and B is the magnetic flux vector. The law states, the force a charged particle experiences are equivalent to the electric force plus the magnetic force. For a permanent magnet where the electric force qE is zero, the magnitude of the force is proportional to the charge of the particle *q*, the velocity of the charged particle *v*, and the magnitude of the applied magnetic field.

$$(2)\ \ \vec{F} = q\vec{v} \times \vec{B}$$

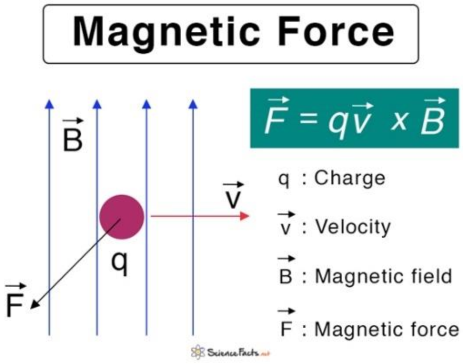


Figure 13: Diagram showing the direction of force a charged particle experiences while traveling through a magnetic field.

The SI unit for a magnetic field is the Tesla, named after famed scientist Nikola Tesla.

$$1\,Tesla\ (T) = \ 1\frac{Newton * sescond}{Coulomb * meter}$$

The magnetic field is also frequently described in the smaller unit Gauss (1 T = 10,000 Gauss). For reference, the earth's magnetic field is approximately ½ Gauss.

2.3.2 Magnetic Flux

In understanding magnets, another important concept related to the magnetic field is the magnetic flux. Simply put, the magnetic flux is the product of the average magnetic field times the perpendicular area that is penetrates. It is quantity of convenience, used in Faraday's Law and when discussing objects like transformers, solenoids, and electric generators. The magnetic flux is commonly denoted with the Greek letter Phi (F). Magnetic flux can be represented by the formula:

$$(3)\ \varphi_B = BxA = BAcos(\theta)$$

Where B is the magnetic field, A is the area, and θ is the angle at which the field lines pass through the given surface area.

Magnetic flux is typically measured with a flux meter. It has the SI unit if Weber (Wb) which has the fundamental unit of Volt/Second. In terms of the magnetic field, the flux has units of Tesla^2.

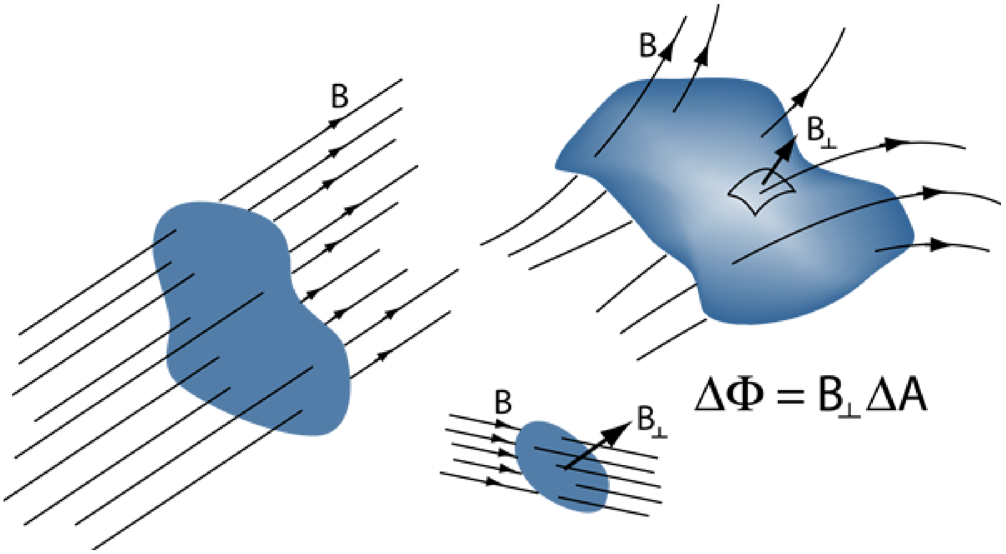


Figure 14: Illustration of magnetic flux through a given surface. Note how equation 3 assumes the field travels uniformly through a given surface when in reality the flux often varies with location.

An important note about magnetic flux, as seen in the equations for flux above, when the surface is perpendicular to the magnetic field the flux is zero (or very near to zero). Additionally, for a closed surface the sum of flux will always be zero (See Gauss' law for magnetism).

2.3.3 Representing Magnetic Fields

The visual representation of magnetic fields with magnetic field lines can be very useful in analyzing the strength and direction of a given field. As a general rule, each line forms a complete loop even if graphically not shown. Additionally, field lines emerge from the north pole and return to the south pole of a magnet. The rules for magnetic field lines are summarized below:

1. The direction of the field is tangent to the field line at any given point in space. The use of a compass will confirm this rule
2. The strength of the field is proportional to the closeness of the lines. The strength is proportional to the number of lines per unit area (called the areal density)

3. Field lines never cross, the field is unique at any point in space
4. Field lines are continuous and must form a closed loop. The loop travels from the N to S pole.
5. The north and south poles cannot be separated. The field lines cannot return the same pole they started at.

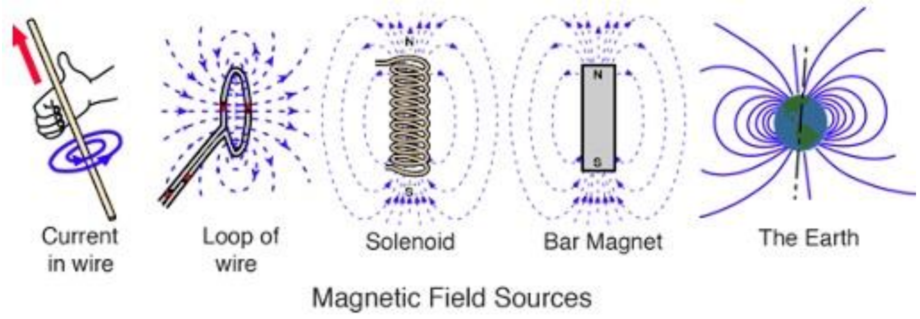


Figure 15: A visual representation of the magnetic field lines for various magnetic sources. From left to right: Current carrying wire, current carrying wire in the shape of a loop, solenoid, a permanent bar magnet, the Earth's magnetic field.

2.3.4 Fleming's Left-Hand Rule and Magnetic Force from a Current Carrying Wire

The magnetic force due to current carried by a wire exposed to magnetic flux, and thus torque generation of a DC motor, can be modeled with Flemings Left Hand Rule. The left-hand rule relates the current through a wire, the surrounding magnetic flux, and the incidental force of the two. The force (F) produced by a current carrying wire in a magnetic field can be represented by the following equation:

$$(4) \quad \vec{F} = I\vec{L} \times \vec{B}\ [N\ or\ Lbf]$$

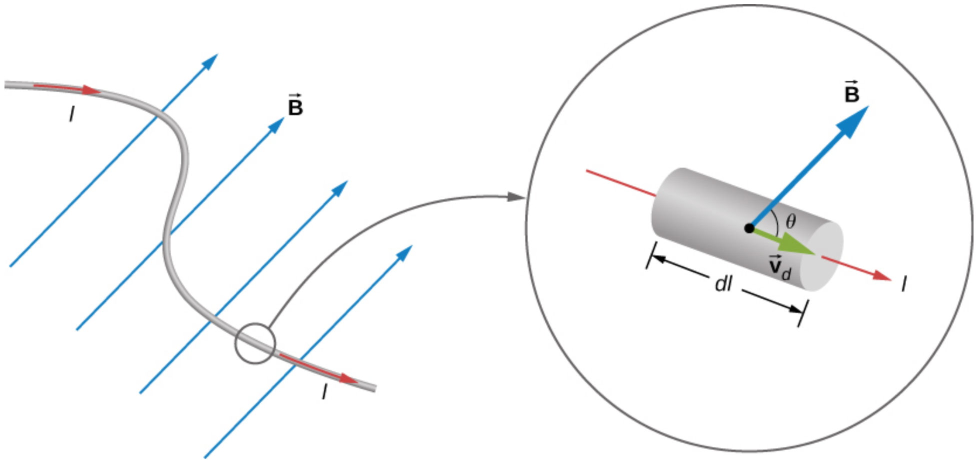


Figure 16: A section of wire carrying current I while exposed to magnetic flux B.

Where I is the current through the wire, L is the length vector of the wire (in the direction of the current) and B is the magnetic flux vector. More simply:

$$(5) \quad F = BIL\ \ [N\ of\ Lbf]$$

Where instead of the force vector, F is simply the magnitude of the generated force. We can then simply use Flemings Left-Hand rule to find the incidental direction. An image of how to use the left-hand rule is shown below:

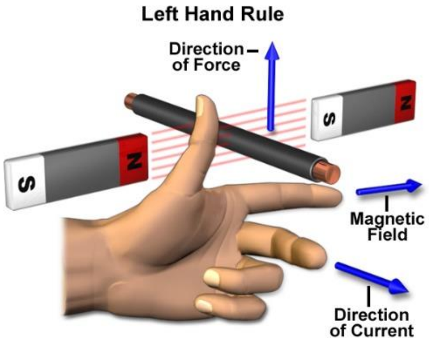


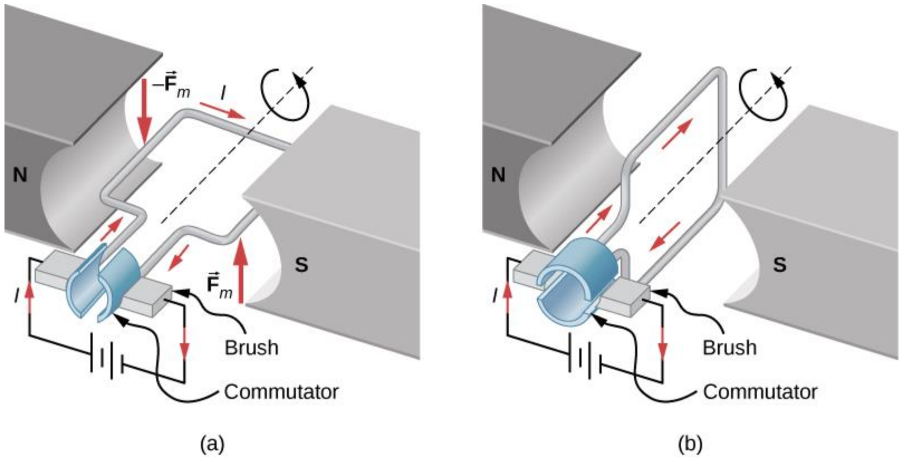
Figure 17: Flemings Left hand rule. The rule describes how the direction of current and magnetic flux relate to the generated force.

To use the left-hand rule, simply point your pointer finger in the direction of the magnetic flux and your middle finger in the direction of the current. Your thumb will then point in the direction of the generated force vector.

In a basic motor, the left-hand rule describes the behavior of the armature when in a magnetic field. As current passes through the armature (which is already exposed to a magnetic flux), a force will be generated perpendicular to the field flux (See Figure 18). The generated force on the wire will create a torque on the armature causing it to rotate. The generated torque can be found by using the equation:

$$(6) \quad T = 2FR = 2RBIL \quad [N * m \; or \; lb - ft]$$

where R is the radial distance from the center of the armature to the outer wire.



(a)

(b)

Figure 18: Simplified version of a dc electric motor. The rectangular wire loop is the armature surrounded by two permanent magnets. The armature is fed current through the brush and commutator. In part a, the current flows through the armature causing a counterclockwise torque which rotates the armature. In part b, the there is no current through the armature, it continues to spin from its initial velocity until it reaches the position in part a where the cycle repeats.

2.3.5 Magnetic Field in Solenoids

A solenoid is a device which consists of a long length of wire wound in a helical pattern. A solenoid produces a magnetic field similar to that of a bar magnet. The strength of the field produced by a solenoid is directly related to the material of the core, number of turns per length (turn density) and the total current through the wire. The relationship between these variables and the magnetic field is given by Ampere's Law:

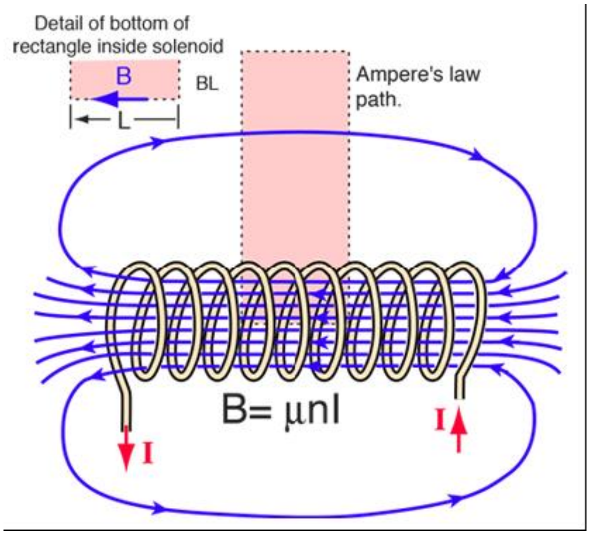


Figure 19: Magnetic Field produced by a solenoid. Note the similarities between the solenoid field lines and the field lines of a bar magnet.

$$B = \mu n I$$

Where:

$$\mu = k * \mu_0$$

k= *relative permeability of the core*

$$\mu_0 = 4\pi * 10^{-7}(\frac{H}{M})$$

$$n = \frac{number\ of\ turns}{length\ of\ solenoid}$$

The solenoid has many practical applications. In the case of a PMDC motor, the armature can be often modeled as a solenoid or arrangement of solenoids.

3.0 Permanent Magnets

3.1 Overview

As seen in the previous section, a critical part of a PMDC, or any motor, is the presence of a magnetic flux. Magnetic flux can be generated in a variety of way but in the case of PMDC motors, as the name suggests the flux is provided by permanent magnets. So, what exactly are permanent magnets?

Figure 20: Example of a Permanent Magnet in the shape of a bar. Iron filings around the magnet follow the magnetic field lines.

Permanent magnets are exactly what they sound like – they are pieces of material which produce a magnetic flux B. Permanent magnet are made from ferromagnetic materials. Ferromagnetic materials experience a long-range ordering phenomenon at the atomic level which causes unpaired electron dipoles to align forming a domain. Inside the formed domain, the magnetic field is intense. Within a large sample, or bulk, the randomly oriented domains tend to cancel each other causing the material to be unmagnetized. Ferromagnetism manifests itself when the material is exposed to an external magnetic field, say from another magnet for example. When exposed to a magnetic field, the domains will tend to rotate so their magnetic dipoles align with the external field. As a result, the piece is magnetized, and the overall field strength is increased.

The key factor relating ferromagnetism to permanent magnets is the fact ferromagnets will tend to remain magnetized following the removal of an external magnetic field. The "magnetic memory" of a ferromagnet is called hysteresis. An example of a hysteresis loop is shown below:

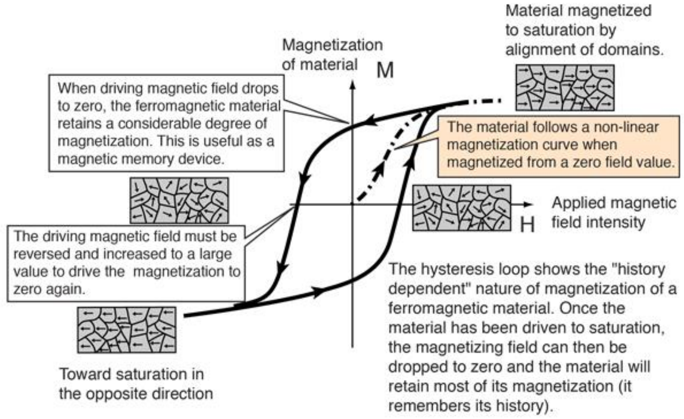


Figure 21: A hysteresis loop. The loop shows the "memory" of a magnetization in a ferromagnetic material. Once the material is driven to saturation the magnetization field can be dropped and the material will retain most of its magnetization. M is the Flux density from the material and H is the applied magnetic field intensity.

The hysteresis chart shows us that in a given ferromagnetic material, once the domains are aligned it requires energy to reorient the dipoles back. As a field is applied to the material, it will follow the curve from saturation point to saturation point. Certain compositions of ferromagnetic materials retain domain alignment significantly better than others making them ideal for permanent magnets. This behavior is demonstrated primarily in the second quadrant of the chart called the demagnetization characteristics. The main points of the demagnetization characteristics relating to PMDC motors are summarized below:

1. Magnetic Remanence / Coercive Force – When a permanent magnet has been magnetized once, it will remain magnetized even if the field is returned to zero. The flux at this point is called the magnetic remanence (designated B_r). The point at which the flux density is zero is called the Coercivity point. It represents the external field intensity required to change the force direction.
2. Energy Product and Max Energy Product – The absolute value of the product of Flux density and Field intensity at each point along the demagnetization curve is the energy product. The maximum value of this product is called the max energy product and is a good index of the magnet performance.
3. Recoil Lines – A minor loop in the second quadrant of the hysteresis loop can be approximated by a straight line and called a recoil line. (See line AC in Figure 22)
4. Stabilization – The torque constant and back EMF constant may decrease if the flux intensity becomes too low while the motor is operating. This is an example of demagnetization. In a

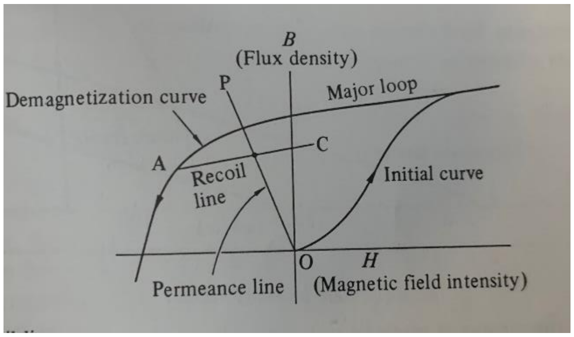


Figure 22: Recoil Line (AC) drawn on hysteresis loop.

PMDC motor, it is important to stabilize the field magnets by locating the operating point, the point on the hysteresis loop specified by the relative flux density and field intensity within the motor, on the recoil line. Stabilization is done to prevent the decreased efficiency of the motor while operating.

Another important characteristic of permanent magnets is known as the Curie Temperature. This is the temperature where the long-range order abruptly disappears. The curie temperatures can give a good idea of the required energy to break dipole alignment in a material. The final importance of the Curie temperature in permanent magnets relates to the operational conditions the magnet will experience. It is critical to design operations where the magnet will stay significantly below its curie temp as to prevent demagnetization during operation.

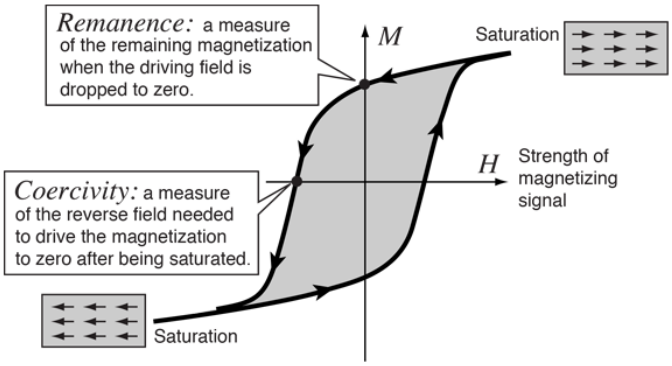


Figure 23: Remanence and coercivity are key properties to consider when selecting a material or a magnet orientation in a motor. The key point of the loop though is that the material is magnetized, it will not return to zero when the field is removed. The M axis represents the flux intensity and H represents the external field intensity.

3.2 Types of Permanent Magnets

Common ferromagnetic materials include iron, nickel, cobalt, and some rare earths (gadolinium, dysprosium). Other materials, such as samarium and neodymium when alloyed with cobalt can produce very strong rare earth magnets. There are basically three types of permanents magnets commonly used in PMDC motors:

1. Alnico Magnet – Made primarily from a blend of copper, nickel, aluminum, and iron. Can be cast or sintered to shape. Alnico were one of the first developed permanent magnets.
2. Ferrite or Ceramic Magnet ($Fe2O3$) – Made primarily from iron oxide and a ceramic material (typically Barium or Strontium). Typically sintered to shape, very hard to machine. Discovered by accident in the 1930s. They are typically cheaper to produce than other types of magnets leading to greater popularity.
3. Rare-earth magnet (Nd-Fe-B or SmCo) – Made from rare earth materials such as cobalt, samarium and Neodymium. Typically sintered to shape and magnetized. Requires coating due to oxidization.

The B-H properties of each magnet varies greatly as seen in figure 24. A summary of these characteristics is provided below:

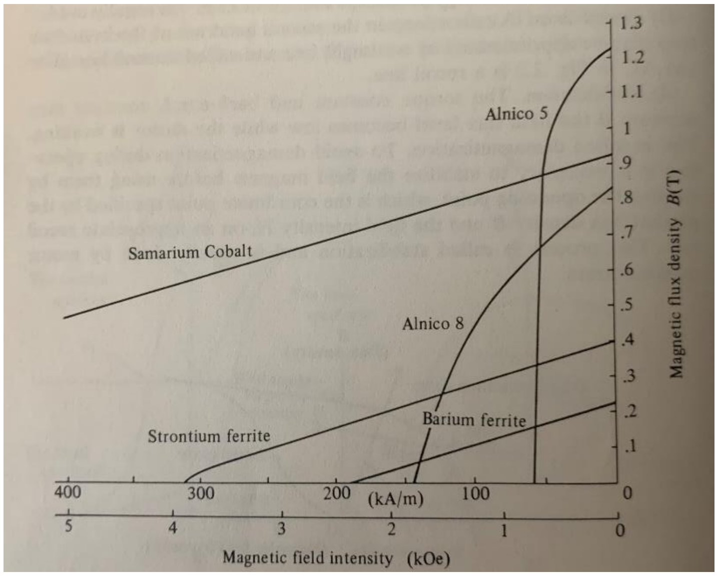


Figure 24: B-H characteristics of Various Ferromagnetic Materials.

1. Alnico – Provides high flux density but low coercive force. Because of the low coercivity, alnico magnets are subject to demagnetization when opposing poles are close to each other. As a result, alnico magnets are typically magnetized lengthwise to reduce coercive effects.
2. Ferrite Magnets – opposite of Alnico magnets. Feature high coercive force but low flux density. Because of the high coercive force, ferrite magnets can be magnetized across their width as well as length.
3. Rare Earth Magnets – Feature both high coercive force and flux density. Can be used to make a large variety of shapes without much worry for demagnetization.

In the design of a PMDC motor, the type of permanent magnet used significantly. If the wrong type of magnet is used in a given structure, the motor can suffer performance issues or may not even work.

3.3 Electric current and Electromotive Force

3.3.1 Conventional Current vs Electron Flow

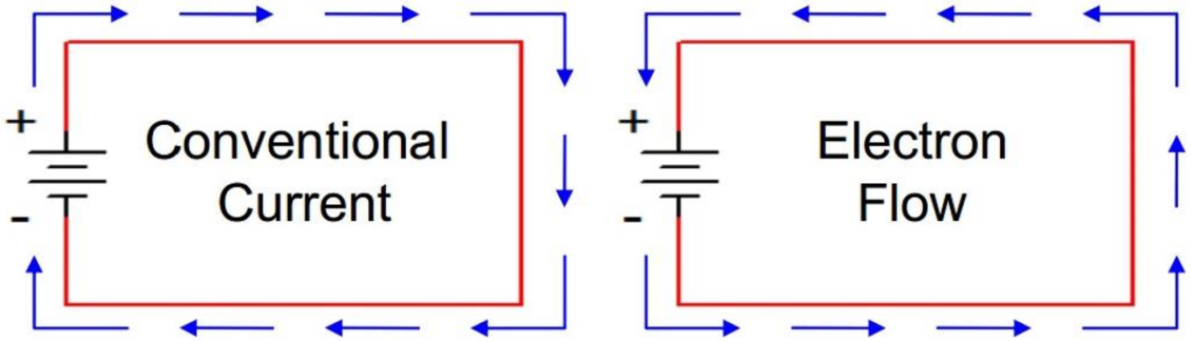


Figure 25: Differences between Conventional Current Flow and Electron Flow in circuit design.

An important distinction to make when analyzing/designing motors is the difference between conventional current and electron flow. Both principles have to do with the way we model the movement of electrical current in a given circuit.

Conventional current, or positive current flow, dates back to before the modern concept of an atom with electrons was realized. Electricity was treated as a “fluid.” The early scientist, Ben Franklin, while observing his kite experiment concluded that the current in a circuit must “flow” from positive to negative. His view became the conventional view of electric current in a circuit. We call this idea Conventional Current flow. In this model current flows from a high voltage source to a lower voltage source. As time progressed, conventional current was quickly disproved.

In actuality, for a given circuit electrons actually move from low voltage to high voltage potential. This movement is known as electron flow. In this scheme, the electrons leave the negative terminal, travel through the load device, and return to the positive terminal. The EMF source acts as a charge pump moving the electrons from the positive terminal to the negative terminal to maintain the potential difference.

Despite now knowing the true direction of electron flow, many of the derived equations were created based on conventional current flow. Additionally, most circuits and practical applications still follow the conventional current flow model. For this paper assume conventional current flow unless noted otherwise.

3.3.2 Electromotive Force (EMF) and Electric Potential

We defined current, but what is the force that drives the flow of electrons in a circuit? The answer in the Electromotive force. EMF is the metaphorical “pump” which produces an electric potential in a circuit. Examples of common EMF sources include batteries or generators. Generally, EMF sources convert one type of energy (chemical, mechanical, thermal, etc.) into electrical energy. An ideal EMF source is one which maintains constant Electric Potential.

The electric potential is a measure of the electric potential energy per unit of charge. The electric potential has the units of Volts

$$(7)\quad \Delta V = V_b - V_a = \frac{\Delta PE}{q}$$

It is important to note that commonly referred to “voltage” is not a measure of energy, it is energy per unit charge. For example, a car battery and a motorcycle battery may have the same 12v reading, but the car battery can move significantly more charge than the motorcycle battery. Another key distinction to make, voltage is not the measure at a single point but rather a difference between two points. In the car battery, the voltage of the battery is the potential between the two terminals. In common electrical diagrams or circuits, the voltage is the potential between the specified point and the circuit “ground.”

3.4 Motor Operation/Construction

3.4.1 Field Structure/Stator

The field structure of a PMDC motor, also known as the stator, plays a significant role in both the power output and efficiency of the motor. The design of the field structure is influenced primarily by the desired power out and the source of the field. This section will describe not only arrangements with permanent magnets but also with electromagnets.

The first major consideration when dealing with a PMDC motor is the type of permanent magnet. Because each type has vastly different B-H characteristics, their individual properties must be considered. The specific properties regarding each type of magnet are summarized below:

1. Alnico Magnets. Since alnico magnets feature a high Br, they are ideal in small motors as well as servomotors. Because they have a low coercive force, they must be magnetized lengthwise, or they will face performance issues while operating. Example configurations of the field arrangements are shown below:

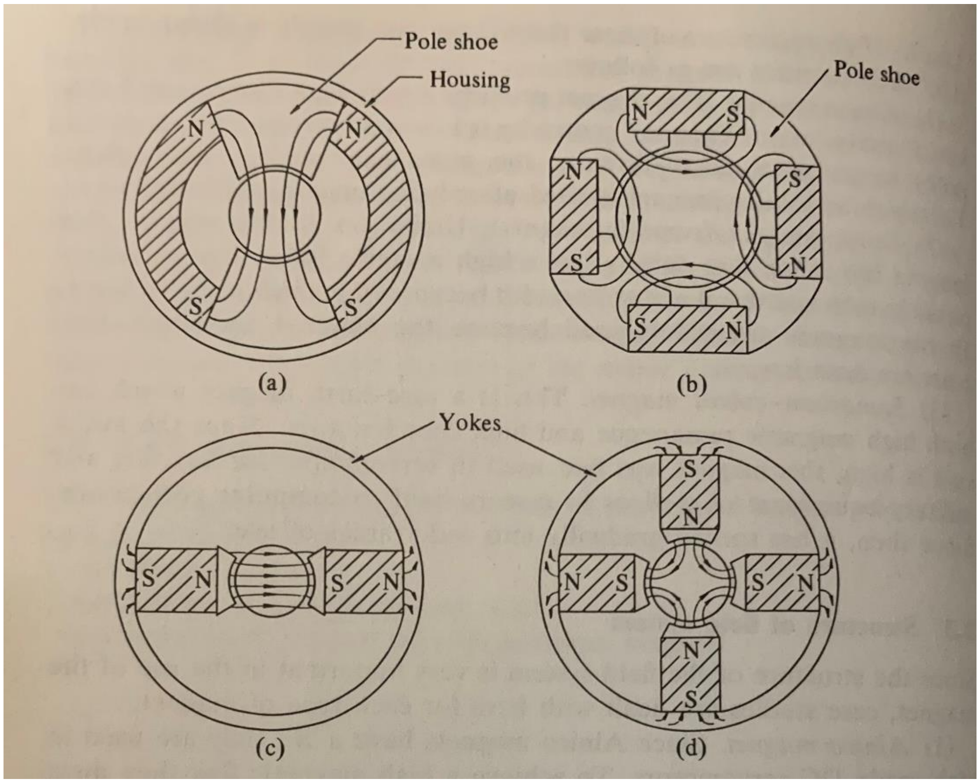


Figure 26: Sample field arrangements for PMDC motors using Alnico based permanent magnets. Structure (a) and (c) are both two pole structures; (a) must have a non-magnetic material as its housing while (c) must have a ferritic housing to help increase magnetic flux. (b) and (d) are both four pole arrangements. (d) uses a cylindrical housing of ferritic material again to serve as a flux path while (b) uses a non-ferritic housing to secure the poles. Typically, the number of poles in the motor is an even number. Most PMDC motors feature either two or four poles.

2. Ferrite Magnets. Because ferrite magnets feature a high coercive force, they can be magnetized both lengthwise as well as widthwise without facing any major issues. Because ferrite magnets have such a low flux density though, they have slightly different arrangements:

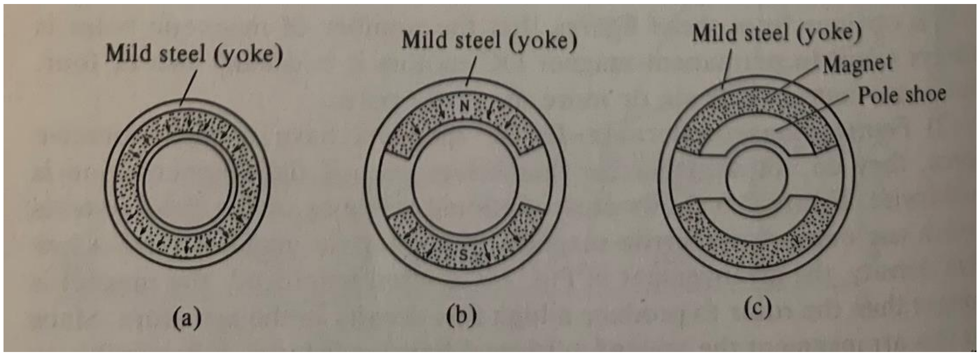


Figure 27: Field arrangements for ferrite magnets. (a) Ringed anisotropic ferrite magnet. (b) anisotropic ferrite magnet is dovetail shape. (c) anisotropic ferrite magnet in dovetail shape with pole shoes.

3. Rare-Earth magnets. Since rare earth magnets feature both a high coercive force as well as a high flux density, the can be magnetized in any arrangement and generally placed in any configuration. However, due to the higher cost of construction, they are often made as this as possible while still performing as well as or better than ferrite magnets.

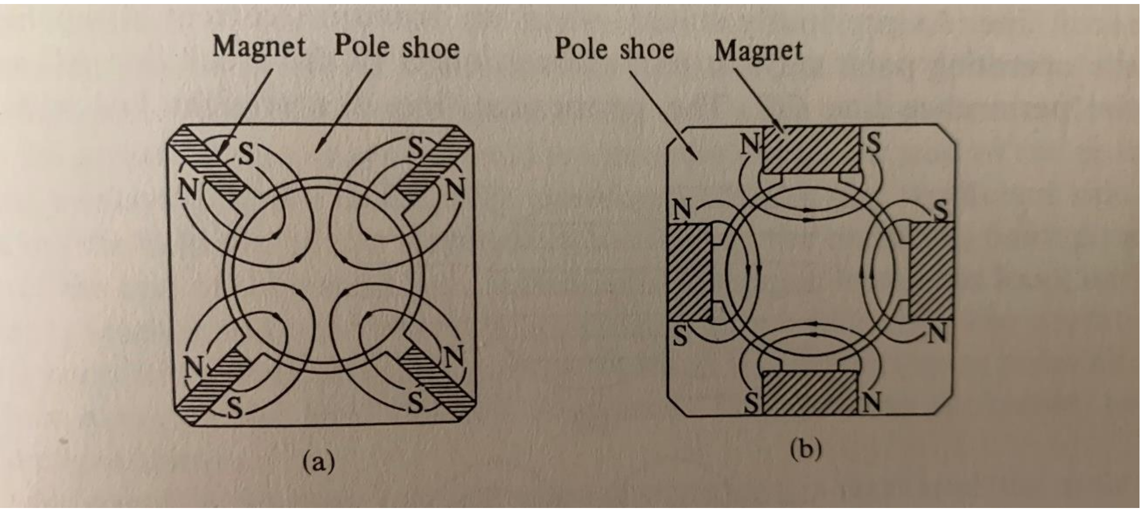


Figure 27: Comparison of field structure for Samarium-Cobalt magnets (a) vs that of alnico magnets (b).

For non PMDC motors, coils or other electromagnet sources are used to generate a magnetic field instead of permanent magnets. The electromagnets effectively “imitate” the flux fields produced by the permanent magnet arrangements. The electromagnets can be wired in series, parallel or a combination of the two depending on specific application. The wiring of field motors is discussed in a later section.

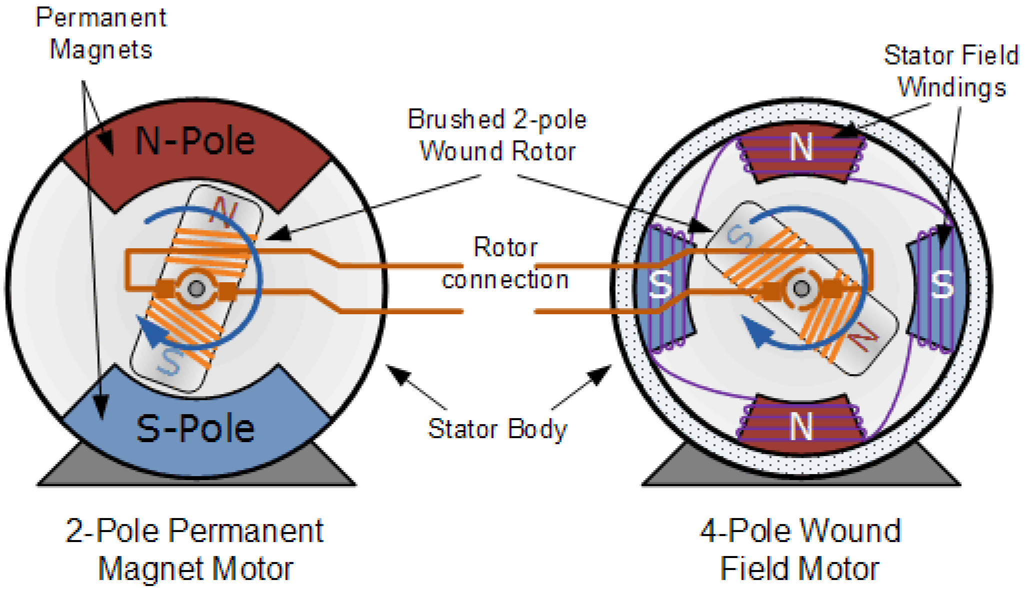


Figure 28: a comparison of a PMDC motor vs a field wound motor.

3.4.2 Armature

As discussed above, the armature is the internal rotating portion of a PMDC Motor. The armature is responsible for generating a magnetic flux which will interact with the stationary field. The interaction of the two fields will create a force at the outer radius of the armature which in turn creates a moment causing rotation. Armature design varies significantly from motor to motor.

3.4.3 Commutator and Brushes

The commutator and brushes are a critical part of a PMDC motor. Together, the commutator and brushes are responsible for energizing the correct portions of the armature at the right time to maintain motor rotation. If either part were to fail, the coils would be energized at the incorrect time and the motor would stall (the forces generated by the armature would cancel out, there would be no torque generated).

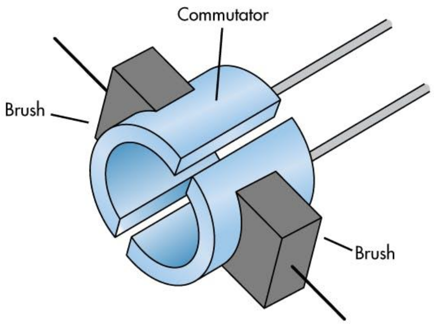


Figure 29: A basic Commutator and Brush arrangement

The commutator is typically a small segment made of copper placed on the rotating assembly. The brushes are typically small pieces of graphite made through compression molding and high temp calcining. Each segment of the commutator is isolated from each other with a piece of mica or plastic. Each commutator is the connected to an individual coil, wire or wire set in the armature. The number of brushes in a motor can vary (especially with size of motor) but always remain a multiple of two. Brush "pairs" are typically placed 180 degrees apart and are opposite polarity. The brushes are held in contact with the commutators with a set of springs or spring like material. See figure 30 below:

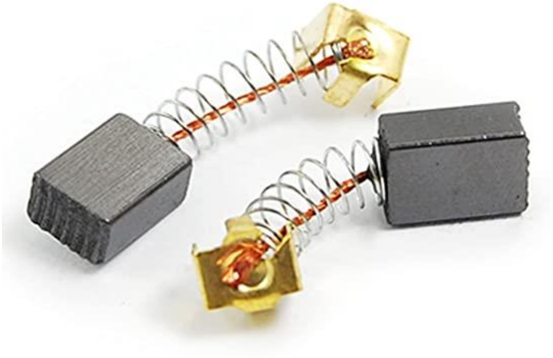


Figure 30: Typical brush for a PMDC motor. The spring is used to hold the brushes in contact with the commutator. These are sold as replacements since the brushes do wear over time.

When the motor is in operation, the brushes contact opposite commutators which creates a closed circuit through the armature. The circuit causes the armature to spin which results in the next set of commutators counting the brushes completing the next circuit. This cycle will continue as long as power is supplied to the motor and the brushes are not completely worn.

3.4.4 Series and Shunt Wound

Series and shunt wound motors have to do with how the field and armature are wired in field motors. Each winding type greatly affects the performance and application of the motor. These benefits are summarized below:

Winding Style	Series Wound	Shunt Wound
Description	Field windings are connected in series with the armature. Field windings will have relatively fewer turns of wire capable of sustaining the full load of the motor. On startup, large current in rush produces a high torque	Field windings are connected in parallel with the armature. Field windings consist of many turns of small wire. Since it is connected across a DC source, its current will be constant and thus will run at a near constant speed.
Benefits	High Starting Torque	Constant output speed independent of load
Applications	Traction Motors, Crane/Winch motors	Conveyor Belts, Machining Tools, Compressors

Table 1: Summary of field wound motor types

Additionally, a field motor can have a combination of the two arrangements commonly called a compound motor. A compound motor will have a mix of windings in parallel and series with the armature. Compound wound motors have the added benefit of higher starting torque than a shunt wound motor but more consistent output speed. Applications include large conveyor systems, mixing drums and other large pieces of equipment. Another added benefit to a compound wound motor is when using a varying voltage source. Since the field and armature will have the same voltage applied, they will have better speed characteristics independent of the actual received voltage.

4.0 Working Davenport Model

In order to connect the theoretical topics discussed above with physical components, a recreation of the original davenport electric motor was created. The recreation is dimensionally similar to the original but has some minor variations in the field structure as well as the commutation structure. Additionally, in remaining true to the Davenport Era, no computer aided design (CAD) or Computer-Aided machining (CAM) was used. Each piece was fabricated and assemble by hand. Additionally, materials used are comparable to what was available at the time of Davenport's model. The process and results of the recreation are summarized below.

The first iteration of the motor is a rebuild of the previous teams' efforts. Most of the components were modified/changed with the exception of the wooden frame and the semi-circular pieces of iron. The previous team was able to get the motor to function on a similar setup, but it required significant power (20+ Amps at 12 volts), produced significant sparking and would "eat" the commutator. In redesigning, the goal was to recreate the motor, but have it operated on much less power (around 6-12 volts, 3-5 Amps). Additionally, the rebuild should be able to function significantly longer without suffering rapid deterioration of any electric component.

4.1 Prototype 1/Initial Model: Field Motor

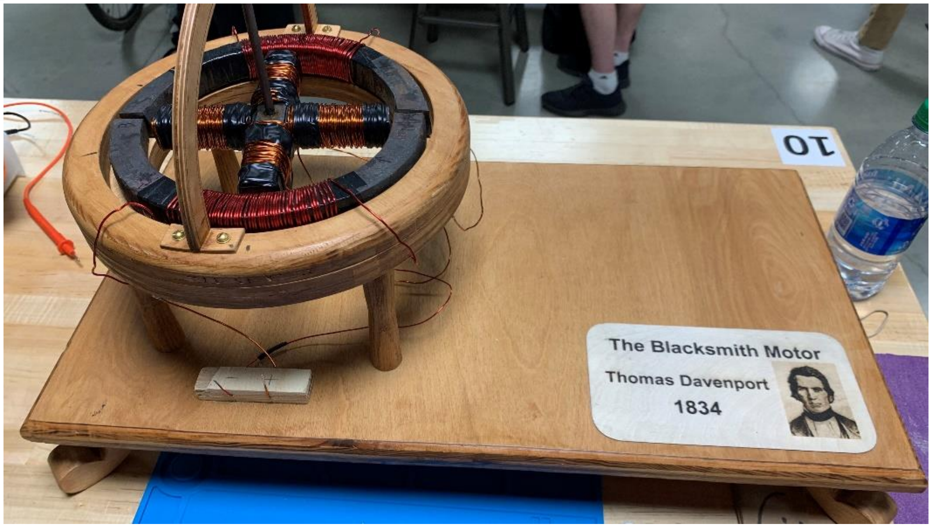


Figure 31: The first prototype developed. This is a field motor modeled after the original Davenport Motor.

4.1.1 Overview/General Construction

To start, the task of just making an electric motor – permanent magnet of field based was chosen. This approach was preferred due to the relative difficulty of acquiring/fabricating permanent magnets based on the dimensions and style of the motor. Using a wound field allowed for more flexibility in terms of construction process and timeline. The first iteration was decided to be a field wound series dc motor.

Conceptually, the field wound motor behaves exactly the same as the permanent magnet motor but instead of having a permanent field present, a generated field is used. Furthermore, the semicircular/half-round field shape was chosen based on its similarity to the davenport design (See Field Structure Section above for more details). With the field structure chosen, two pieces of steel were formed into a rough half-circle radius and would with 18-gauge magnet wire. Each field winding has approximately 25 turns (±5 turns). The two separate field windings were then wired in series to each other as well as in series with the armature.

For the armature/main shaft assembly, a fair amount of mechanical work was required. The previous main shaft was bent significantly to where the motor would not want to turn without moderate effort. Additionally, the bushing in the baseplate of the motor was causing binding to occur as the armature would spin. The first step was the replacement of the driveshaft on the armature. The new driveshaft is made out of ¼" steel rod approximately 13" in length. At one end, the shaft was milled to a fine point and the other was polished with 400 grit sandpaper. The pointed end will be the bottom that sits in the brass alignment bushing while the polished end will sit inside of the bronze bushing. The next piece to be fixed was the brass bushing. The old one was already drilled of center so a new one was cut from fresh stock. It is approximately 1-1/4" in diameter and just under 5/16" thick. It features a small indent in the center to provide a spot for the driveshaft to sit. The angle of the hole sides is less than the driveshaft, so the point sits nicely inside the bottom of the divot (see figure below). With the new driveshaft and base bushing, the main shaft/armature spin with significantly less resistance.

The next piece of the assembly was the actual armature. The previous windings were removed, and the armature was completely rewired. For wire, 16 gauge "magnet wire" was used due to its simplicity to work with. The old setup had approximately 25-30 windings on each arm while the new setup has approximately 60 windings (±2). When winding, opposite arms are wound in the same direction, this connects to the idea of a solenoid behaving as a bar magnet. If the opposing legs were wound opposite, they would cancel each other out and there would be no field. The choice to have more windings was based on the principle that more windings will produce a stronger field meaning the motor can be run with less current.

The next, and final major piece that was redesigned from scratch was the commutator. The previous commutator design functioned but produced a significant amount of sparking and began to wear out rapidly. The design also caused the motor to bind a low speed. Unfortunately, not much information exists about the davenport commutator but going off of the concepts he created and with the goal of producing a more efficient commutator, one based on a rotating design similar the ones presented in the above sections was chosen (see figure below). A wooden dowel was chosen to hold the copper segments. This would keep the copper pieces isolated from each other as well as the metal main shaft to reduce the possibility of a short. The copper segments were made from taking a 5/8" piece of copper pipe and cutting it in half twice. A total of four equal half circle segments were made. The dowel was turned down to match the radius of the copper tubing.

At this point, the motor was completely assembled minus the commutator. This was because of the need to set the "timing" of the motor. Similar to a car, if the time each piece of the armature is not energized at the correct moment, the motor will fail to spin. Each set of legs has its own commutator, since there are two pairs of arms, there are two "separate" commutators (Separate is in quotes because while they function separately, they are still part of the same motor). The individual commutator segments are placed 180 degrees apart with their separation lying on the same plane as the leg they connect to. This is done so as the leg of the armature passes either pole of the permanent field, its polarity reverses to keep the motor in motion. The two sets of commutators are placed 90 degrees out of phase in accordance with the armature design. In effect, the motor has two primary armature windings operating in parallel increasing the output force of the motor.

For the brushes, strips of brass were used. Normally brushes are made of carbon, but carbon brushes were not present when davenport constructed his original model hence the selection of brass. The brass is stiff enough where it can be bent into a shape for the contact but also not too hard where it will excessively wear out the commutator. The brass was bent into a simple shape where only one point touches the commutator. This design reduces the amount of sparking since the point only contacts both commutators for a very brief moment (the previous design had a large amount of overlap which in effect shorts the power supply causing sparks). For support, the brushes are simple glued to wooden supports. This simple system holds the brushes firmly enough without the need of extra fasteners. The brush and commutator setup provides efficient control over direction of current while providing minimal resistance to rotation.

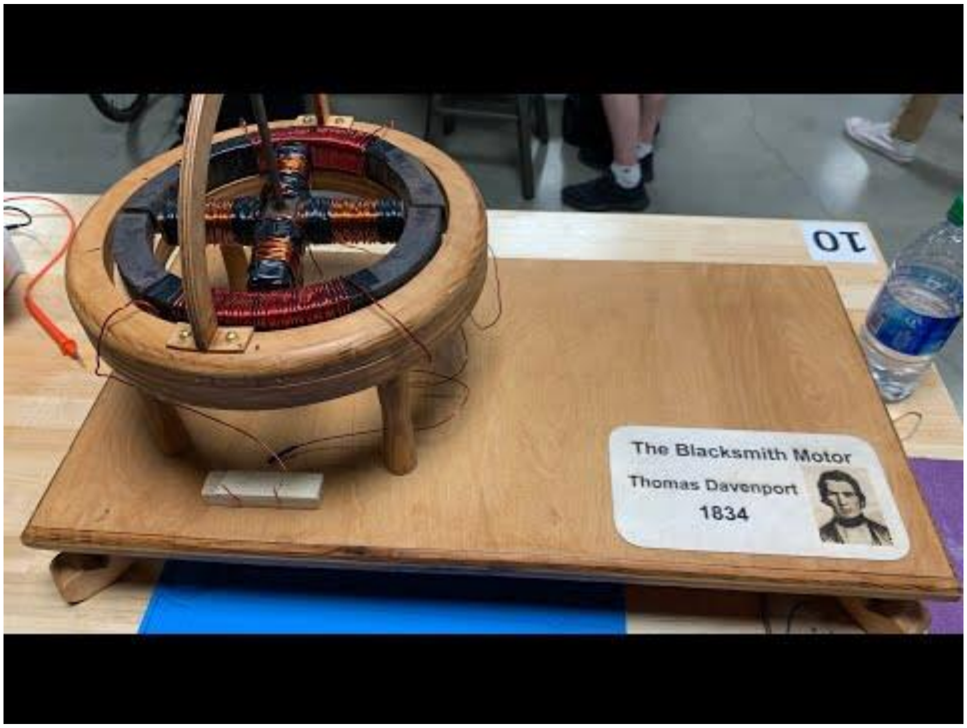
At this point, all of the connections were soldered together following the wiring diagram in the figure below:

4.1.2 Testing

The motor was tested using a benchtop power supply current limited at 3.13A. The supply is capable of providing up to 15V.

For the first test, the motor failed to run. There was voltage and amperage were verified to be present, but the motor did not spin on its own or with starting assistance. Following the test, it was discovered the field had been wired incorrectly. The field was wired in parallel which by the Kirchhoff Current Law means each field winding was only receiving half of the 3A of power, effectively running at half strength. Additionally, the original steel brushes were discovered to be causing excessive wear in the copper commutator.

For the next test, a more methodical approach was used. The motor was disassembled, and each component was tested separate using a compass to verify the presence of a magnetic field. For the field, the change from parallel to series wiring was made. With the compass placed in the center of the field, the power supply was turned on. Almost immediately the compass needle tracked to follow the predicted field arrangement. At this point the field was verified working. Next, each leg of the armature was tested in a similar fashion. Each leg was verified to be producing a field. At this point it was clear the primary culprit of the first test was improper wiring. The field was rewired in series and the commutator was rechecked for proper timing. After the motor was reassembled and powered almost instantly the motor began to spin (see video 1). After stabilizing, the motor runs at approximately 180-200 RPM at 2.6-3.2V and approximately 3 Amps. The motor comparable to a hit and miss motor when starting. If the armature is in certain positions, it requires a small bump to start but once running will continue to do so.



Video 1: This video shows the first successful test of the motor. The Ammeter pictured was used to verify the current in the wire was accurate to the power supplies displayed value. (https://youtu.be/k4ngmdVQgx4)

During operation, the principles used during design proved to be true. The commutator, both with the redesign combined with lower current did not produce any significant sparks. Additionally, no part of the motor heated up significantly above base temperature during the approximate 3-minute run time. Overall, the test proved the concepts governing the operation of the electric motor are not only true but can be applied to recreating a piece of American History.

For future test, a couple of possible improvements were noted:

1. Reinforcing top support bearing. During operation, the attraction forces between the armature and the field cause the entire top support piece to be bent out of alignment. Reinforcing the support may help reduce mechanical loss during operation as well as binding at low speeds
2. Increasing the field strength/Increasing the number of windings in the field. Since we are working with a limited amperage power supply, increasing the number of windings in the field will help increase the produced torque of the motor at the same amperage (the power supply can theoretically supply up to 15V*3A = 45W, we are currently only using around 9W. The current field is not high enough resistance which causes the power supply to current limit before the voltage rises).
3. Permanent Magnets. Ultimately, the goal of this project is to get the motor to operate on permanent magnets. The field arrangement proved the concepts are true and the motor functions, but the permanent magnets will be truer to the Davenport design.
4. Addition of mechanical components. The final addition recommended is a small assembly of gears. These gears can help to convey the idea of converting electrical energy into mechanical energy.

4.2 Prototype/Iteration 2: Field Wound with Mechanical Rework

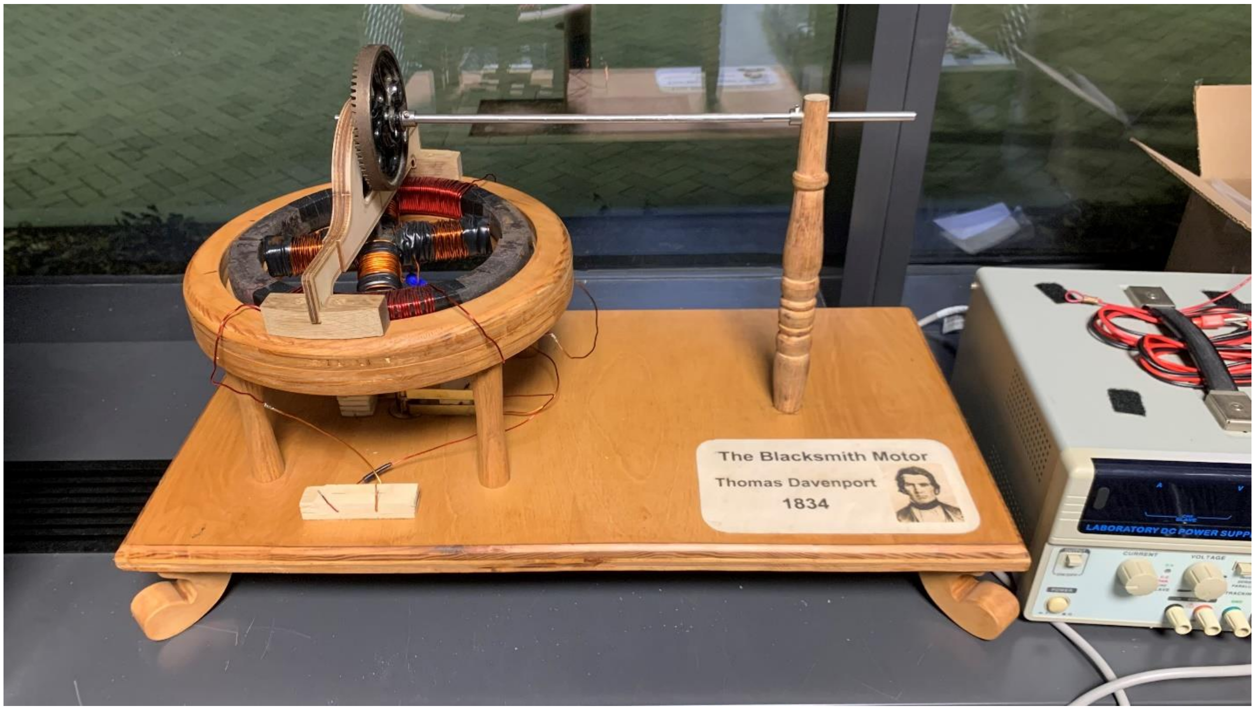


Figure 32: Image of reworked model. At its core this model is similar to the first prototype but has had revisions to the upper support as well as the addition of the horizontal output shaft. The power supply also remains unchanged.

4.2.1 Construction Revisions and Additions

At its core, this model is mostly unchanged from its first version. The commutator/armature piece is mostly unchanged. The base support is also unchanged. For this iteration, the focus was to further increase the efficiency of the motor as well as provides a mean for power output – in this case the output shaft. As such, the top armature support was redesigned to accommodate the gearing and to provide a support for the horizontal shaft. A vertical support was also added to hold the far end of the output shaft.

The first piece to be redesigned was the top armature support. As noted in the previous trial, the original support would flex significantly during operation causing the whole assembly to contact the field magnets or to bind. To fix this issue, the new support piece would not only be thicker, but feature larger mounting pieces to counteract the lateral forces. Also, having the bearing be more in plane with the supports, the structure doesn't experience much torque on the base. As a result, the piece doesn't show nearly as much flex. The support is made of layered pine board which was glued together for the desired thickness. The added thickness also allowed for the bearing supporting the horizontal shaft to be pressed in.

The new upper support required some simple modification to the armature shaft. Since the piece hold the horizontal support bearing, the shaft had to be shortened as to fit in the support piece. See video 2. Additionally, the new bearing location also required the armature shaft to be re-polished to reduce friction with the bushing. These were the only modifications made to the armature shaft.

The Horizontal shaft is made out of the same stock as the armature shaft (1/4" Steel). The shaft is polished on the ends to reduce friction in the bushings which are made of brass. The shaft holds the larger bevel gear. It is secured between the supports using two fabricated collars. The geared end of the shaft is supported by the upper armature support while the opposite has its own vertical support. The gear ratio is approximately #.

The final piece manufactured was the vertical support for the shaft. The support tis made from a piece of a chair leg. The chair leg piece was chosen to match the aesthetic of the already built structure as well as the craftsmanship of that era. The leg was put in a lathe and stripped down to bare finish. Additionally, the piece was turned to help reduce its lateral runout. The end of the piece was center drilled for mounting to the platform. The opposing end had a horizontal hole drilled and a brass bushing pressed in. The shaft rests in the bushing and spins freely. Overall, the piece matches the structure well and provides a more tangible means to use the motors output.

4.2.2 Testing

The testing conditions are similar to the conditions present in trial 1. The same power supply was used except the out was instead fixed 5V @ 3A.

Overall, the test was successful. With some minor adjustment to the vertical support and gear spacing, the motor ran excellent. It spins at a slightly higher RPM than previously. The motors operation is actually slightly quieter since the armature no longer binds in the upper support. The gears mesh nicely with little noise and the output shaft spins at a nice constant speed (See Video 2).

Video 2: Video showing the second iteration of the Motor in operation. Note the rotation of the horizontal output shaft as well as the lack of flex in the supports. The changes made the motor operate more quietly than the first test. (https://youtu.be/6QKlEezhT4c)

The motor is now ready for the next set of iteration which will include the following:

1. The field magnets will be replaced with permanent magnets. This will make the motor function truly in the same way as Davenports model. Addition, the removal of the field coils should help lower power consumption even further.
2. The next iteration will also feature a tool to be powered by the motor to demonstrate the usefulness of the electric motor. This piece will also directly relate to Davenports original goal with his invention.

4.3 Prototype/Iteration 3: First Attempt at Permanent Magnet Motor

Figure 33: Image of motor with first iteration of permanent magnets. The frame is the same as in iteration 2 – only the field magnets changed. This version also features a new power supply setup.

4.3.1 Construction Revisions and Additions

For this iteration, the motor structure remains mostly unchanged. Maintenance was performed and all bushings were lubricated to help quiet operation. The main change for this test was the field magnets. The field magnets were replaced with newly made low carbon steel rings with the intent to serve as permanent magnets.

For material, 1018 steel was selected based on its lower carbon content and high magnetic permeability. For these reasons it was believed to be easily formed into permanent magnets. Additionally, as opposed to getting a piece of bar stock to be rolled into the half circle shape, thin plate was purchased to be cut and subsequently stacked into the housing. The final material purchased was ¼” thick 1018 steel flat stock.

To cut the metal a plasma cutting table was used. While not historically accurate to how Davenport would cut or form the metal in 1836, it was the most feasible option in the school machine shop. A simple design for the semi-circle was generated in Autodesk Fusion 360 along with a CNC (Computer Numeric Control) profile. The profile was then input into the plasma table and the semi-circles were cut out. See figures below:

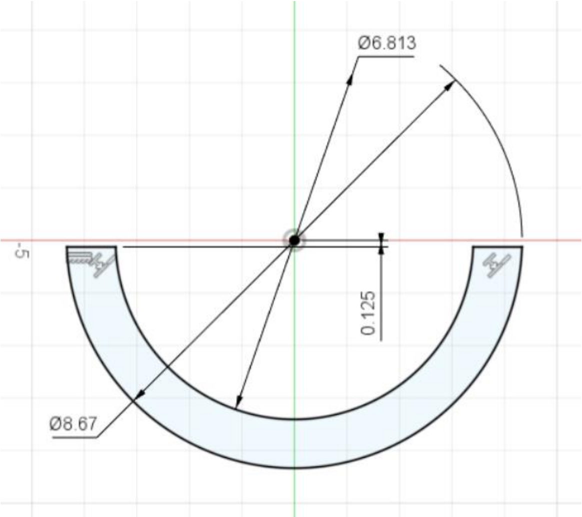


Figure 34: 2D sketch of one semi-circle segment for field.

Figure 35: Image of cut semi-circles in plate and after finishing. The bur on the edge of the steel was removed by simply striking with a hammer (middle). The final product post cleaning (right)

Video 3: Plasma table cutting process. The plasma torch generates an electric arc which travels in a gas through a restricted opening. The electric arc heats the metal and the gas cuts through the molten metal leaving a precise cut. (https://youtu.be/9UA9ZovW_u0)

In total, six semi-circle rings were cut. When stacked they created a thickness of ¾”. The rings were labeled #1-#6 and assigned in batches for magnetization. Pieces 1-3 were a set ad 4-6 were a set. The semi-circles fit the motor frame well and resulted in less contact with the armature. Additionally, small shims of cardboard were made to keep the magnets fixed during motor operation.

The only other change present for iteration 3 is the power supply. Due to the observation of the motor being power limited rather than field limited in previous trials, the decision to construct a new power system was developed. The new supply consisted of a Lionel toy train transformer rated at 160w, an AC rectifier, an analog ammeter, and a mechanical switch. The new power supply would allow for up to 18v at more than 15 amps. The transformer takes line voltage AC (115v-120v) in and outputs AC voltage (7v-18v). The output AC voltage is then fed to a 100-amp full wave rectifier to output DC voltage similar to the transformer. The switch is used to isolate the motor and the ammeter allows for monitoring of the applied current.

4.3.2 Testing

For the first test, the power supply change was verified to operate the motor. The supply was connected to the second iteration of the motor (series wound field magnets) and powered on. The new supply worked phenomenally. The motor quickly accelerated up to speed. Because there was no load on the motor and it being series wound, the motor quickly began to operate at speeds much higher than desired. The power supply proved it was more than capable of operating the motor.

The focus was then shifted onto the permanent magnets. The cut rings had no magnetic field when taken of the plasma table. To magnetize, the “single touch” method described in the Henry Notebooks. In the single touch method, an already existing permanent magnet is swiped against a piece of steel to magnetize it. The pole direction matters, the north pole of the existing permanent magnet is drawn over half the piece of steel a number of times. Then the south pole is drawn over the other half of the steel piece a similar number times. The end swiped with the north pole of the permanent magnet will become the south pole of the new magnet.

All 6 semi-circles were magnetized using the single touch. For the first test each piece was swiped approximately 40 times on each end (20 on the top of the piece 20 on the bottom of the piece) with a reasonably powerful horseshoe magnet. Care was taken to ensure the opposing pole would not contact the side being magnetized. Each piece was visually verified with the use of a compass to indicate field presence and proper orientation. Concluding the magnetization, the new “permanent” magnets were loaded into the motor for a test.

The test of the motor with the “permanent” magnets was successful with a catch – the “permanent” magnets weren’t so permanent. The motor would spin up to speed, albeit less than with the wound field arrangement, and operate for a minute or two then quickly lose performance until failing to operate completely and stalling. See the video below for the motor in operation:

Video 4: Iteration 3 motor in operation. Shortly after the video was stopped the motor’s performance deteriorated quickly. (https://youtu.be/7dkv4IdKNYo)

The new magnets functioned well for a short duration but would quickly lose their field strength causing the motor to completely stall. Upon inspection, it was clear the magnets had lost their strength significantly. When fresh after magnetizing they were capable of picking up small steel objects and even each other in the right conditions. Following motor operation, they would barely move the compass needle. Upon further research, it was concluded the material used, 1018 steel, was like the primary culprit. 1018’s low carbon content results in the material being classified as “soft iron”. Soft iron is ideally used in electromagnet operations as it is features a low coercivity force – it is easily magnetized and demagnetized. In the case of the motor, this is likely why the single touch method produces a comparably strong magnet which doesn’t survive the motor. The strong magnetic field produced by the armature is able to overpower the 1018 steel thus casing demagnetization (see section 3.1 and demagnetization).

This iteration of the motor proved three key points:

- The new power supply has much more potential for high power output – stronger fields in the motor result in more torque available
- Low carbon steel along with the single touch method for creating magnets does not result in a long-term solution but rather one suitable for demonstrating the magnetization and demagnetization of ferromagnetic materials.
- More research is needed into magnetic materials and methods of magnetization

5.0 More testing and Final Thoughts/Conclusion

5.1 Further testing of Magnetization in Metal

With time getting closer to the end, a greater emphasis was placed on determining the root methods behind the magnetization/creation of permanent magnets. In particular the test from motor iteration three was reperformed with the assistance of modern sensor technology. While Davenport certainly did not use a computer with a magnetic flux meter during the creation of his magnets, these tools can be invaluable in cracking the code of his permanent magnets.

For the test, the single touch method of magnetization described in the Henry notes on permanent magnets was tried on a variety of materials available. The goal of the test was to prove not only can metal be magnetized using the methods but to determine if certain materials exhibit better capability to be permanently magnetized. For testing, a Vernier Lab Pro interface along with a Vernier Magnetic Field Sensor were used to objectively compare the field intensities of the various test samples.

The first method tested was the single touch method. For the test each piece was swiped on end with a large permanent magnet. The magnet has a field strength at 1” of approximately 8.13mT – a relatively powerful magnet. The idea behind the method is that the force exerted by the field of the permanent magnet will overpower the magnetic domains already present in the metal causing them to align indefinitely. The aligned domains would then provide a magnetic field of their own and the piece of metal would be “magnetized.” The second test was a variation on the single touch method where the opposite pole of the magnet is swiped on the opposite side of the piece being magnetized helping to further increase the strength of the magnet. It operates on the same principle as described above only with the intent of being more thorough.

For testing, each piece would be magnetized using a specific method. The initial field strength was recorded. The strength would then be recorded during set intervals as to determine the point in which the method yielded max results (finding the point of diminishing returns). The test was repeated on various grades of steel. For recording, the probe was placed 1 inch from the end of each magnetic sample to keep results consistent. Results were collected using the software Logger Pro. A summary of the results is presented below:

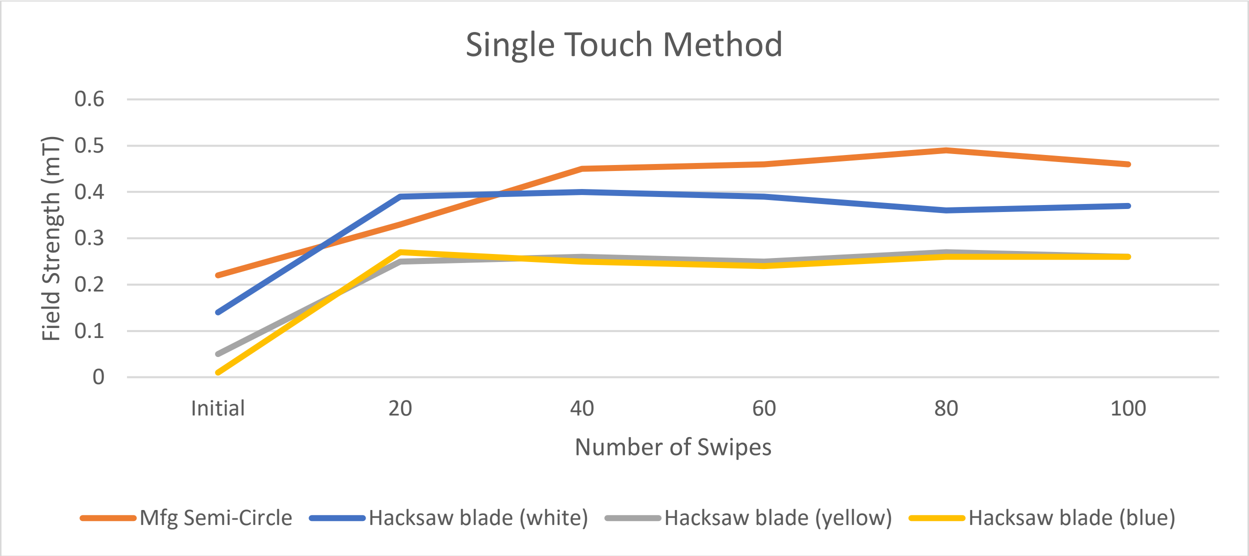


Figure 36: Chart summarizing results from single touch method of magnetization. From the data, it is clear using the reference magnet after approximately 50 swipes the pieces are magnetized to as strong as they will become.

Object	*20/20*	*40/40*	*60/60*
Mfg. Semi-Circle	0.515mT	0.5mT	0.52mT
Hacksaw blade (white)	0.36mT	0.35mT	0.34mT

Table 2: Results of modified single touch method. Note that by the end of the first trial the metal pieces are already at their max field strength.

As seen in the chart above, there is a clear point in which the single touch method yields declining result. That point occurs around 40 swipes (less than 20 on each end for modified single touch) for each material. Another key takeaway from the chart is the limits of magnetization. It is pretty clear certain materials will magnetize easier than others. The semi-circle ring, as described under iteration three was constructed of 1018 low carbon steel. Its max field produced from magnetization was around 0.45mT. The next objects tested were three different hacksaw blades likely made from High-Speed Steel (HSS) – a material commonly using in cutting tools due to its hardness. From testing it was clear the three blades were not made equal. The white hacksaw blade (DeWalt) performed much better than its competition reaching a max field strength of .39mT. The white blade nearly reached the strength of the 1018 steel ring despite being made of significantly less material. For this reason, we are led to believe the use of an alloy steel is likely more promising in the creation of permanent magnets than carbon steels. Online information confirms this belief, quoting 1018 steel ideal for its “soft” magnetic properties and suitability as cores for electromagnets.

Future Testing into alloy steels as opposed to carbon steels may yield to more promising results in the creation of permanent magnets. While modern steel grades had not yet been invented during Davenport’s time, the same impurities used to alloy steel existed in Vermont in 1837. Future investigation should look to determine the composition of the metal he used.

5.2 Final Thoughts/Conclusion

Overall, while the exact physical goal of the project was not entirely reached, the investigation and work behind the project can be seen as a success. The project called upon a wide variety of skills in manufacturing, STEM, and communication. A functioning direct current motor was produced; at the minimum necessary machine work was completed to facilitate further testing of new magnetic fields for improved motor operation. The motor demonstrated operation with both a wound and a “semi” permanent magnet field. Additionally, research has provided more insight about the inner workings behind the great invention of the Brandon Blacksmith. The knowledge gained in the project can be applied to many fields of science and engineering today. With the rise of modern electric vehicles and a push to move away from combustion the knowledge presented becomes even more valuable. Electric motors are not disappearing anytime soon, we are witnessing a new age of power technology - an age which can be credited to a poor blacksmith in rural Vermont.

6.0 Equipment and Tools List

Throughout the project, numerous pieces of equipment and tools were used in the exploration, testing and construction of the motor model. They are summarized below:

Industrial Machines:

- Do All Industrial Equipment (WPI Washburn Manufacturing Labs)
    - Engine Lathe
    - Manual End Mill with Digital Readout
    - Bandsaw (Vertical + Horizontal)
    - Drill Press
    - Belt Sander
- Hypertherm 1000 Powermax G3 Plasma torch with Crossfire V1.1 CNC table
- Full Spectrum 48”x36” CO_2 Laser Cutter
- Oxyacetylene Cutting Torch
- Hakko FX-888 Soldering Station
- Weller 100w Soldering Gun

Hand Tools:

- Hand tools common to most machine shops/makerspaces were utilized including:
    - Hacksaw
    - Hand Drill
    - Files
    - Screw Drivers
    - Allen Wrenches
    - Sandpaper/Sanding Block
    - Dremel Hand Router
    - Pliers
    - Hammer
    - Combination Square
- Compass (for verifying magnetic fields)
- Unbranded Horseshoe Permanent Magnet

Lab Equipment/Power Supplies:

- Vernier Lab Pro Interface with Magnetic Field Probe
- GW INSTEK GPS-3303 Laboratory Power Supply
- Lionel Type TW Train Transformer
- Unbranded 100A (1600W) AC Rectifier
- Ford Motor Co. Ammeter (-20A to 20A)
- Blade type Power Switch

Software:

- Autodesk Fusion with CAM Addon
- Logger Pro
- Microsoft Office Suite

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