Magic Magnets

Introduction

The term "magic" in the title is meant to convey the strangeness, in particular, of permanent magnets. To be clear, there are natural magnets, man-made permanent magnets, and electromagnets. Each of these will be discussed in this article, but the major focus will be on the permanent magnets, which display unusual behavior that is still not fully theoretically understood. The perplexities are in the energy of magnets and in their behavior.

Magnets provide a force, do work, and transfer energy without contact. The absence of contact implies a field. The concept of fields is a wonderful construct to explain the behavior of electricity, gravity, and magnetic action at a distance, but we do not really know what they are and the medium of transmission. Magnets are a source of potential energy. The basic functions of magnets are --

1. Exert a non-contact force.
2. Hold something in contact.
3. Induce a voltage in a conductor with relative motion.
4. Separate materials - magnetic from non-magnetic.
5. Sense position or direction, as in a compass.
6.Control other devices, as in actuators via coils.
7. Focus beam of charged particles.

This article will delve lightly into the theory of magnets, describe some practical aspects and some unusual behaviors, while emphasizing the unknowns.

Theory

Charges in motion generate a magnetic field. Similarly, a magnetic field in motion will generate charges. These are the basic principles of electric generators and motors. Those are empirical facts that are known from observation. They are known with certainty and are universally true. The theory of permanent magnets is based on that simple fact that magnetic fields are created from charges is motion.

When we look at a permanent magnet, it appears to be a solid metal. Most permanent magnets are engineered alloys made from a composition of materials with a history of processing to achieve those properties of being magnetic. Still, they are solids. Where are the charges in motion if we are to believe that the magnetic field arises from moving charges? The current thinking is that the moving charges are spinning electrons around the nucleus of atoms. Specifically, it is the unbalanced spin of electrons in the third incomplete quantum shell of ferromagnetic materials - which are iron, cobalt, nickel, and some rare earth metals. These atomic charges in motion fit nicely with the magnetic fields produced in stars and planetary objects that are believed to have molten iron cores in rotation. This makes the theory consistent with natural astronomic observations.

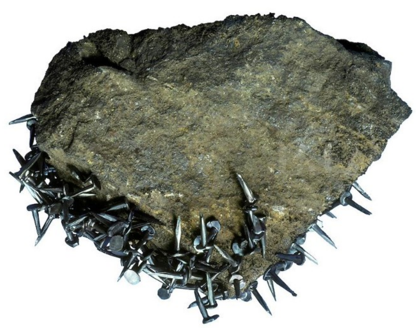
In permanent magnet materials, the atomic magnetic moments clump together into domains about the size of 25 microns in diameter (.000 0025 meters or 0.001 inch). The domains are randomly organized in non-magnetized materials. The process of energizing a material to form a permanent magnet is to expose the material to a very strong magnetic field to orient the domains to be polarized and biased in specific directions. The magnetic moments of the individual domains are then additive to produce a stronger external magnetic field. This is a consistent, believable, and palatable theory that is supported by some good observations. The strangeness is how this field translates into energy that can do useful work, store that energy, and retain that ability for centuries. In other words, what keeps them oriented? Why don't the domains just randomly disperse in accordance with the second law of thermodynamics? The simple answer is that they do, but only after being raised to the Curie temperature. At normal temperatures, the domains remain "frozen". At very low temperatures, near absolute zero, the magnetic behavior becomes even stranger (to be covered later under superconductivity).

The engineering units to quantify that energy is just as strange. Magnetic flux (symbol ϕ) is called "Maxwell" (also called one line) in the CGS system of units and "Weber" in the SI system. Magnetic flux density (symbol B) is "Gauss" or "Tesla". Magnetic potential (magnetomotive force, symbol F) is "Gilbert" or "Ampere-turn". Magnetic field strength (symbol H) is "Oersted" or "Ampere/meter". The mathematics of magnetic circuit equations uses these symbols in algebraic equations that are highly non-linear with many "fudge factors" for reluctance and leakage. They will not be discussed in this article as much of that is just as much art as science. This area of magnetic circuit design is one of the more challenging engineering fields.

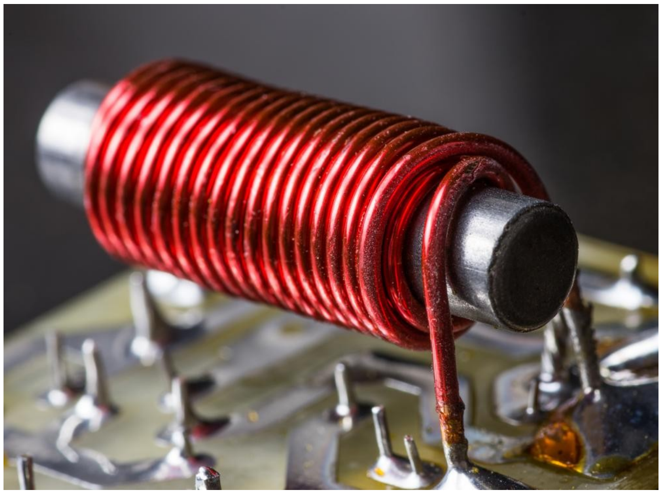
Celestial Magnets

Why do magnets even exist? This is a rather moot question for whom only God knows the answer. Most celestial bodies have magnetic fields that are natural. The Earth has a weak magnetic field of about one gauss. It is unlike the magnetic fields from permanent magnets or electromagnets, which are much stronger, on the order of 3,000 to 12,000 gauss, and are very short range, only several inches. The Earth’s magnetic field is similar to the magnetic fields from other planetary bodies and solar magnetic fields, being also relatively weak but long range, that is, not diminishing rapidly with distance. In that context, the celestial magnetic fields are natural anomalies compared to the man-made magnets. These celestial magnetic fields behave more like a gravity field, which is also weak and long range. This suggests that celestial magnetic fields are not the same phenomena that we experience in permanent magnets from rocks or electromagnets that we create. We can measure the field strength with a sense coil and it reacts with other magnets, i.e. a compass needle, but the celestial magnetic field does not make iron move.

Celestial magnetic fields are believed to be created by molten iron or other ferromagnetic material with charges in motion. The mystery is that many of these large bodies are stars that are also very hot, so thermal energy seems to be coexistent with magnetism. If it is just the convection currents created by the thermal agitation, then the theory is consistent. If it is also the additional thermal motion of the high energy atoms and molecules, then the theory is still good if there is some mechanism for aligning the domains. The problem with this line of reasoning is that thermal energy tends to randomize things and in fact will de-magnetize a permanent magnet.



Lodestones are natural permanent magnets resident in the earth rocks that have been around for millennia. They are an ore of magnetite, an oxide of iron. Where did they come from? One theory is that lightning bolts may have provided the initial strong magnetic field to magnetize them permanently. Lodestones were initially described about 600 BC, but were around prior to their formal discovery and documentation. This speaks of the permanence of permanent magnets. If they store energy, then the perplexing engineering question is "How can they store energy for so long with out going stale?" This same question applies to all permanent magnets today.



Electromagnets

An electric current flowing in a wire will produce a magnetic field around the wire. If the wire is a coil of many turns, then the magnetic field is strengthened. In addition, if a soft magnetic material is placed inside the coil, then the magnetic field is magnified even further. The soft magnetic material being iron, cobalt, or nickel. Why this happens is theoretical and based on the surface atoms and their electron spin alignments, called “Amperian Currents”.

A soft magnetic material is one that will not retain a significant residual magnetic field when the current is discontinued. That is, the magnetic field will collapse quickly. In engineering terms, it has a narrow hysteresis loop. In contrast, a hard magnetic material will retain a strong magnetic field once energized. Hard magnetic materials have a very wide hysteresis loop. Permanent magnets are made from hard magnetic materials. They are highly engineered with specific composition and processing steps.

Electromagnets are an engineered device. They do not exist in nature. They are a human invention for the purpose on being able to turn on and off a magnetic field by controlling the current. In addition, they can push or pull by reversing the current. There is an analogy here that helps us understand permanent magnets. We understand electromagnets as a magnetic field created when we turn on a current, so it is an easy step to imagine permanent magnets as a current of some kind, that is, charges in motion. There is a significant difference though in that we cannot turn on and off the imaginary current in a permanent magnet. Since the "current" cannot be controlled in a permanent magnet, then it cannot transmit information like an electromagnet can. The field of a permanent magnet, however, can be controlled to some extent by placing other materials near it to shunt the field, direct it, or to enhance it.

The magnetic field surrounding a current carrying conductor is really the operative phenomena that transmits information over a distance. When a voltage is applied to conductor, a current is created in that wire. We have been taught that the electron flow is what transmits information, but the velocity is too slow for that to happen. The drift velocity of electrons along a copper wire is about 10 cm per second. There is no way for that signal to travel hundreds of feet to close a switch across town. The magnetic field surrounding the wire is established almost instantaneously and that can travel to the other end to actuate some device even miles away, apparently without delay. A permanent magnet cannot do this. I suppose it is possible to imagine that the electron flow communicates to it's neighbor, who passes that influence along to it's neighbor, and so forth down the line in an almost instantaneous fashion. The controversy remains as to what actually transmits information -- is it the electron flow or is it the magnetic field created by the electron flow?

So the primary difference between electromagnets and permanent magnets is that the electromagnet has the ability to control some device and to transmit information over long distances. The permanent magnet is only a local device. Combining the two into a configuration in close proximity makes wonderful electric motors and generators.

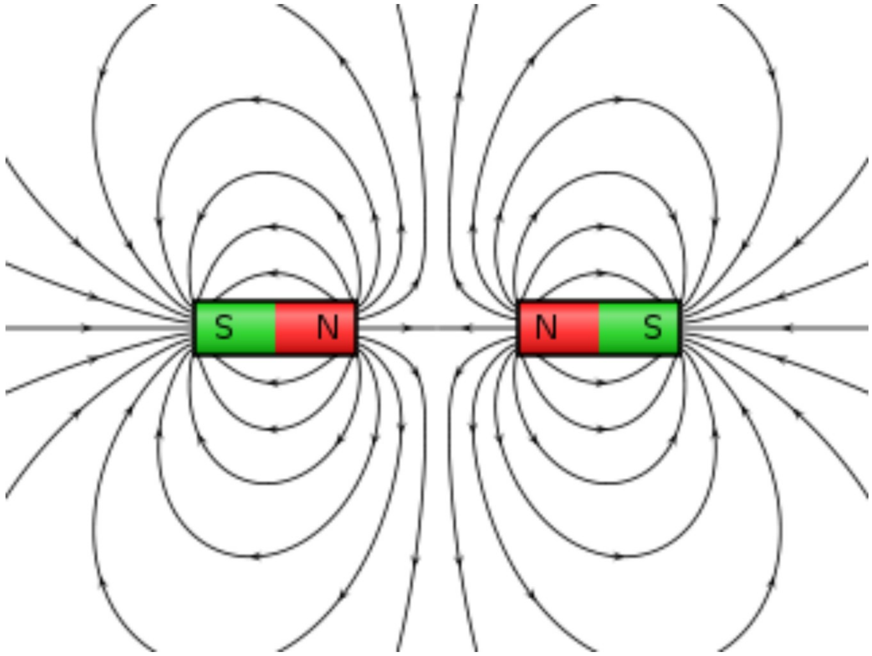
Materials

Hard permanent magnet materials are alloys of iron, nickel, cobalt, and some rare earth minerals. These hard magnetic materials can accept a strong magnetization and keep it - thus becoming permanent. In contrast, soft magnetic materials, of which low carbon steel and cast iron are two, will not retain the strong magnetization after the energizing force (the magnetic field strength H) is removed. The soft magnetic materials can be magnetized to very large flux densities, but can't keep it.

One anomaly here is austenitic stainless steel. It contains much iron and nickel, but is transparent to magnetic flux. That is, it cannot be magnetized, not even as a soft magnetic material. Ferritic and martensitic stainless steels can be magnetized to some extent. The differences appear to be in the crystals structures and prior processing steps.

What is so special about the hard magnetic materials that they can become permanent magnets, while other materials are excluded? The answer, theoretically, is the uncompensated electron spins in the 3rd shell of these atoms. Being uncompensated means that the individual atoms possess a magnetic moment at the atomic level. That is, they are tiny magnets themselves because they have a charge in motion. These tiny magnetic moments are normally randomly oriented, but can be coerced into alignment when exposed to an external magnetic field. Thereafter, they retain that alignment and appear "permanent". The external field can be another more powerful permanent magnet, or it can be a strong pulse from an electromagnet. The rare earth permanent magnets, samarian cobalt and neodymium iron boron, can only be energized by strong pulses from electromagnets. The domains are aligned within the magnetizing fixture. So permanent magnets get their initial energy from another magnet. The mystery is how do they keep it for so long. Why does it not leak out? There is an external flux in the form of a field. This field, supposedly, stores energy and conducts energy. How come that energy does not just evaporate away into the surrounding space?

The production of a permanent magnet is just as much a recipe of material composition as it is a history of processing. This is the art in magnet production. So we know how to make a permanent magnet, but we don't know what mechanism keeps it that way. It stores energy by some unknown mechanism that will be discussed later in another section.



Field

The magnetic field around and within a magnet is visualized as lines of flux. Most people have seen the iron filings sprinkled around a magnet and seen how they orient to line up with what we have described as "lines of flux". What is flux anyway? The answer is still an unknown, but we have at least created a word to describe what we imagine and a mathematical symbol, ϕ. Early investigators contrived the concept of flux to describe what is believed to be happening in the field.

Flux has been likened to electric current. This makes us happy because we know what electric current is and we have algebraic equations to describe current behavior is electric circuits with voltage and resistance. In an analogous manner, if flux in a magnetic circuit is likened to current in an electric circuit, then we can create analogies to electric voltage and electric resistance, which are magnetomotive force F, and reluctance R. The magnetomotive force, F, is what drives the flux around a magnetic circuit and the reluctance, R, is what inhibits it. The magnet creates the magnetomotive force. We can then derive an analogous equation to Ohm's Law V = IR. The basic DC magnetic circuit equation is F = ϕR. Other design equations for magnetic circuit analysis are derived from this. Life is good and the Earth still spins in the correct direction. But it is not that simple. If the magnetic flux is alternating, or just being turned on and off, then hysteresis becomes active, the behavior is non-linear, heating is happening, and the analysis is more complicated. I suppose we can compare this to AC circuit theory, but alternating magnetic field behavior is not that well developed. Furthermore, if the magnetic field is made strong enough (greater than 50 Teslas), then the material (iron) can come apart in an explosive manner. So the material stores magnetic energy, but at some level it can no longer contain it within the structure.

The analogy to electric circuits is not perfect. First, when electric current flows in an electric circuit, the resistance causes heating. Flux flowing in a magnetic circuit does not cause heating (unless the magnetic flux is alternating and there are hysteresis losses). Second, when the voltage is removed, the electric current stops flowing. When the magnetomotive force is removed from a magnetic circuit, that is, the electromagnet is turned off or the permanent magnet is removed, some residual flux remains in materials. In addition, when the current is abruptly cut off in a coil, then there is a transient inductive effect with a large pulse (a kick back) as the magnetic field collapses, because energy was stored in the magnetic field. Third, the analogy between electrical circuits and magnetic circuits has one profound difference in that electric current flow through a resistance constitutes energy dissipation whereas flux flow through a reluctance does not lose energy but rather constitutes energy storage.

Magnetic flux appears to be a form of energy. Iron conducts magnetic flux very well. It seems to draw energy from the magnet and multiply the flux. The iron in close proximity to the magnet enhances the magnet and makes it look bigger. How is that possible? Does the magnet itself become weaker as the flux is drawn away from it? As the iron is brought closer to the magnet, does some of that energy flow into the iron, and when withdrawn, does it return to the magnet? The iron magnetic circuit conducts flux and when the magnetic circuit is broken with an airgap, the flux changes but continues to flow. This is different than an electric circuit, for when the switch is opened, direct current stops flowing. When the iron is completely withdrawn, making the magnet "open circuit", the energy of the flux remains and is not depleted.

Philosophically, what does it mean to "conduct" flux? The flux is always there as witnessed by the iron filings lining up to the field. The flux is measurable with a guassmeter. It is static and not moving, sort of like gravity which is always there and measurable. Gravity does not flow in a circuit. These are the mysteries of the "field". Is the flux a fluid, a particle, a wave, or something else? The field, the flux, and the energy are invisible. They are abstract concepts. What is not abstract is the motion produced when iron strays nearby.

Energy

Let's start with the fundamental atomic charge in motion. If the electron spin creates a magnetic dipole, then that becomes a tiny magnet. Multiple atomic dipoles can sum to form a domain, and the domains can be aligned to create an external magnetic field. The magnetic field is a source of energy because it can cause something to move. Specifically, it is perceived as potential energy. It is lying in wait for something to get close, then snatches it. The permanent magnet is a magnetomotive force that drives a flux, similar to a voltage being a force that can drive a current. So the permanent magnet is a type of potential energy that gets it's beginnings in the atomic electron spins. What keeps the electrons spinning? What is it's source of energy? I don't know, so I will leave that question for the physicists and philosophers.

The story gets even more complicated. The magnet is a form of energy in that it can exert a force to make a body move. The force comes from the field because it begins to move even before contact. The field obviously gives energy to the body - energy of motion. Does the body draw some energy away from the field? Does the field lose some potential energy briefly as the body draws near, then attains some condition of equilibrium as the magnet and iron slam together and remain stuck? And when the iron is withdrawn, does it return that energy back to the field? The fundamental questions are:

"How is the energy stored?"

"How is it dissipated?" and

"How is it transferred?"

Some experiments with electromagnets can shed light on these questions with measurements of voltage and current.

A magnetic field has energy in storage. We know that because it takes energy input into the material to create it and a field can move metal, but only specific kinds. The energy is microscopic, possibly atomic. The permanent magnet does not seem to give up any energy in doing work. It maintains it’s original flux density even after operating a motor for many hours.

Mechanical energy stored within a material is typically described as a stress or strain. Strain is pressure within a volume. If I multiply pressure x volume, then I will get work energy.

Pressure, Lb/ft^2 x volume, ft^3 = work energy, Lb-Ft

The suggestion here is that a magnet is in strain storing internal energy. It can not only store that energy, but hold it for an indefinite period of time - strange.

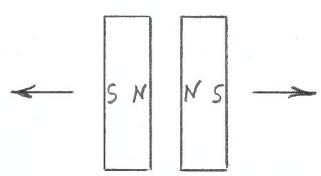
Behavior

The strangeness of permanent magnets is how they behave. They are not isolated and passive solids. They react to and respond to the material around them. They are environmentally sensitive. This does not happen until they are energized. A magnetic material, prior to being energized, is just that, a metal alloy. It has no magnetic properties, which is beneficial for safe handling. It is always preferred to delay energizing a magnetic material until as late as possible in the manufacturing of a device. Ideally, it should be energized after assembly into it's final configuration. This avoids the safety hazards of handling and picking up tramp metals of filings and dust that must be removed later.

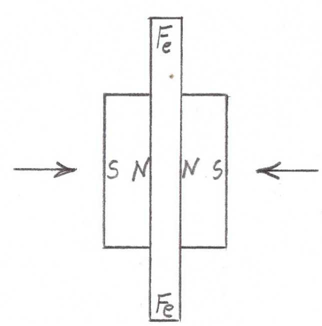
A magnet has a holding power and a reach power. These characteristics are determined by the method and level of energizing, by the shape, and by the ferrous pole pieces nearby. Energizing a magnet is a separate art and science left to those skilled in the art. However, it should be emphasized that energizing a powerful magnet must be done with care so that it is done in a controlled environment with out additional ferrous metals nearby. The operators should be careful about bringing any metal objects into the room, like pens, jewelry, coins, or even eyeglass frames of metal. Magnetic materials can be energized, de-energized, then re-energized at will multiple times.

Every school child knows that like poles repel and unlike poles attract. This intimate behavior is complex. It depends on distance and whats in that space. The behavior is highly non-linear and the flux leaks around to unexpected areas depending on the surrounding material. When attracted or repelled by another magnet, do they exchange stored energy? What happens to the field? More questions.

The first anomaly is that either pole will attract iron. A north pole of a magnet will pick up and stick to a piece of iron. A south pole of a magnet will likewise pick up and stick to that same piece of iron. Why is that so? I do not have an answer. There are other anomalies.



In this figure, two north facing magnets repel.



When a piece of iron is placed between them, then they will attract. How is that possible?

The next anomaly is a stack of magnets in a gravity field, Figures 4a &4b.

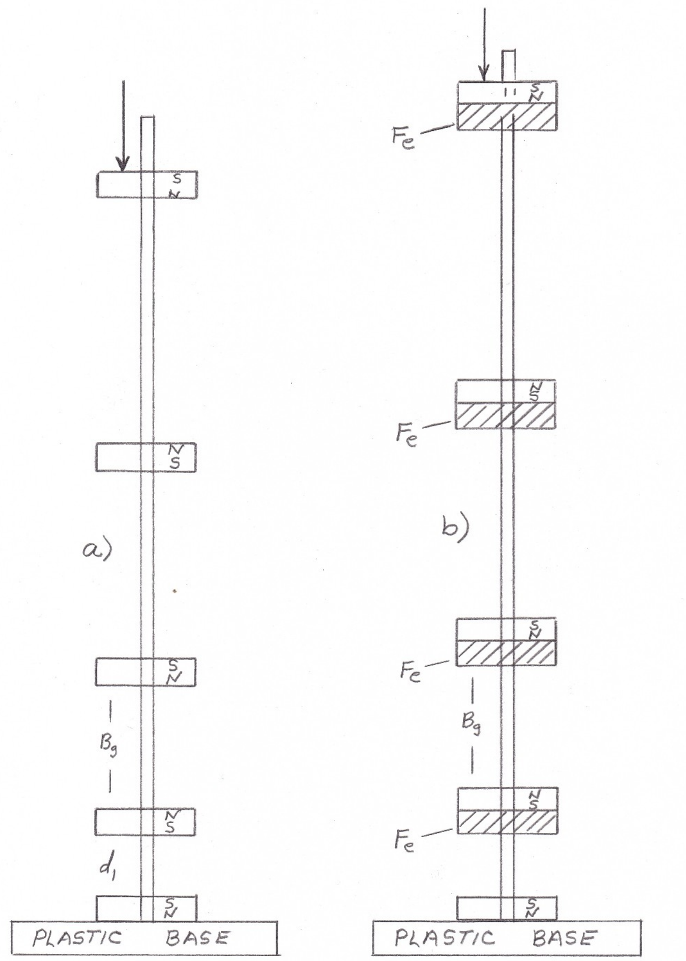


Figure 4a shows a stack of rare earth magnets on an aluminum or brass rod (non-magnetic) with a clearance hole so that they can slide up or down. They are oriented vertically in a gravity field. Two forces are operative in this example. Gravity tends to pull them down, but the magnetic repulsion keeps them apart.

The magnets are arranged so that like poles repel each other and the magnets stay away from each other. That is as expected. They are suspended as if mounted on an invisible spring. They are levitated in a gravity field. How does a magnet stay suspended in a gravity field and not lose or gain energy? The bottom two magnets have some separation distance, d_1. The separation distance gets progressively longer going up the stack. If I press down on the top magnet, then the spacing adjusts in proportion to the applied force. They all sag down as if the spring between each of them is compressed. The mass of each magnet has some potential energy in a gravity field, but they don't drop. The magnetic flux between them also has some potential energy (similar to a mechanical spring) that keeps them suspended. The flux between each magnet can be visualized as a spring that has some elasticity. One strange behavior is that the flux density between each magnet decreases as the top magnet is depressed, as measured with a gaussmeter. Further downward force compresses the spacings to be smaller and the magnets will continue to resist compression as if the magnetic spring gets progressively stiffer. The stack can be fully collapsed with sufficient force such that the airgaps reduce to zero. The implication is that the physical downward force fully overcomes the magnetic spring effect. Some effort is needed to hold them down.

Figure 4b Shows a similar arrangement of stacked rare earth magnets, but this time there is an iron ring below each magnet. The orientation is the same with like poles facing each other so that they repel. Applying a downward force to the top magnet will similarly compress the stack up to a point. The flux density between each magnet will likewise decrease, but a point will be reached where they strongly attract, slam together, and stay stuck. I will attempt some reasoning to this without admitting to a full theoretical explanation.

A magnetic field stores energy. The quantity of potential energy that it stores depends on the amount of compression, or the length of the airgap. A smaller airgap stores more energy. The magnet itself does not store the energy, but rather the field does. So a piece of space with some magnetic flux co-habitating that space, can store energy. The amount of compression in the airgap represents strain energy applied to the field. This observation suggests that a relation can be found between the quantity of compression and the quantity of strain energy resident in the field by relating it to the gravity force. Some experimentation is in order here. As to the coming together of like poles in figure 4b, that can be likened to the effect observed in figure 3b. Still, the presence of the iron between the like poles is an anomaly.

The environment around a magnet profoundly affects its behavior. The permeability of the surrounding space can enhance the magnet strength, direct it elsewhere, and focus it.

The vibration and temperature that the magnet is exposed to also affect it. Both of these factors weaken it. They weaken the magnet material itself, not the field. Permanent magnets exposed to an oscillating motion, like vibration, will cause it to lose strength. A large shock, as from a steel hammer impact, can seriously weaken a permanent magnet. The amplitude and frequency of vibration is not well characterized, but the effect is well known. Vibration is known to relax residual stresses from localized welding and this is known to be a time and temperature effect. That is, residual stresses in metals will naturally relax over time and that effect is accelerated at elevated temperature. The same may be true for permanent magnets. This vibration affect does not apply to electromagnets.

Elevated temperature alone will cause permanent magnets to lose strength. This is a material property and not related to the field, except that the flux density will decrease with temperature because the magnet is not capable of supporting it at the same level. A more serious effect is total de-magnetization at the Curie temperature. The magnetic dipoles randomize, or the domain wall bonds are removed. After being de-magnetized, permanent magnets can be fully restored to their original strength by being energized again. This exposure to vibration and temperature begs the question of "What keeps the magnetic dipoles oriented"? Why do they just not randomize themselves over time as the material ages?

These anomalous behaviors sing loud and clear that the nature of permanent magnets is not fully clear to our linear and symmetric mindsets. Still, permanent magnets are used ubiquitously in many consumer and engineered products. They can be turned on & off at will. They can be focused, channeled, amplified, and shunted. Therein lies their great utility.

Superconductivity

A superconductor is a material that loses electrical resistance when cooled to a low enough temperature. This phenomena was first observed in 1911 when approaching absolute zero (around 4°K). The resistance appeared to vanish abruptly as the current continued to flow indefinitely with no apparent applied voltage. The strange behavior is that the superconducting material also completely excludes any magnetic field. That is, a magnetic field will normally penetrate the material at normal temperatures, but cannot do so when it becomes superconducting. If the external magnetic field is increased strong enough to penetrate, then the superconducting behavior is also lost. So there appears to be a relationship between magnetic fields and superconductivity. Both of these phenomena are theorized to be related to electron behavior.

Conclusions

One conclusion is that we do not need to fully understand permanent magnets to use them. Any final theory of permanent magnets must explain --

1. What is the source energy?
2. Why do north and south poles attract iron equally?
3. Why does the force of attraction increase dramatically with small airgaps?
4. How can a magnet repel and support another magnet across empty space?

The unexplained character of the magnetic field is that it just exists with no known cost. It does not consume energy, nor transmit any. However, when something strays near, the magnet grabs it. When a conductor moves within the flux field, then it can generate some energy as a voltage. The motion of the conductor is the source of energy for the induced voltage. If the magnetic field is undisturbed, then it is content to exist and remain passive not bothering anyone. It has an appetite for iron, and nickel and cobalt.