Magnetic Materials: The Atomic Origins of Magnetism

Subhan Razzaq – April 2026

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Introduction:

When a magnet is held up to different materials, the interactions between the magnet and the material can vary depending on the properties of the material. While iron sticks strongly, aluminum barely reacts, and materials like copper or water are sometimes pushed away by a tiny amount. This behaviour is not just random but comes down to the atomic structure of the material, like how electrons inside the atoms of the material are arranged and interact with each other and the external magnetic field. Materials fall into one of three main categories: diamagnetic, paramagnetic, and ferromagnetic. This write-up delves into where magnetism comes from at the atomic level, explains the differences between the three categories of materials, and discusses why they matter in the field of engineering.

The Physical Origin of Magnetism:

Magnetism in materials comes from two properties of electrons: orbital motion of electrons around the nucleus and the intrinsic spin of electrons. The orbital motion of electrons around the nucleus acts like a small current loop and produces a magnetic dipole moment. The intrinsic spin of the electron also produces a magnetic moment even though the electron is not physically spinning in a classical sense. In most atoms, electrons are paired up with opposite spins so that their moments cancel, but some atoms have unpaired electrons that leave the atom with a net magnetic moment. Whether a material reacts strongly or weakly to magnetic forces and magnets, critically depends on these atomic moments and whether they cancel completely, partially, or line up with each other. A key parameter used to describe the strength of a material's magnetic response is called magnetic susceptibility, χ_m, which relates the magnetization M to the applied field H through the relationship $M = \chi_m H$. The relative permeability is related to the magnetic susceptibility through the equation: $\mu_r = 1 + \chi_m$. Figure 1 below shows two sources of the electron's magnetic moment.

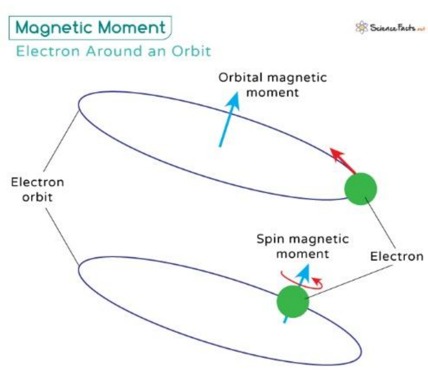

Figure 1. Shows the sources of an electron's magnetic moment adapted from [1].

Diamagnetic Materials:

Diamagnetic materials are materials that have all their electrons paired up resulting in the net magnetic moment of each atom being zero when no field is applied. When an external field is applied, the orbital motion of the electron shifts in a way that opposes the field, which is a consequence of Lenz's law ($\varepsilon = -N\frac{d\phi}{dt}$). This shifting produces a very weak negative magnetization, meaning the material is slightly repelled from the magnet. In this case, the susceptibility χ_m is small and negative usually on the order of -10^{-5}. Common examples of diamagnetic materials are copper, gold, silver, water, and bismuth which is the strongest naturally occurring diamagnet. Diamagnetism is present in almost every material but is overpowered by stronger effects in paramagnetic and ferromagnetic materials so it only shows up and matters when those effects are absent. An application of diamagnetic materials is diamagnetic levitation, where a piece of pyrolytic graphite is suspended above a strong magnet.

Paramagnetic Materials:

Paramagnetic materials have atoms with unpaired electrons, so even without an external field, each atom has a magnetic dipole moment. However, thermal motion causes these moments to point in random directions, so the bulk material has zero net magnetization. When an external field is applied, the dipoles partially align producing a weak positive magnetization. In this case, the susceptibility χ_m is small and positive usually in the order of 10^{-5} to 10^{-3}, and it decreases with temperature according to Curie's law $\chi_m = \frac{C}{T}$, since higher temperatures result in alignment being more randomized. Examples of paramagnetic materials include aluminum, platinum, magnesium, and liquid oxygen. A major application is MRI scanners, where paramagnetic compounds are used as contrast agents to enhance image quality.

Ferromagnetic Materials:

Ferromagnetic materials are the ones most people associate when they hear magnetic. Their atoms have unpaired electrons like paramagnetic materials, but they also have strong quantum effects like the exchange interaction, which causes neighbouring moments to line up with each other. This causes the material to break into regions called magnetic domains, where all the dipoles point in the same direction. In an unmagnetized piece of iron, these domains point in random directions and cancel out on average which is why a block of iron alone does not act as a magnet. However, when an external field is applied, the domains that are aligned with the field grow until the material is saturated. In this case, the susceptibility χ_m is large and positive usually in the order of 10^2 to 10^5, which is why ferromagnets respond so strongly magnetically. Ferromagnetic materials also retain some magnetization after the external field is removed which is what allows permanent magnets to exist. If the material is heated above a certain temperature called the Curie temperature, the thermal energy breaks down the domain alignment and the magnet becomes paramagnetic. Common examples of ferromagnetic materials are iron, nickel, and cobalt. Ferromagnets are used in almost every major electrical technology like electric motors, inductors, and hard drive storage.

Summarized Comparison:

Table 1, as seen below, summarizes the three categories of materials and their magnetic properties.

Table 1. Summary of the three categories of materials.

Type	**Source**	χ_m	**Examples**	**Response**

Diamagnetic	Paired electrons, induced opposing moment	Small, Negative ($\sim -10^{-5}$)	Cu, Au, H_2O, Bi	Weakly repelled
Paramagnetic	Unpaired electrons, partial alignment	Small, Positive ($\sim 10^{-5}$ to 10^{-3})	Al, Pt, O_2 (l)	Weakly attracted
Ferromagnetic	Unpaired electrons, exchange interaction, domains	Large, Positive ($\sim 10^{2}$ to 10^{5})	Fe, Ni, Co	Strongly attracted, retains magnetization

Engineering Relevance:

The range of susceptibility values across the categories allows engineers to pick materials based on the magnetic behaviour they need for their purpose. Ferromagnets are crucial for power electronics and data storage as their permeability makes them ideal for transformer and inductor cores. They also retain their magnetism, making them essential for use in hard drives and as permanent magnets. Paramagnetic materials are used in MRI imaging and in precision magnetic sensors. Diamagnetic materials are important in superconducting applications as superconductors behave as perfect diamagnets that expel magnetic fields which is crucial for magnetic levitation in maglev trains.

Conclusion:

The three categories of magnetic materials can all be explained by looking at the arrangement of electrons inside their atomic structure. Diamagnets have all paired electrons and respond weakly by opposing the applied field while paramagnets have unpaired electrons that align weakly with the field causing a weak response aligned with the field. Ferromagnets have unpaired electrons that align strongly due to the exchange interaction phenomena and the formation of magnetic domains. Understanding these differences is what allows engineers to make crucial decisions to choose the right material for any application where magnetic behaviour matters and plays an important role.

References:

[1] S. Bhuyan, “Magnetic Moment: Definition, Formula, and Examples,” *Science Facts*, Oct. 18, 2024. https://www.sciencefacts.net/magnetic-moment.html

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[3] D. J. Griffiths, *Introduction to Electrodynamics*, 4th ed. Cambridge, UK: Cambridge University Press, 2017.

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