NATIONAL HIGH MAGNETIC FIELD LABORATORY

Fundamentals of Permanent Magnets

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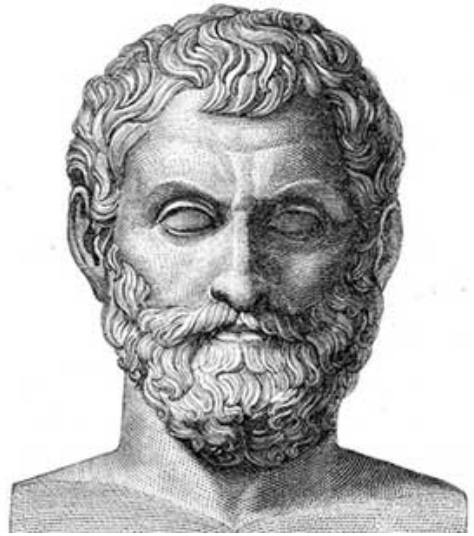
Earliest Known History of Magnetism

Magnetism has been known from at least the time of Thales in Greece around 600 BC.

It has been claimed that the compass was in use by the Chinese as early as 2500 BC. Therefore,…

The discovery and use of magnetism and magnetic materials constitute one of Man's earliest scientific endeavors.



Thales

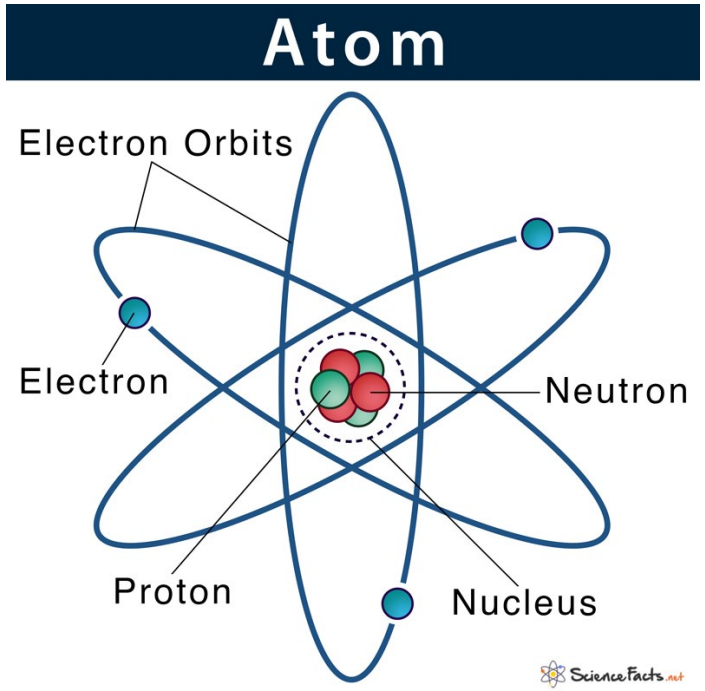
Early Chinese Compass *ca.* 400 BC

The importance of magnetism and Man's need for versatile magnetic materials has only **increased** with time.

What is magnetism?

The **Standard Model** of Physics is our best understanding of three of the four known fundamental forces:

1. The strong nuclear force
2. Electromagnetism
3. The weak nuclear force
4. Gravity



The source of electromagnetic force in materials is the **electron**.

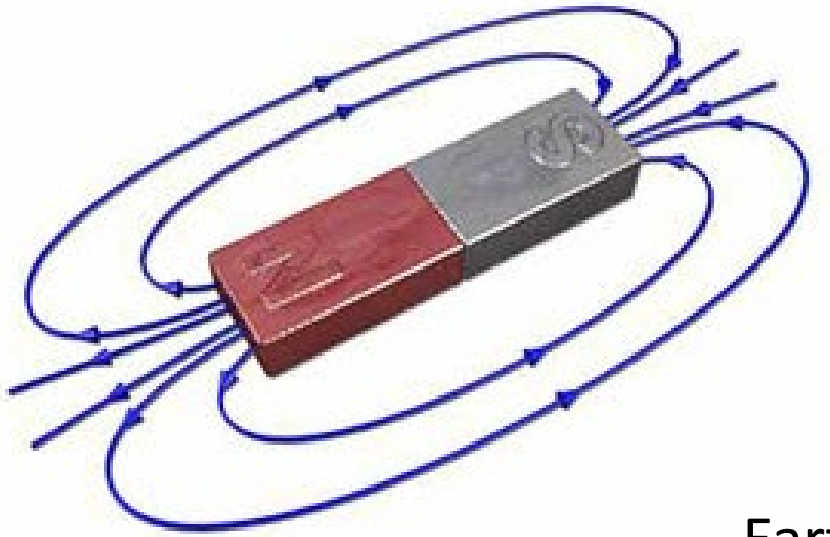
The electron is a particle with a single unit of negative electric charge. It is also a tiny magnet.

Two types of magnetism

Induced magnetism: magnetic force induced by a current of electric charge.

Permanent magnetism: magnetic force that exists in the absence of an inducing current.

Permanent magnets,
Or just, magnets



e.g. Samarium Cobalt,
Neodymium Iron Boron

cgs units: Oe, Mx, G

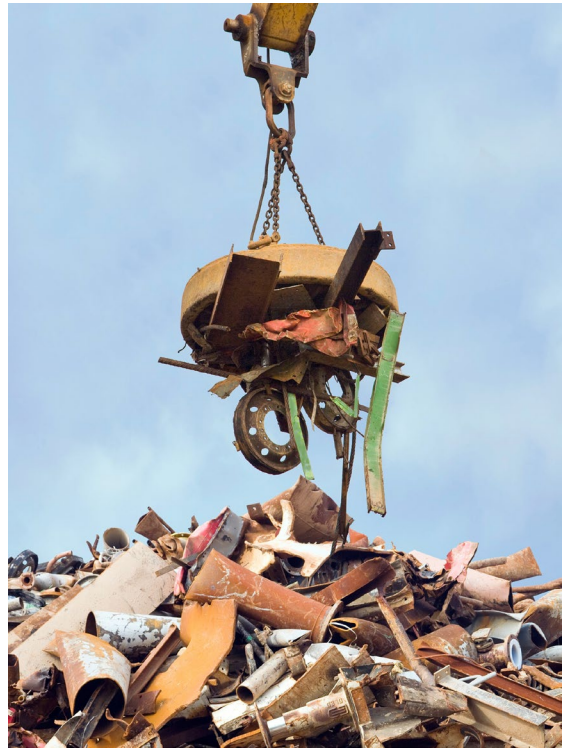
SI units: A/m, Wb, T

1 T = 10,000 G

Earth's magnetic field ≈ 0.5 G

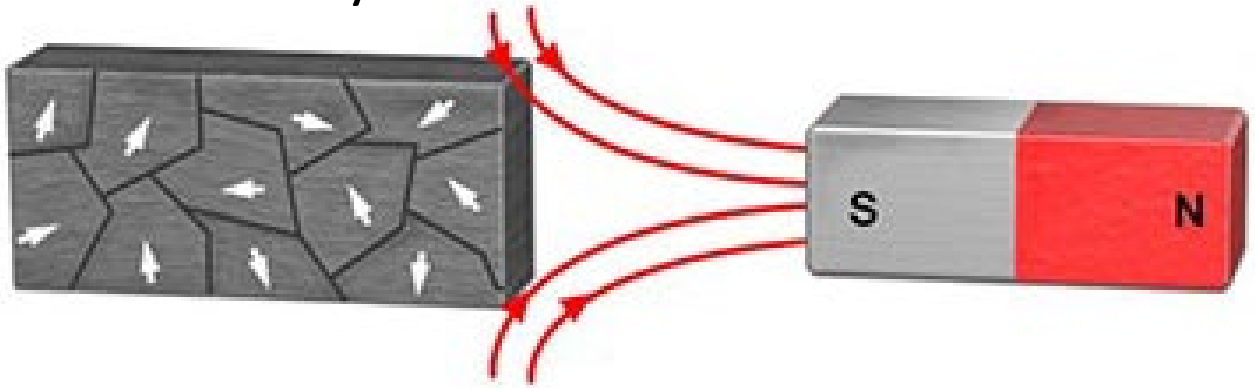
Electromagnets
(Electrically switched on/off)

e.g. Junkyard magnet,
MRI

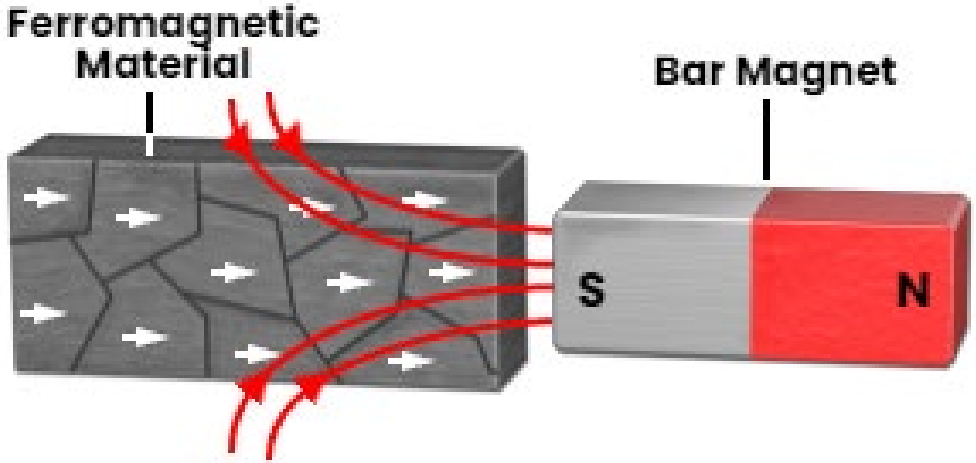


Permanent Magnets

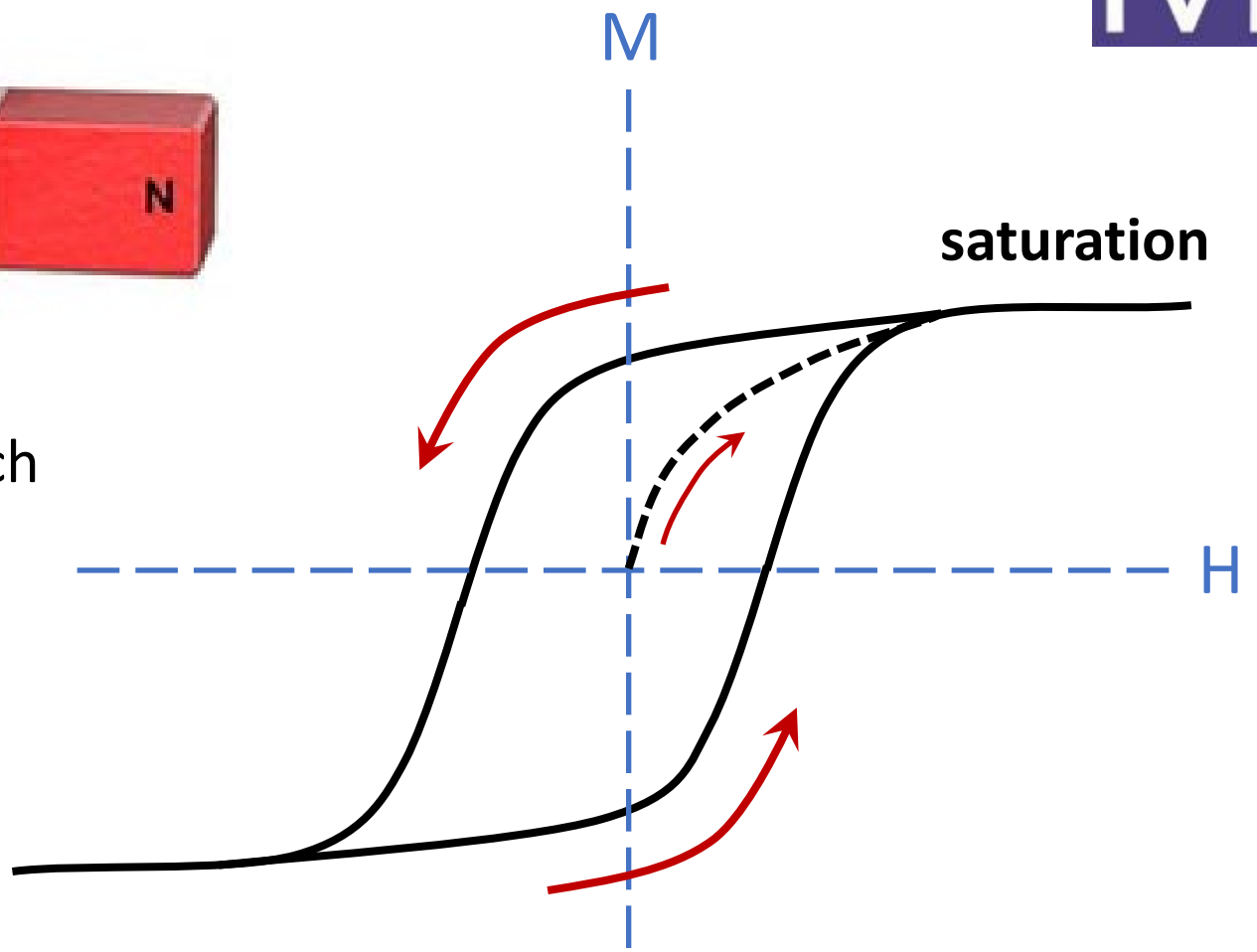
Domains Randomly oriented



Domains – regions within a magnet in which the magnetic ions are aligned



Domains fully aligned by external field, saturation



Magnetic Hysteresis Loop

Magnetic Concepts

Magnetization – the strength and direction of the magnetic field produced by a permanent magnet. Also called the **magnetic moment**.

Magnetic Susceptibility – the amount and direction of magnetization induced by an applied magnetizing field.

Paramagnetic – the material's magnetization **aligns** with the applied field and is **attracted** into the applied magnetic field.

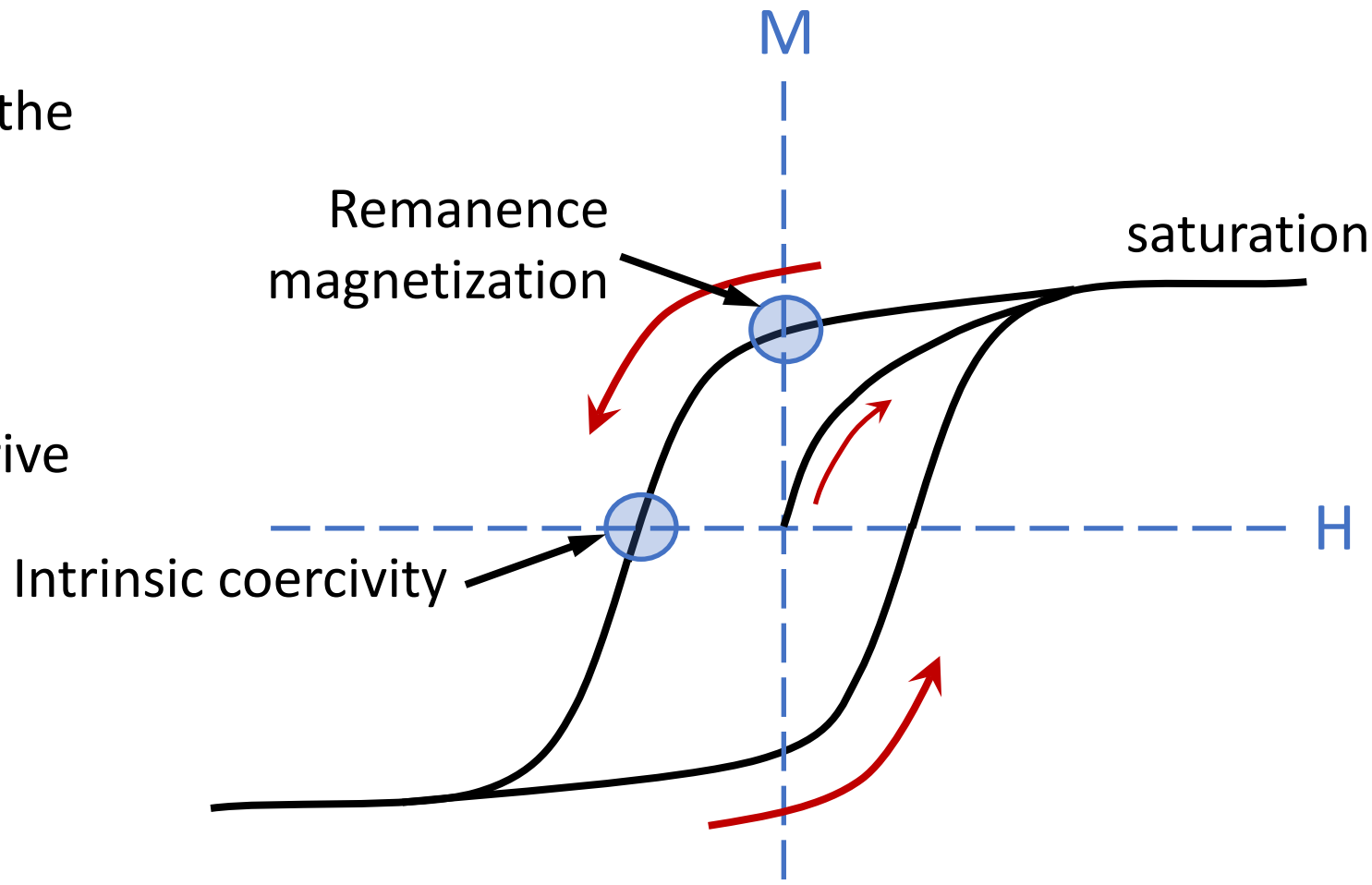
Diamagnetic – the material's magnetization **anti-aligns** with the applied field and is **repelled** from the applied magnetic field.

Saturation – the maximum magnetization is called the saturation magnetization

Magnetic Hysteresis Loop

Remanence – a measure of the remaining magnetization when the magnetizing field is removed.

Coercivity – a measure of the magnetizing field required to drive the magnetization to zero after being saturated.



Magnetic Hysteresis Loop

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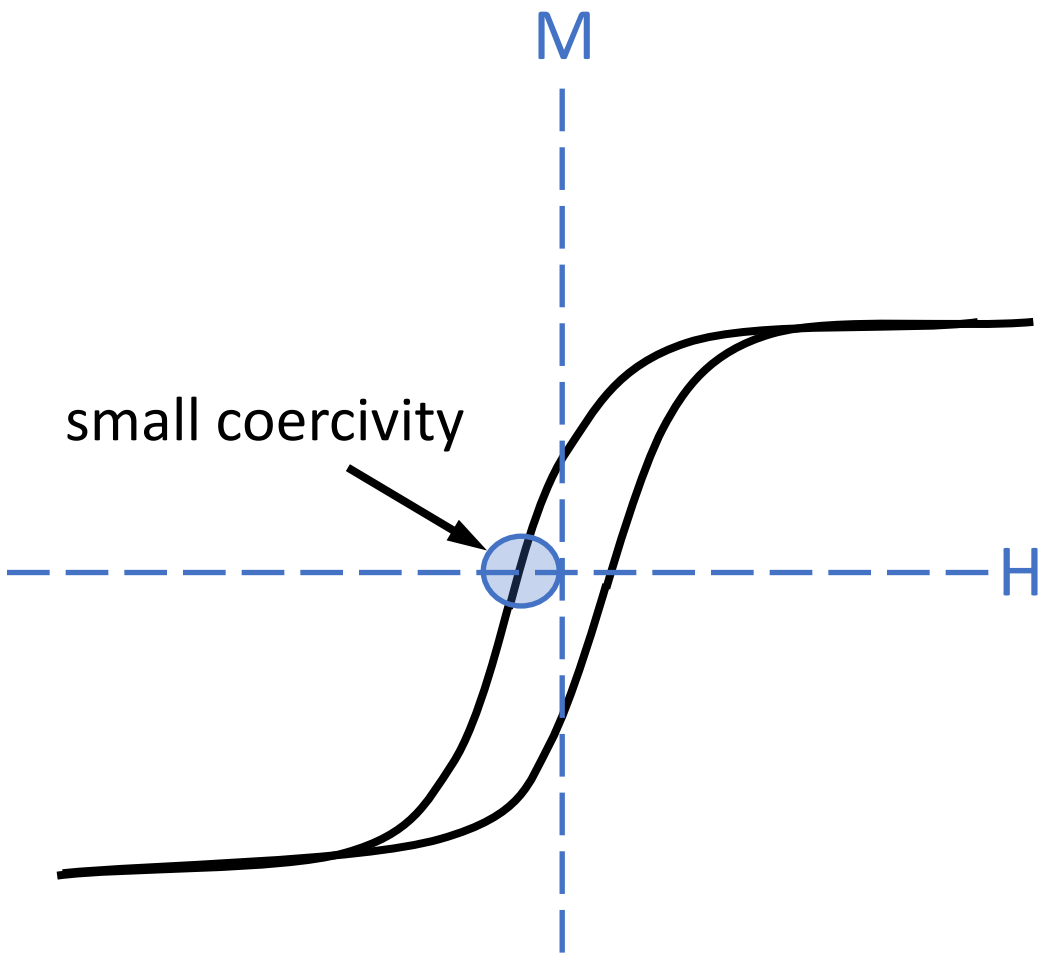
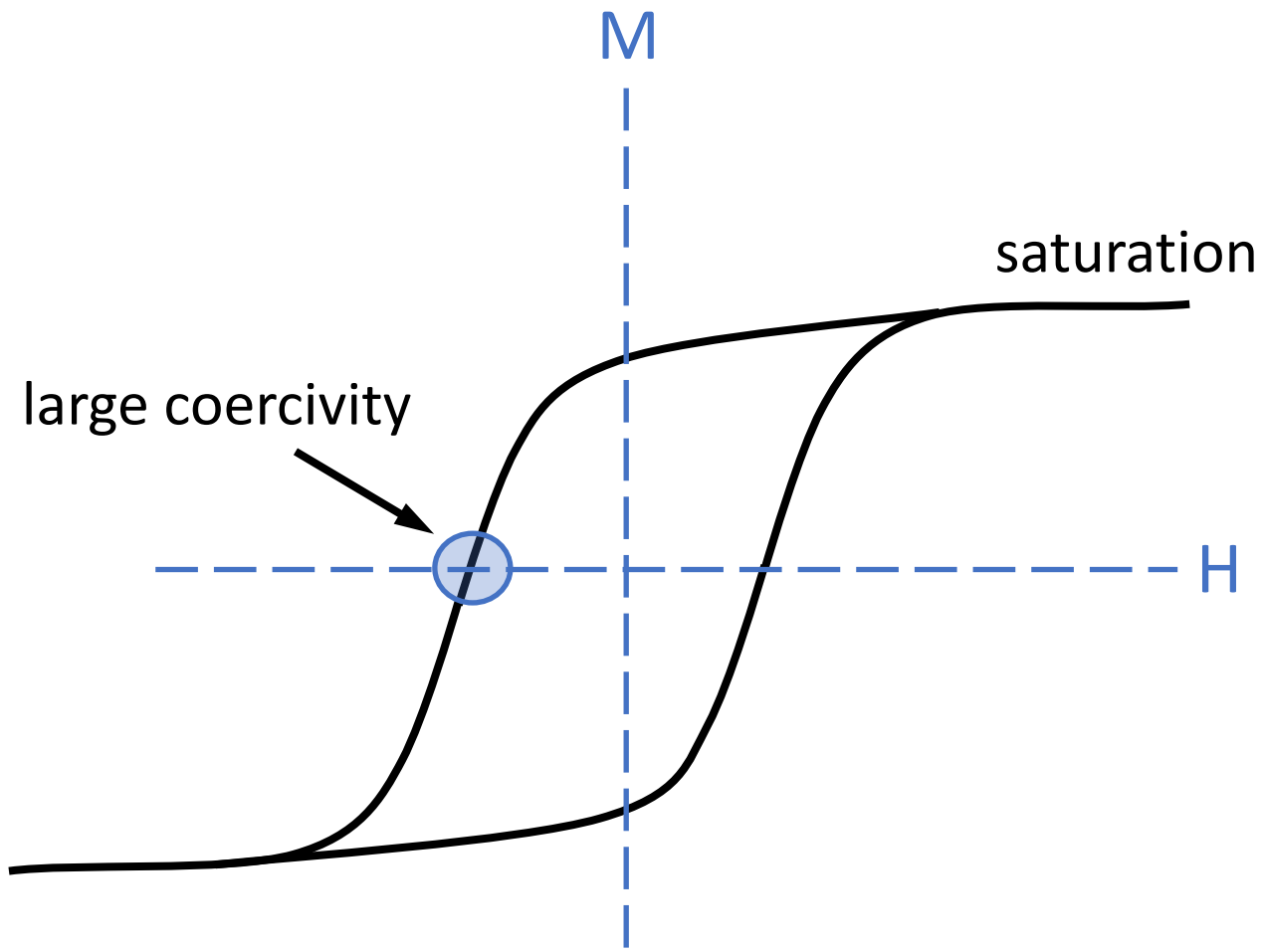
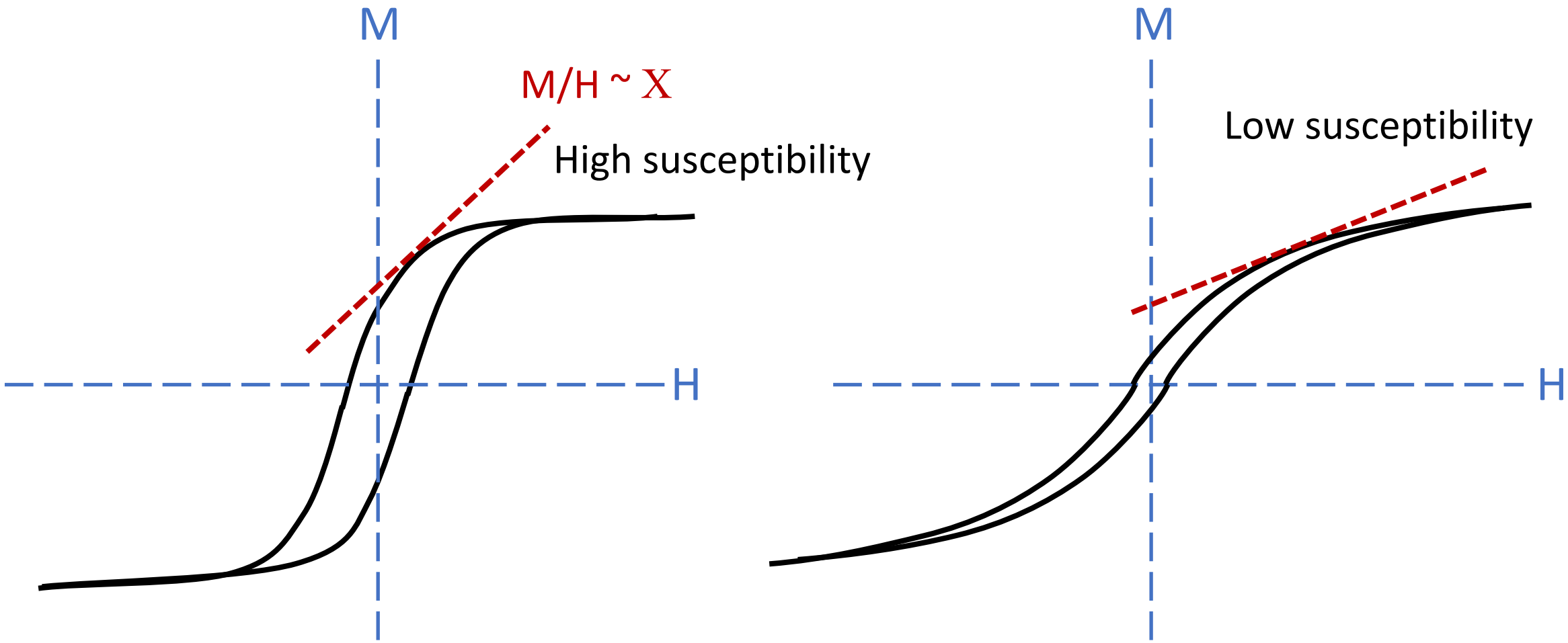




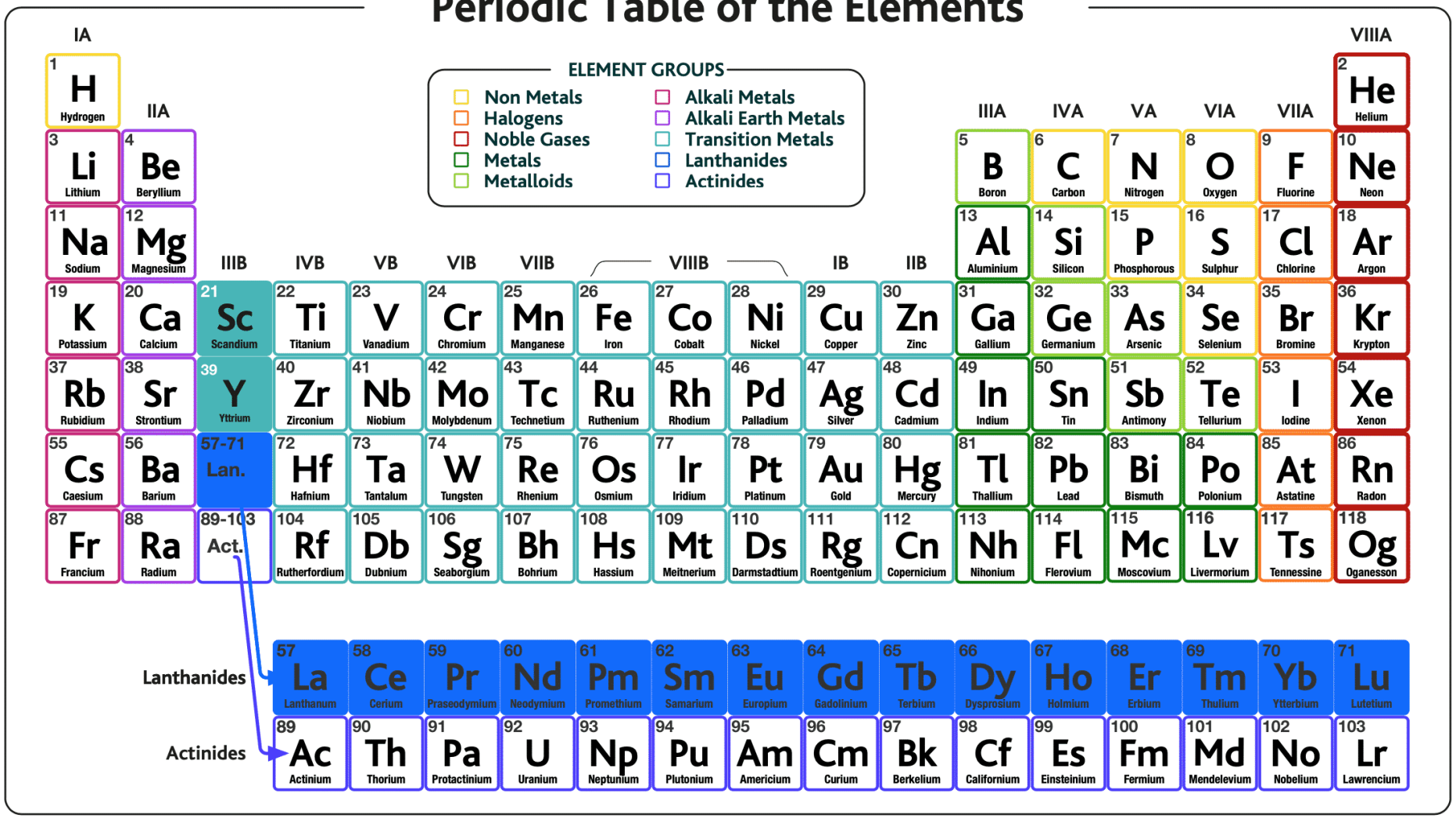
Magnetic Susceptibility

Magnetic Susceptibility – the amount and direction of magnetization induced by an applied magnetizing field.



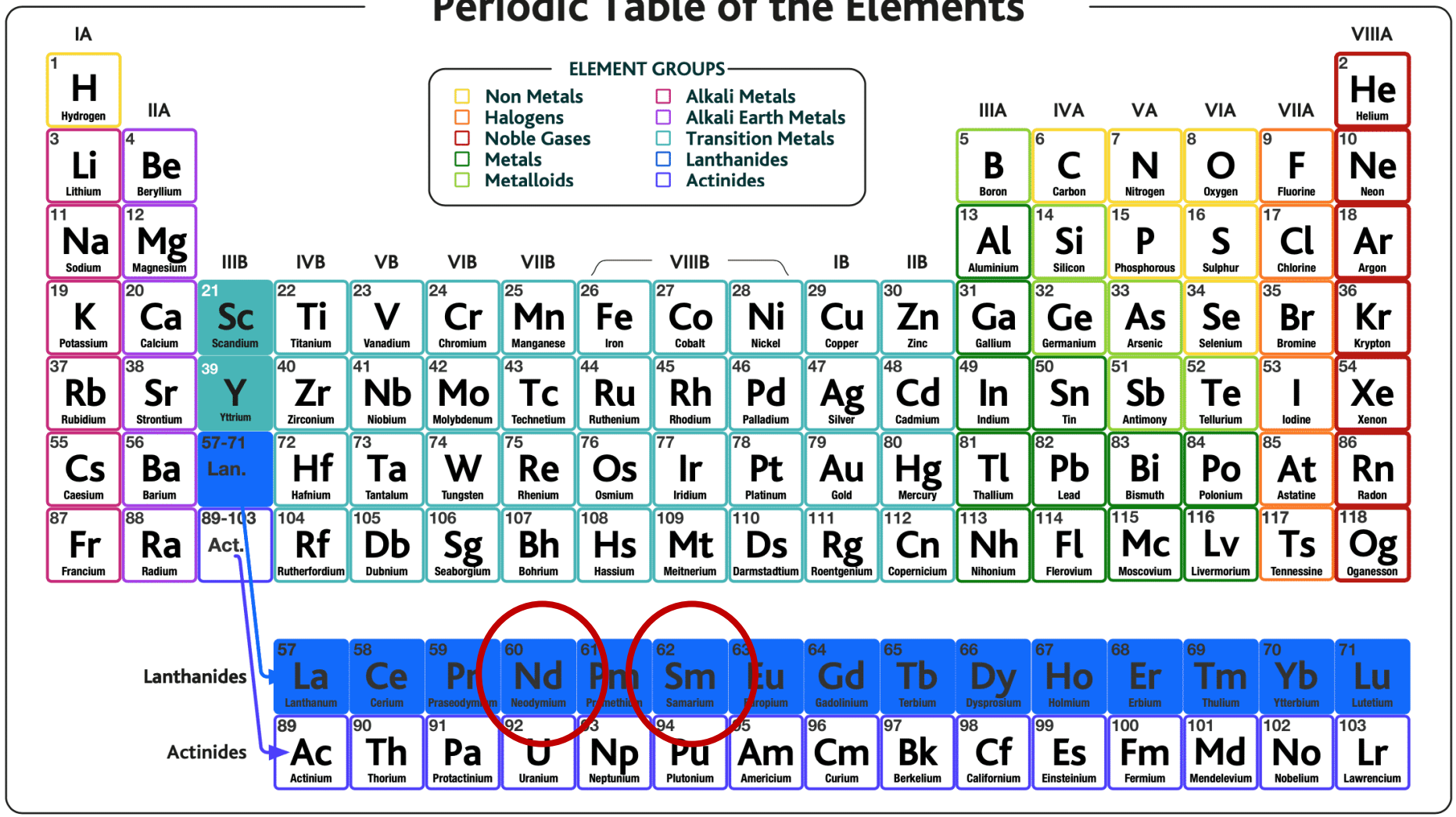
Rare Earth Metals

The rare earth metals are a set of seventeen metallic elements consisting of the lanthanide group (in blue) plus scandium and yttrium (in green)



Neodymium & Samarium Magnets

Samarium and Neodymium rare-earth permanent magnets have produced the largest magnetic fields with the least mass



1st and 2nd Generation

$SmCo_5$ (1:5)

Sm_2Co_{17} (2:17)

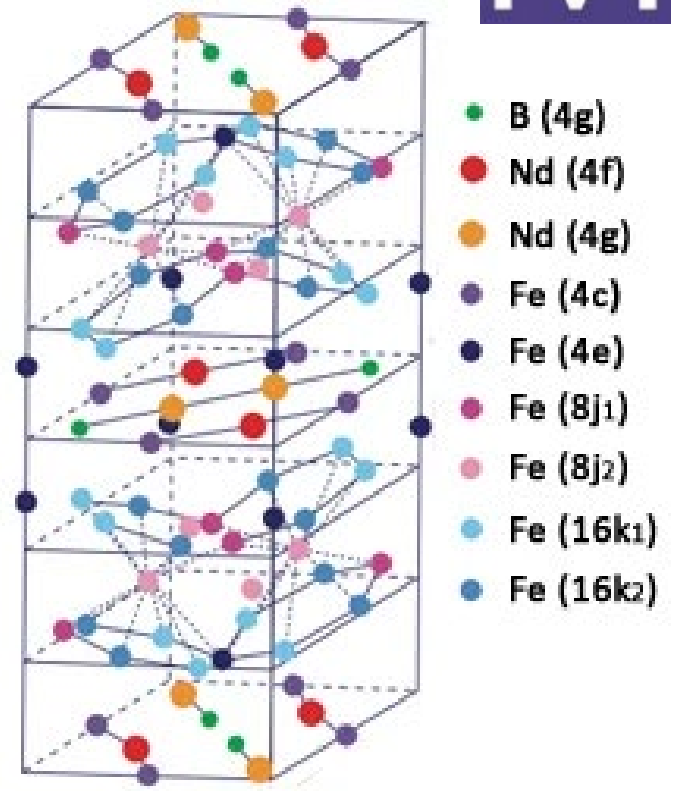
3rd Generation

$Nd_2Fe_{14}B$

Neodymium Iron Boron, NdFeB

Neodymium magnets are the strongest commercially available permanent magnets. The list of applications is extensive and includes motors, sensors, mobile phones and computer hard drives. There are a range of different grades to suit specific applications with the highest grade rated at 52 MG·Oe compared with Samarium Cobalt at 32 MG·Oe.

Depending on the grade, Neodymium magnets are suited to maintain a good magnetic performance up to 200 °C, with the magnetic strength only falling below Samarium Cobalt at 150 °C. Although not naturally resistant to corrosion, Neodymium magnets generally receive a galvanic nickel coating (Ni-Cu-Ni) for protection.



$Nd_2Fe_{14}B$ Crystal Structure

Magnet Grades – Type & Energy Product

N35 12,200 Gauss	N45 13,700 Gauss
N38 12,600 Gauss	N48 14,100 Gauss
N42 13,300 Gauss	N52 14,800 Gauss

N 42

"N" stands for the magnet type:
N, Neodymium
S, Samarium

42 stands for the Maximum Energy Product in MG·Oe (an expression of the stored magnetic energy in a permanent magnet)

Magnet Grades – Intrinsic Coercivity & Working Temperature

N42◯ The default designation (no suffix) indicates an intrinsic coercivity of at least 12 kOe & max working temperature of 80 °C (176 F)
(60 °C for N50 and N52)

N42M "Medium" – Intrinsic Coercivity ≥ **14 kOe**, 100 °C (212 °F)

N42H "High" – Intrinsic Coercivity ≥ **17 kOe**, 120 °C (248 °F)

N42SH "Super High" – Intrinsic Coercivity ≥ **20 kOe**, 150 °C (302 °F)

N42UH "Ultra High" – Intrinsic Coercivity ≥ **25 kOe**, 180 °C (356 °F)

N42EH "Extremely High" – Intrinsic Coercivity ≥ **30 kOe**, 200 °C (392 °F)

N42AH "Abnormally High" – Intrinsic Coercivity ≥ **35 kOe**, 230 °C (446 °F)

A permanent magnet with higher coercivity means that it has more ability to resist demagnetization including field demagnetization and thermal demagnetization.

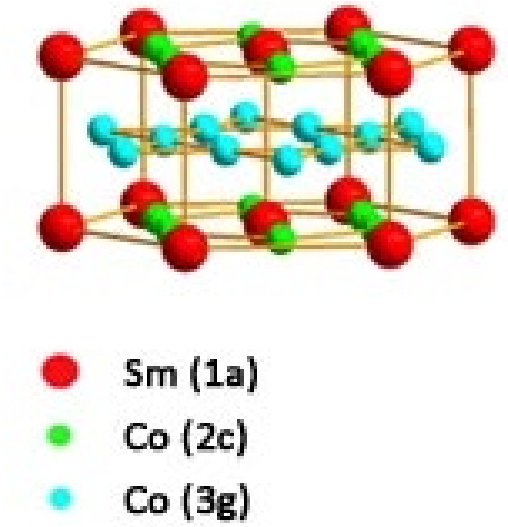
Samarium Cobalt Magnets

First Generation, 1:5 $SmCo_5$

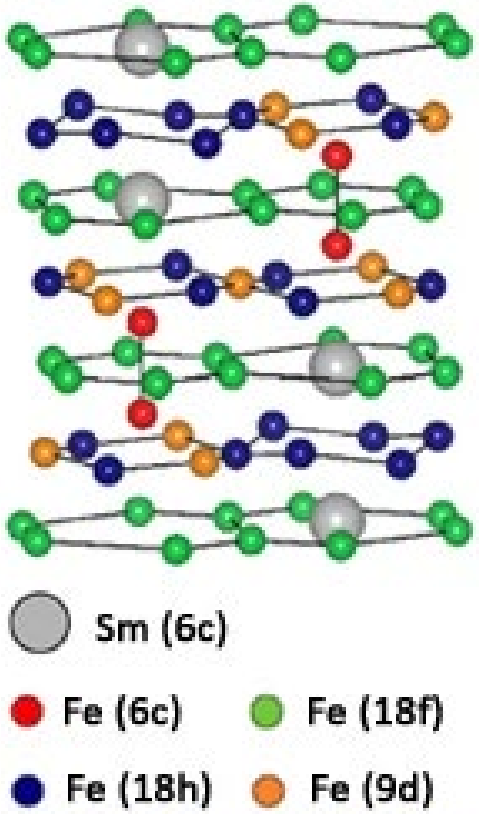
First samarium cobalt magnet produced, superseded by second generation (2:17) magnets. Its maximum energy product is 15 to 24 MG·Oe. This type of samarium cobalt magnet is highly resistant to corrosion.

Second Generation, 2:17 $Sm2Co_{17}$

Sm_2Co_{17} has gained wider popularity than 1:5 for being stronger. Its maximum energy product is 20 to 32 MG·Oe. It can be used at higher temperatures than 1:5 but is also more susceptible to corrosion in water.

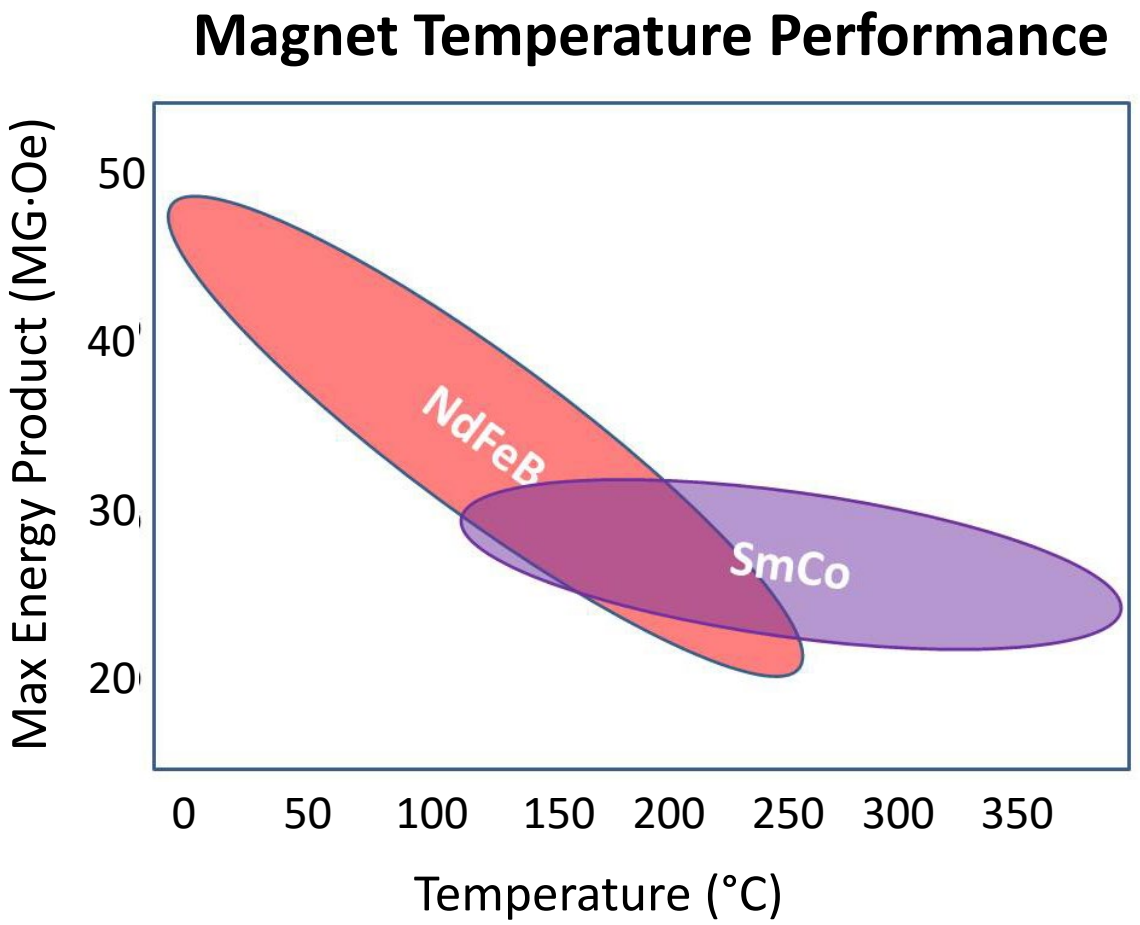


SmCo5 Crystal Structure



Sm2Co17 Crystal Structure

Neodymium & Samarium Magnet Comparison



SamCo excels at high temperature performance and has a flatter temperature coefficient than NdFeB, but NdFeB achieves very high magnetic strength near room temperature

Neodymium & Samarium Magnet Comparison

General Properties of 1st through 3rd Generation Rare Earth Magnets*

Material	Coercivity (T)	Remanence (T)	Max Energy Product (kJ/m^3)
$SmCo_5$	1.0	0.83	160
Sm_2Co_{17}	0.6†	1.15	215
$Nd_2Fe_{14}B$	1.2	1.2	260

†Fe, Cu, and Zr additives are used to raise the coercivity of Sm_2Co_{17} magnets

*Data from Myers, H. P., Introductory Solid-State Physics, 2nd. Ed., Taylor & Francis, 1997.

For Further Reading

Check out the National MagLab's **Magnet Academy** online at https://nationalmaglab.org/magnet-academy/