



NATIONAL HIGH
MAGNETIC FIELD LABORATORY

Fundamentals of Permanent Magnets

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Dr. Stephen McGill



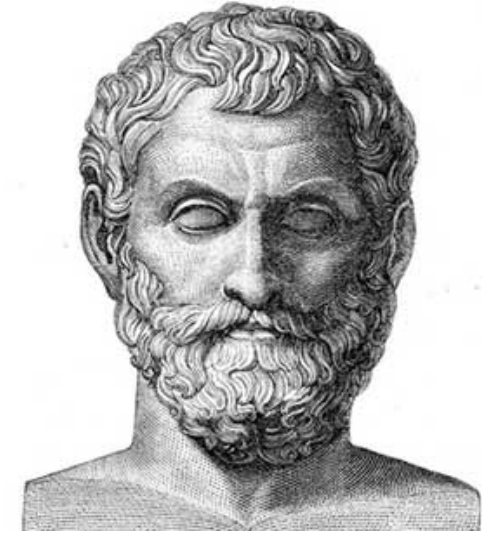
Earliest Known History of Magnetism



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

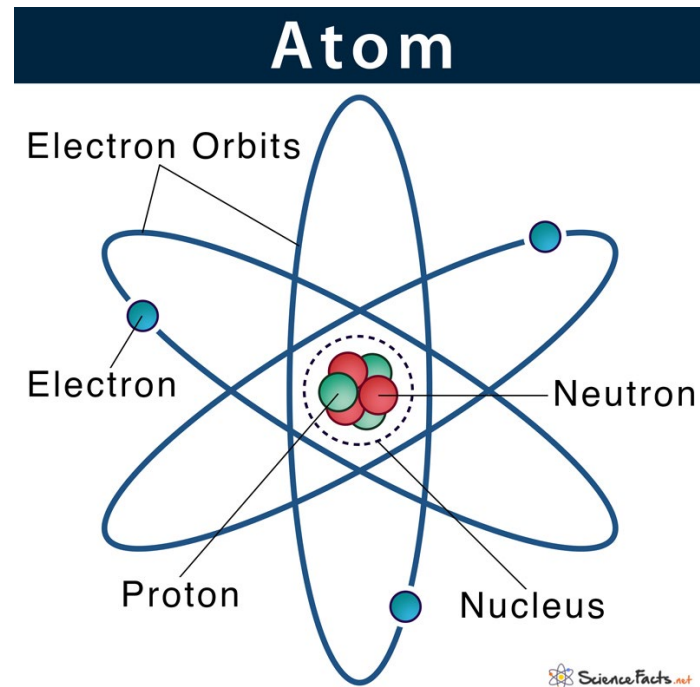
The importance of magnetism and Man's need for versatile magnetic materials has only **increased** with time.

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.

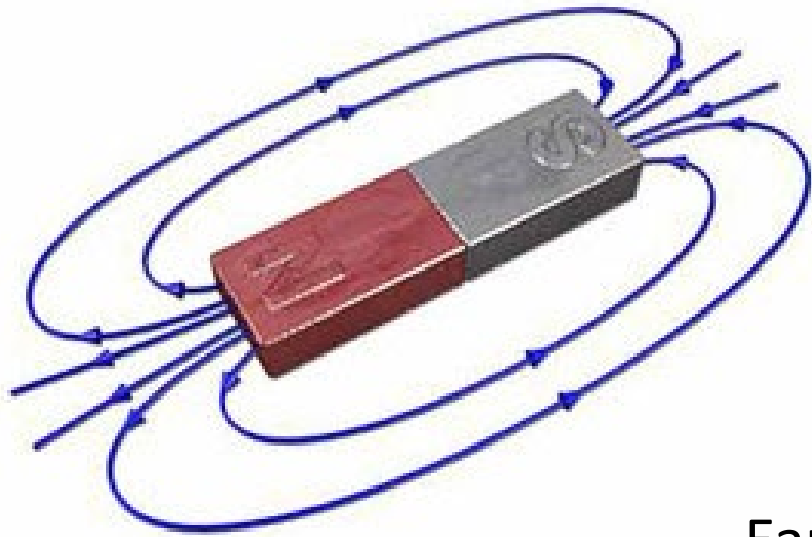
Permanent magnetism: magnetic force that exists in the absence of an inducing current.

Permanent magnets,
Or just, magnets



Electromagnets

(Electrically switched on/off)



e.g. Samarium Cobalt,
Neodymium Iron Boron

e.g. Junkyard magnet,
MRI

cgs units: Oe, Mx, G

SI units: A/m, Wb, T

1 T = 10,000 G

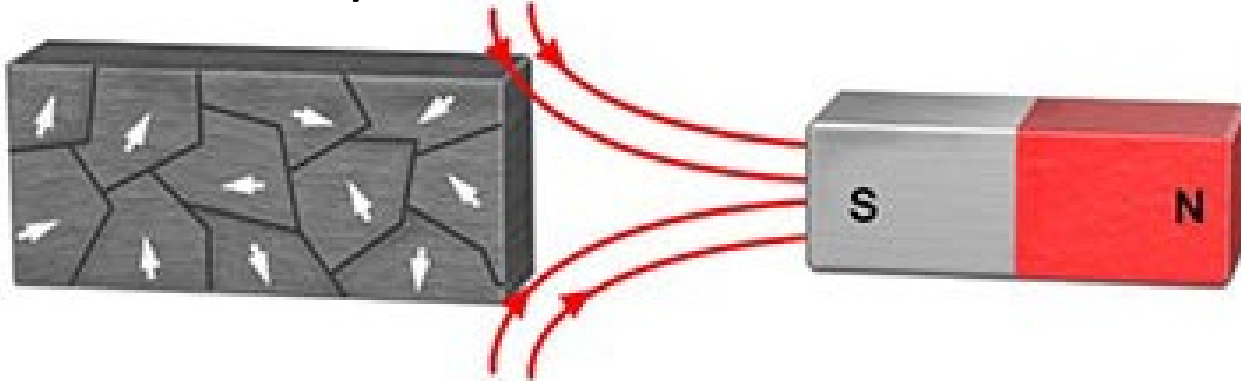
Earth's magnetic field \approx 0.5 G



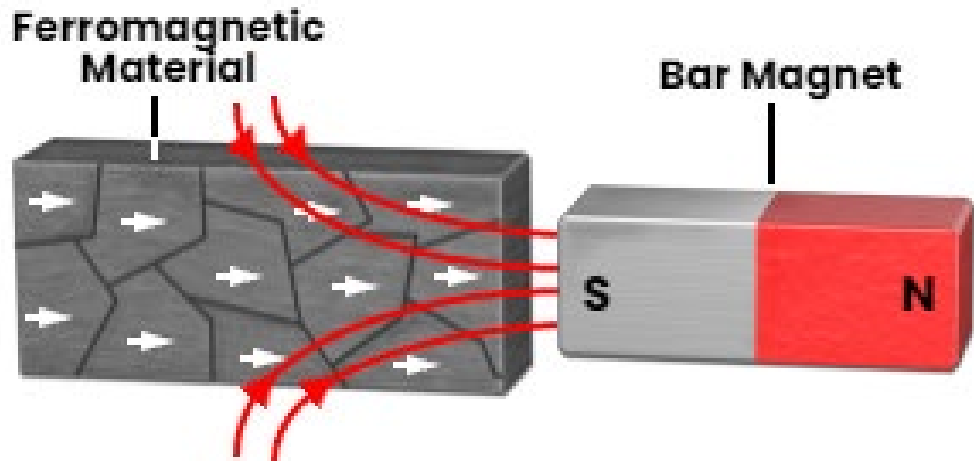
Permanent Magnets



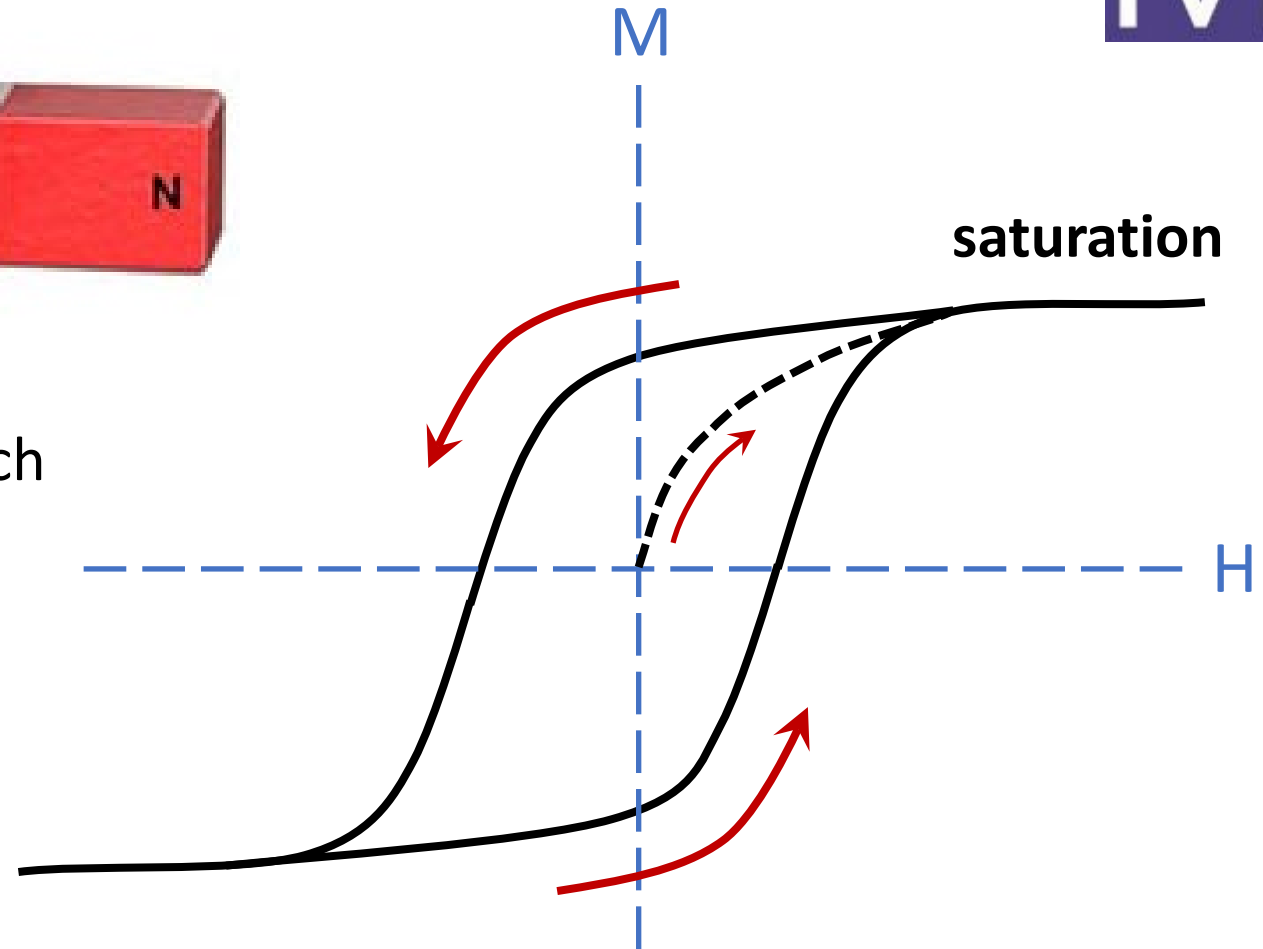
Domains Randomly oriented



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.

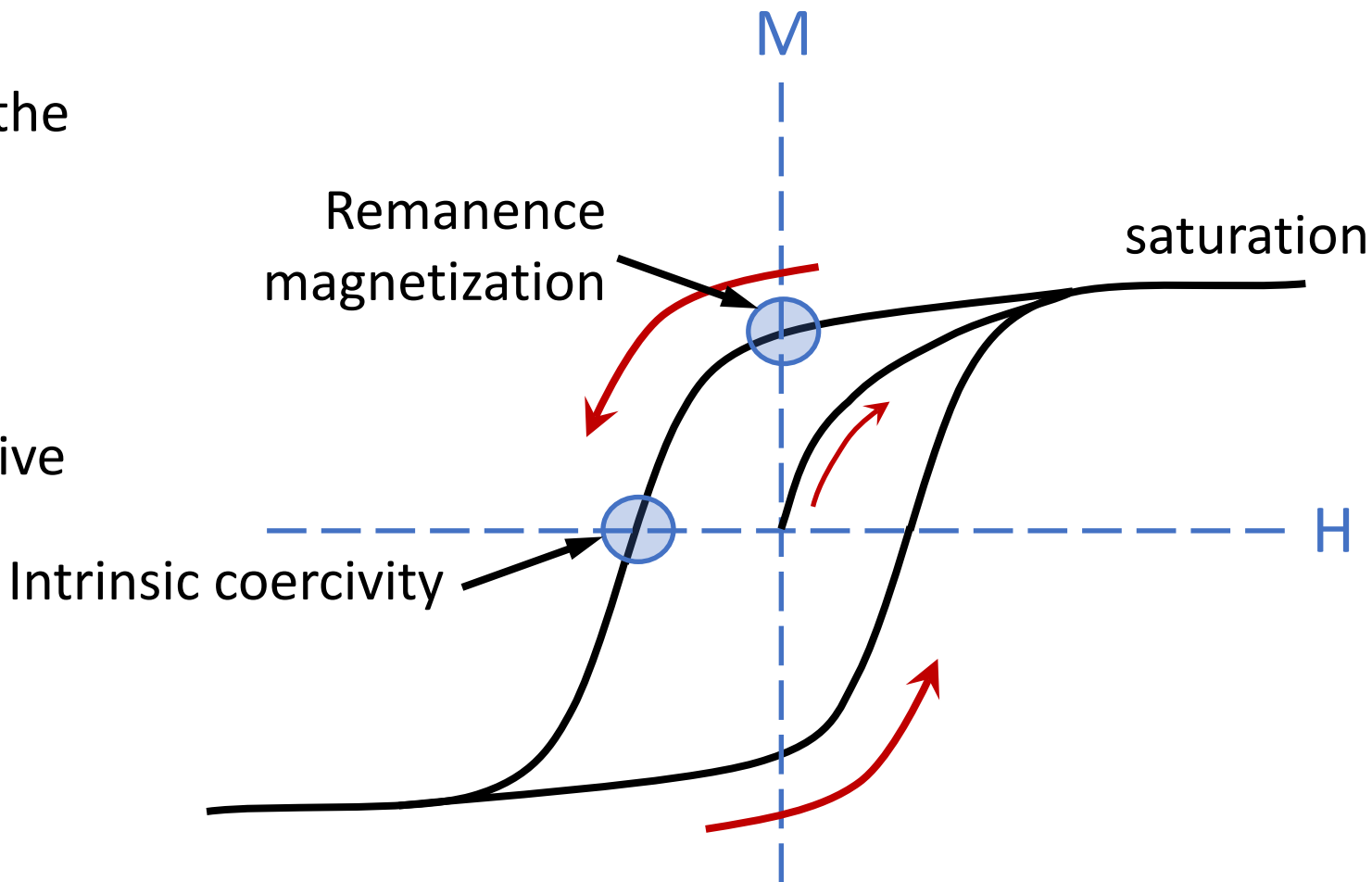
Saturation – the maximum magnetization is called the saturation magnetization

Magnetic Hysteresis Loop



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

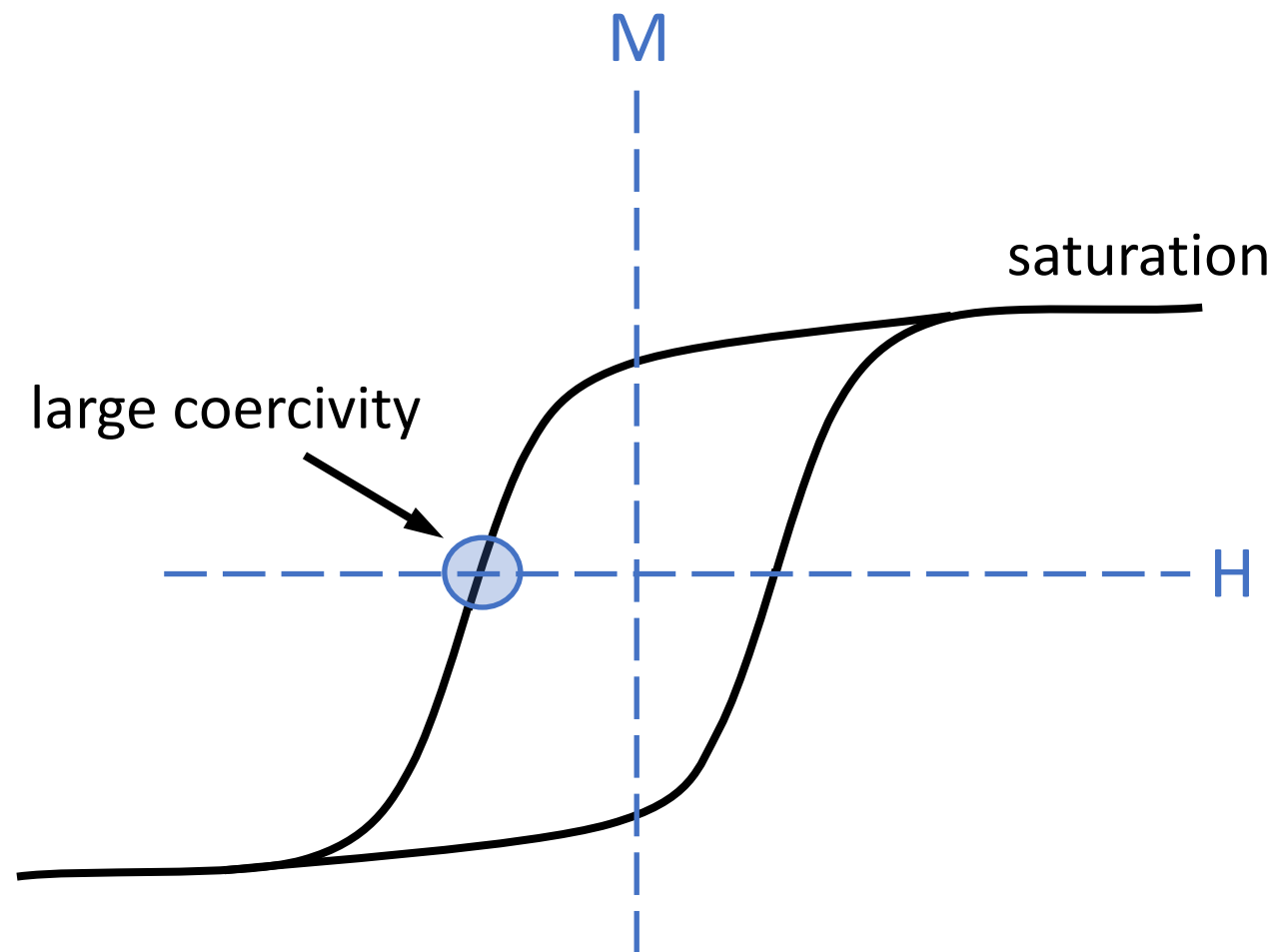
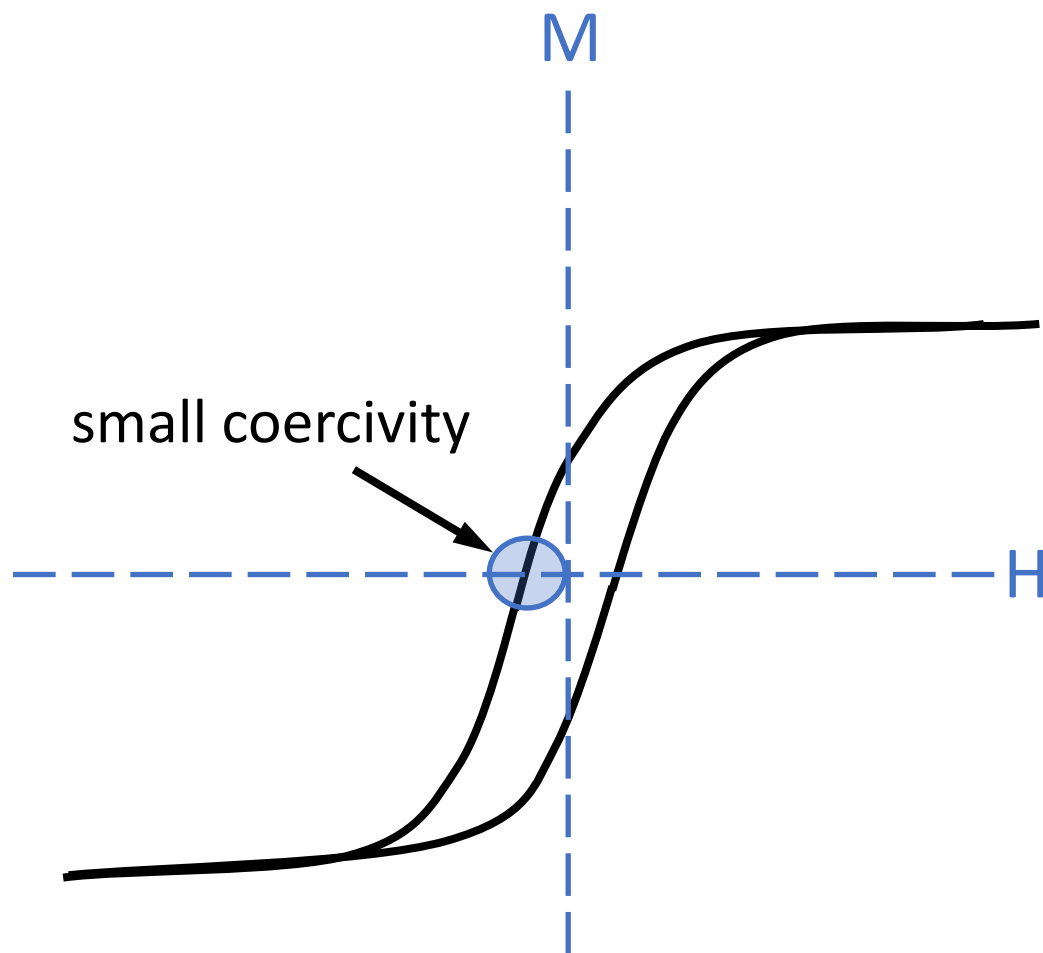
Coercivity – a measure of the magnetizing field required to drive the magnetization to zero after being saturated.



Magnetic Hysteresis Loop



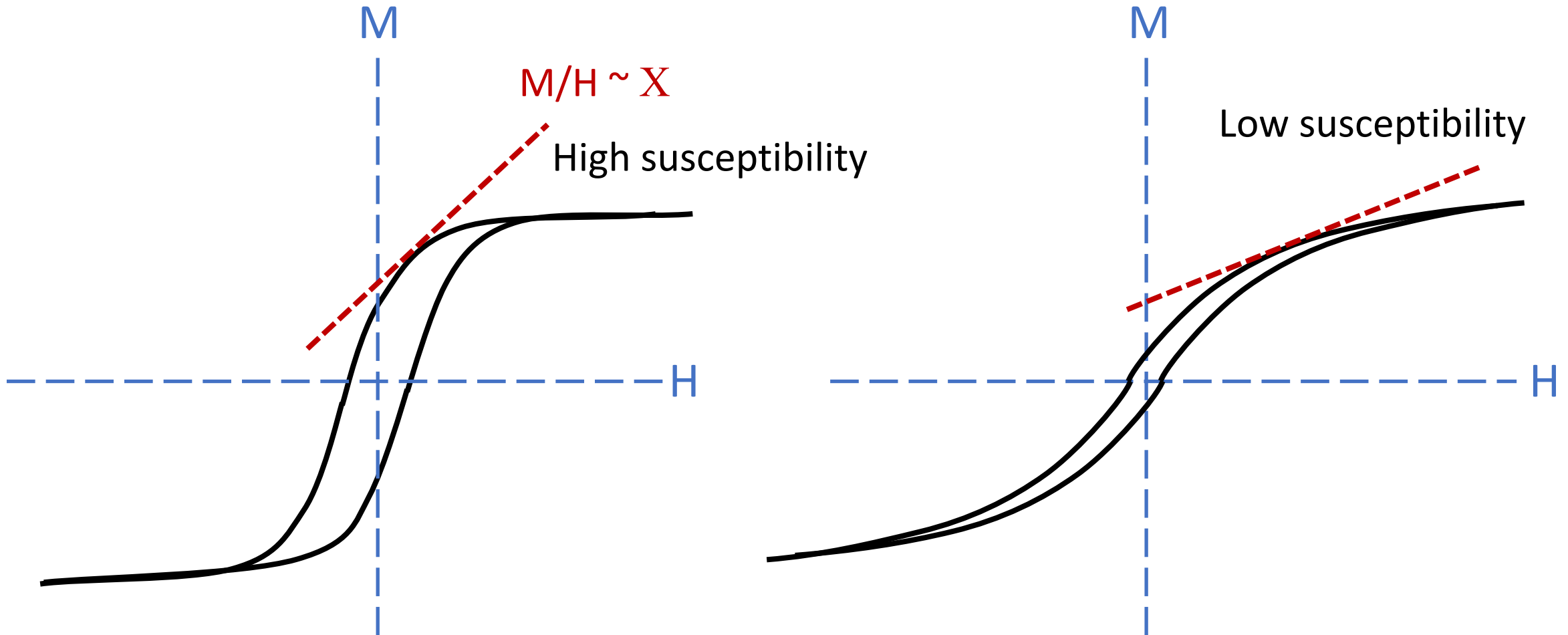
Coercivity – a measure of the magnetizing field required to drive the magnetization to zero after being saturated.



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)

Periodic Table of the Elements

ELEMENT GROUPS

- Non Metals
- Halogens
- Noble Gases
- Metals
- Metalloids
- Alkali Metals
- Alkali Earth Metals
- Transition Metals
- Lanthanides
- Actinides

1 H Hydrogen																	2 He Helium	
3 Li Lithium	4 Be Beryllium											5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon	
11 Na Sodium	12 Mg Magnesium											13 Al Aluminium	14 Si Silicon	15 P Phosphorus	16 S Sulphur	17 Cl Chlorine	18 Ar Argon	
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton	
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon	
55 Cs Caesium	56 Ba Barium	57-71 Lan.	72 Hf Hafnium	73 Ta Tantalum	74 W Tungsten	75 Re Rhenium	76 Os Osmium	77 Ir Iridium	78 Pt Platinum	79 Au Gold	80 Hg Mercury	81 Tl Thallium	82 Pb Lead	83 Bi Bismuth	84 Po Polonium	85 At Astatine	86 Rn Radon	
87 Fr Francium	88 Ra Radium	89-103 Act.	104 Rf Rutherfordium	105 Db Dubnium	106 Sg Seaborgium	107 Bh Bohrium	108 Hs Hassium	109 Mt Meitnerium	110 Ds Darmstadtium	111 Rg Roentgenium	112 Cn Copernicium	113 Nh Nihonium	114 Fl Flerovium	115 Mc Moscovium	116 Lv Livermorium	117 Ts Tennessine	118 Og Oganesson	
Lanthanides		57 La Lanthanum	58 Ce Cerium	59 Pr Praseodymium	60 Nd Neodymium	61 Pm Promethium	62 Sm Samarium	63 Eu Europium	64 Gd Gadolinium	65 Tb Terbium	66 Dy Dysprosium	67 Ho Holmium	68 Er Erbium	69 Tm Thulium	70 Yb Ytterbium	71 Lu Lutetium		
Actinides		89 Ac Actinium	90 Th Thorium	91 Pa Protactinium	92 U Uranium	93 Np Neptunium	94 Pu Plutonium	95 Am Americium	96 Cm Curium	97 Bk Berkelium	98 Cf Californium	99 Es Einsteinium	100 Fm Fermium	101 Md Mendelevium	102 No Nobelium	103 Lr Lawrencium		

Neodymium & Samarium Magnets

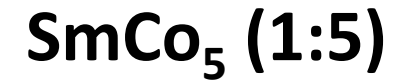


Samarium and Neodymium rare-earth permanent magnets have produced the largest magnetic fields with the least mass

Periodic Table of the Elements

IA		ELEMENT GROUPS										VIII A						
1 H Hydrogen		IIA												2 He Helium				
3 Li Lithium	4 Be Beryllium												5 B Boron	6 C Carbon	7 N Nitrogen	8 O Oxygen	9 F Fluorine	10 Ne Neon
11 Na Sodium	12 Mg Magnesium		III B	IV B	VB	VIB	VIIB	VIII B		IB	IIB	13 Al Aluminium	14 Si Silicon	15 P Phosphorous	16 S Sulphur	17 Cl Chlorine	18 Ar Argon	
19 K Potassium	20 Ca Calcium	21 Sc Scandium	22 Ti Titanium	23 V Vanadium	24 Cr Chromium	25 Mn Manganese	26 Fe Iron	27 Co Cobalt	28 Ni Nickel	29 Cu Copper	30 Zn Zinc	31 Ga Gallium	32 Ge Germanium	33 As Arsenic	34 Se Selenium	35 Br Bromine	36 Kr Krypton	
37 Rb Rubidium	38 Sr Strontium	39 Y Yttrium	40 Zr Zirconium	41 Nb Niobium	42 Mo Molybdenum	43 Tc Technetium	44 Ru Ruthenium	45 Rh Rhodium	46 Pd Palladium	47 Ag Silver	48 Cd Cadmium	49 In Indium	50 Sn Tin	51 Sb Antimony	52 Te Tellurium	53 I Iodine	54 Xe Xenon	
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1st and 2nd Generation



3rd Generation

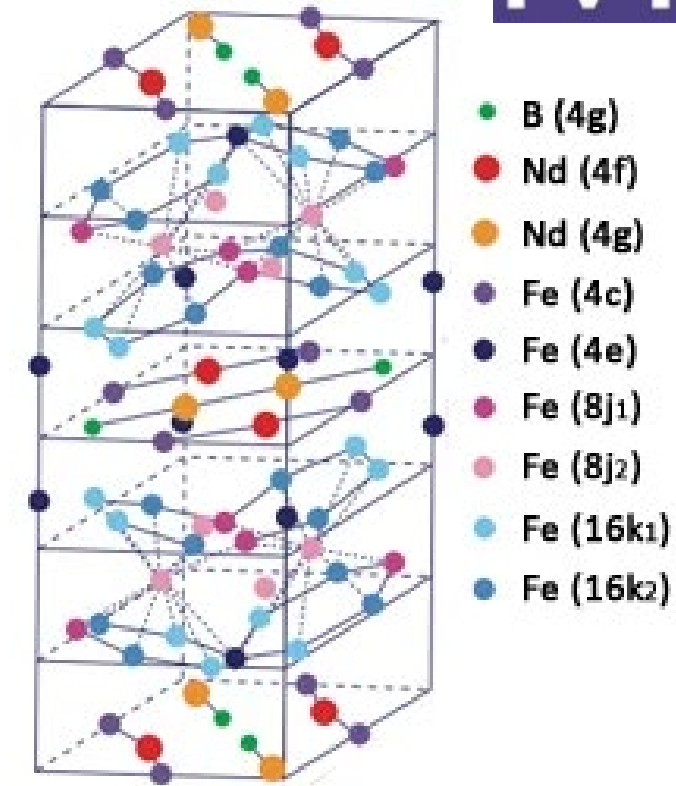


Neodymium Iron Boron, NdFeB



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.



Nd₂Fe₁₄B 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

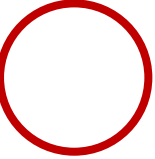
N 42

“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 \geq **14 kOe**, 100 °C (212 °F)

N42H “High” – Intrinsic Coercivity \geq **17 kOe**, 120 °C (248 °F)

N42SH “Super High” – Intrinsic Coercivity \geq **20 kOe**, 150 °C (302 °F)

N42UH “Ultra High” – Intrinsic Coercivity \geq **25 kOe**, 180 °C (356 °F)

N42EH “Extremely High” – Intrinsic Coercivity \geq **30 kOe**, 200 °C (392 °F)

N42AH “Abnormally High” – Intrinsic Coercivity \geq **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

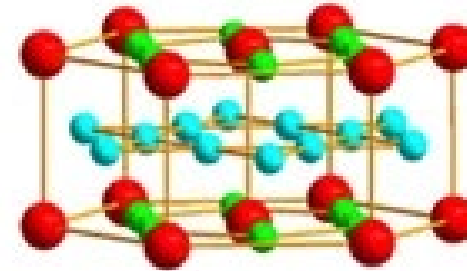


First Generation, 1:5 SmCo_5

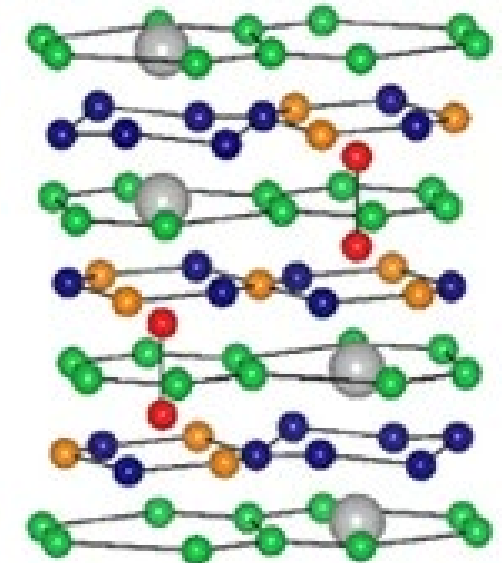
First samarium cobalt magnet produced, superseded by second generation (2:17) magnets. Its maximum energy product is 15 to 24 $\text{MG}\cdot\text{Oe}$. This type of samarium cobalt magnet is highly resistant to corrosion.

Second Generation, 2:17 $\text{Sm}_2\text{Co}_{17}$

$\text{Sm}_2\text{Co}_{17}$ has gained wider popularity than 1:5 for being stronger. Its maximum energy product is 20 to 32 $\text{MG}\cdot\text{Oe}$. It can be used at higher temperatures than 1:5 but is also more susceptible to corrosion in water.



SmCo_5 Crystal Structure

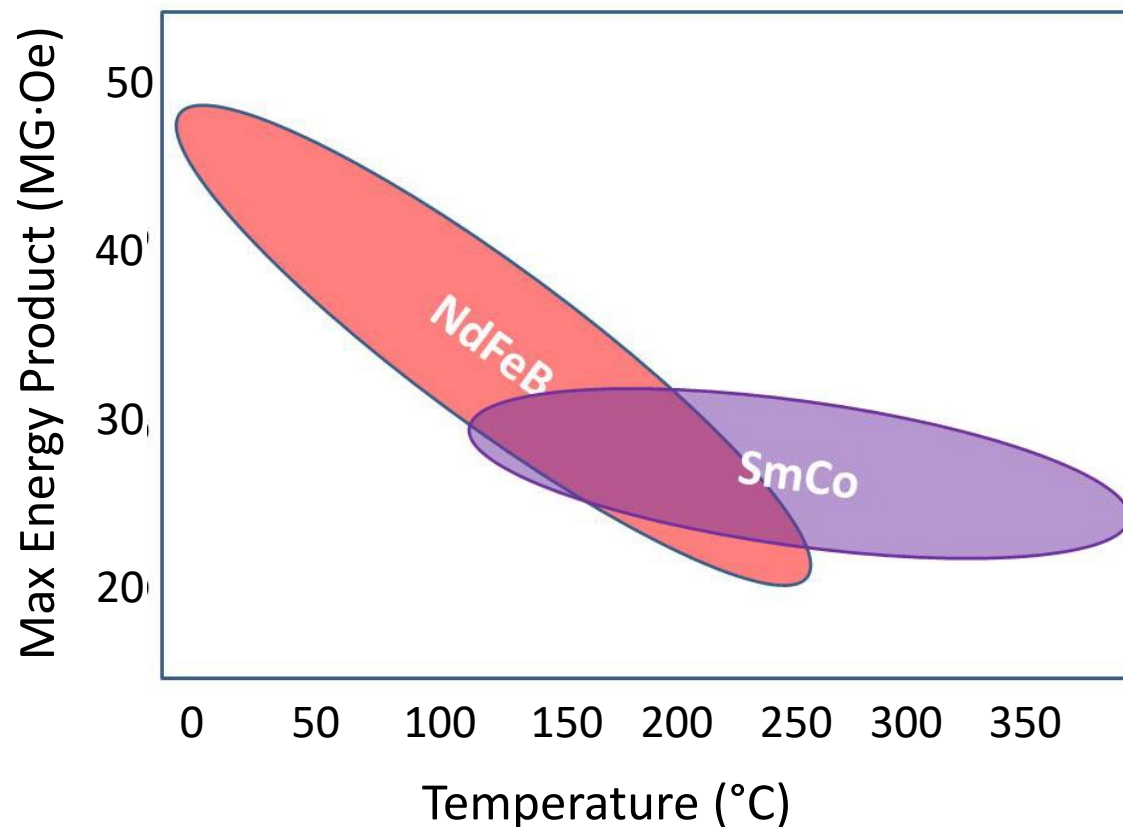


$\text{Sm}_2\text{Co}_{17}$ Crystal Structure

Neodymium & Samarium Magnet Comparison



Magnet Temperature Performance



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 ₂ Co ₁₇	0.6 [†]	1.15	215
Nd ₂ Fe ₁₄ B	1.2	1.2	260

[†]Fe, Cu, and Zr additives are used to raise the coercivity of Sm₂Co₁₇ 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/>



The screenshot shows the Magnet Academy website interface. At the top left is the National MagLab logo. To the right, it states: "The National MagLab is funded by the National Science Foundation and the State of Florida." Below this is a blue header with the "MAGNET ACADEMY" logo and a search bar. A green navigation bar contains links for "Watch & Play", "Read Science Stories", "Explore History", "Try This at Home", and "Plan a Lesson". The main content area features a 3D illustration of a solenoid with magnetic field lines. Text on the left reads: "Explore the world of electricity and magnetism. We've got [videos](#), [hands-on activities](#), [games](#) and more, this site answers your questions about all things electric and magnetic." At the bottom, a purple bar titled "Find content catered to your learning style" includes icons and labels for "Watch", "Read", "Play", "Build", "Teach", and "Visit".