Magnetism

Discussion

history

Outline of the story told historically. Basic ideas that even young children now know. Keep everything to an introductory level.

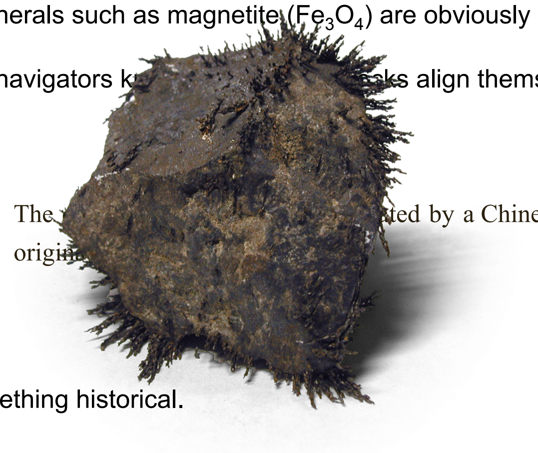
- There are rocks that attract other rocks, but only if they're of the right kind
- These rocks will try to align themselves north-south (roughly speaking)

First comes Thales of Miletus (635–543 BCE) Greece (Ionia). Miletus is now on the western coast of Turkey in what was then a region of Greece known as Ionia (source of the chemical term ion, but that's another story).

- The stones of Magnesia (μαγνήτης λίθος)
- Μαγνησία now Manisa, Turkey
- Magnetite. A piece of magnetite with an exceptionally strong magnetic action is sometimes called a lodestone.

> A nice quote from Thales would be nice here.

Some minerals such as magnetite (Fe_3O_4) are obviously magnetic.



Chinese navigators k... ...cks align themselves north-south (the south-pointing spoon).

> The ... ted by a Chinese geomantic omen master in late Tang Dynasty, who origi...

Find something historical.

The north magnetic pole of a compass points in the general direction of the north geographic pole of the earth. Since opposite magnetic poles attract, this means that the south magnetic pole of the earth is very near to its north geographic pole.

Next comes Peter Peregrinus (as he is known in English) a.k.a. Pierre Pèlerin de Maricourt (presumably his proper french name) a.k.a. Petrus Peregrinus de Maharncuria (his latin title, which means "Peter the Pilgrim of Maricourt"). Peter wrote what is commonly known as the *Epistole de Magnete* or *Letter on the Magnet*. It's full title is *Epistola Petri Peregrini de Maricourt ad Sygerum de Foucaucourt, militem, de magnete* (*Letter on the Magnet of Peter Peregrinus of Maricourt to Sygerus of Foucaucourt, Soldier*"). It was written on 8 August 1269 during the siege of the city of Lucera — the last remaining stronghold of Islam on the "calf muscle" of the boot-shaped peninsula that is now called Italy.

> Peter's work was so complete that no further studies on the properties of magnets were done until the monumental work of William Gilbert in 1600 — *Tractatus sive Physiologia Nova de Magnete, Magneticisque Corporibus, et Magno Magnete Tellure* (On the Magnet, Magnetic Bodies, and the Great Magnet of the Earth). *De Magnete* was the text in which Gilbert revealed the results of his research on magnetism and attempted to explain the nature of magnets and the five motions associated with magnetic phenomena. The work met with great acclaim and was republished in 1628 and 1633.

William Gilbert (1544–1603) England

> Find something.

fundamentals

magnetic elements

- The big three
  - iron (Fe)
  - nickel (Ni)
  - cobalt (Co)
- plus the oddballs
  - gadolinium (Gd)
  - dysprosium (Dy)

More on ferromagnetism later

The earth is a magnet, geomagnetism, poles: north seeking and south seeking

rule of action: opposite poles attract, like poles repel

types of magnets

- permanent
- induced
- electromagnet

A lifting magnet in action — Brooklyn, New York (Source: ToddCam)

magnetic field

informal definition: compare to the other fields

A comparison of force fields

phenomena	origin	field	symbol
gravity	force due to mass	force per mass	**g**
electricity	force due to charge	force per charge	**E**
magnetism	force due to poles?*	force per pole?*	**B**

* Most emphatically, No! The magnetic field has a very odd definition.

the real definition appears later

dilemma: breaking a magnet, there is no magnetic monopole, even down on the atomic scale there is no magnetic monopole, field lines heal themselves

Still, even though we don't have a formal definition of the magnetic field there's no reason why an informal definition can't suite us for awhile.

properties of magnetic field lines

- direction determined from the north pole of a compass
- strength proportional to the density of the field lines
- field lines are closed loops
- field lines penetrate magnetic materials (compare this to electric field lines, which terminate on the surface of conductors)

- field lines bend at the surface of a magnetic material

The symbol for the magnetic field is **B** (boldface) when describing the full vector quantity and *B* (italic) when describing the magnitude alone.

The SI unit of the magnetic field is the tesla [T], named in honor of the Serbian-American electrical engineer Nikola Tesla (1856–1943) born in a part of the Austro-Hungarian or Hapsburg Empire that is now the independent nation of Croatia. Tesla was a pioneer in the associated disciplines of alternating electric current and rotating magnetic fields. His basic designs for electric motors, generators and transformers in the early part of the Twentieth Century were little changed by the beginning of the Twenty first Century.

Another unit in common usage is the gauss [G], named in honor of the German mathematician Carl Friedrich Gauss (1777–1855). Gauss is generally regarded as the greatest mathematician of all time. Of particular interest to physicists were Gauss' work on curved surfaces, which were important in the fields of electrostatics and general relativity (all puns intended). The gauss is also a unit in the cgs system that was originally developed by Gauss and is sometimes also known as the Gaussian system.

Each of these units will be defined formally in a later section of this book. Right now I will tell you that the tesla is the bigger unit.

1 T = 10,000 G

The tesla is in fact too big for most practical purposes. As such it is usually divided into microtesla [μT] or nanotesla [nT]. The gauss is also a bit too large, but not as bad as the tesla, so milligauss [mG] and microgauss [μG] are more common.

1 T = 10 kG
1 mT = 10 G
1 μT = 10 mG
1 nT = 10 μG

The following table lists the magnetic field strength for various devices, events, or phenomena. Whenever possible a location was also specified. Like the gravitational and electric fields, the magnetic field grows smaller with increasing distance form the source.

Selected Magnetic Field Values

B (T)	location, event
10^{13}	neutron star, theoretical upper limit
10^{10}–10^{11}	neutron star, magnetar
10^{8}–10^{9}	neutron star, radio pulsar
1000	highest laboratory field, ephemeral
100	white dwarf star
45	highest laboratory field, sustained
16	strong enough to levitate frogs
13	strongest superconding magnet
2.4	strongest permanent magnet
1–4	MRI
1	strong laboratory magnet

0.45	large sunspot
0.15	iron bar magnet, at poles
0.10	refrigerator magnet
0.001	sun, poles
400×10^{-6}	jupiter, surface mean
100×10^{-6}	sun, surface mean
60×10^{-6}	earth, poles
45×10^{-6}	earth, surface mean
30×10^{-6}	earth, equator
10×10^{-6}	am radio broadcast at receiver
1×10^{-6}	solar radiation on earth's surface
180×10^{-9}	100 W light bulb at 1 m, peak
150×10^{-9}	mercury, surface mean
150×10^{-9}	earth, altitude of geosynchronous orbit
50×10^{-9}	earth, magnetosphere nose
35×10^{-9}	moon, surface
5×10^{-9}	interplanetary space near earth
1×10^{-9}	earth, magnetosphere tail
500×10^{-12}	interstellar space
100×10^{-12}	intergalactic space
50×10^{-12}	human heart
100×10^{-15}	human brain

ferromagnetism

This section is intended to be a discussion of magnetism on the small scale, not just the magnetism of iron, nickel, and cobalt (although that will be its primary focus). Perhaps it should be titled "micromagnetism".

Everything's due to electron spin. Well, almost everything.

Types of magnetic behavior (in order of decreasing strength)

type	spin alignment	examples
ferromagnetic	all spins align parallel to one another	iron, cobalt, nickel, gadolinium, dysprosium, heusler alloys
ferrimagnetic	most spins parallel to one another, some spins antiparallel	magnetite (Fe_3O_4), yttrium iron garnet (YIG)
antiferromagnetic	periodic parallel-antiparallel spin distribution	chromium, FeMn, NiO
paramagnetic	spins tend to align parallel to an external magnetic field	oxygen, sodium, aluminum, calcium, uranium
diamagnetic	spins tend to align antiparallel to an external magnetic field	nitrogen, copper, silver, gold, water, organic compounds
superdiamagnetic	all spins align antiparallel to an external field	meisner effect in superconductors

alloys

Steel…

Basic types of steel (in order of increasing carbon content)

type	composition	magnetic?	other characteristics
ferritic stainless	Fe, Cr, C	yes	moderate corrosion resistance, moderate durability
austenitic stainless	Fe, Cr, Ni, C	no	high corrosion resistance, moderate durability
martensitic stainless	Fe, Cr, C	yes	moderate corrosion resistance, high durability
nonstainless (high carbon)	Fe, C	yes	low corrosion resistance, high durability

Alloys made expressly for permanent magnets…

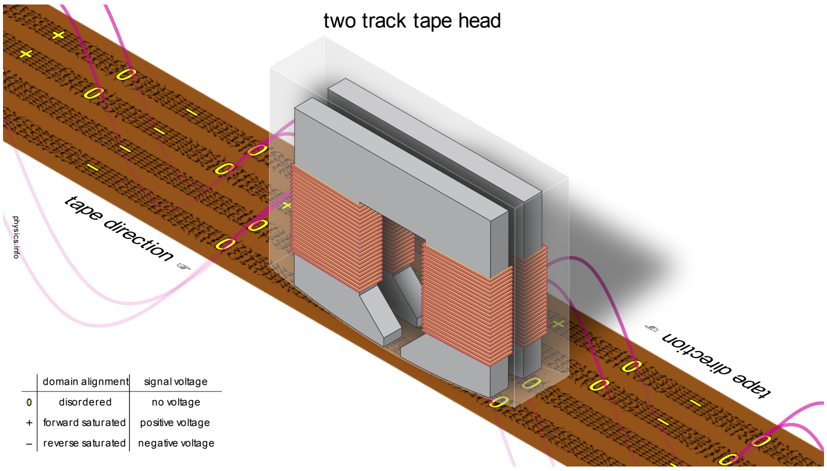
- Alnico
- Samarium alloys
- Neodymium alloys

Ferromagnetic alloys made entirely of nonferrous metals…

- Heusler alloy: copper, tin, manganese in the ratio 2:1:1. Friedrich Heusler (1866–1947) Germany. The copper may be replaced by silver. The tin may be replaced by aluminum, arsenic, antimony, bismuth, or boron.
- CrO_2
- EuO

magnetic recording

the basic mechanism



- drums
- disks

substrates

- flexible: tape and floppy disks, typically polyester
- rigid: hard drives, typically aluminum

ferromagnetic material

- hard vs. soft
    - Hard magnetic materials require relatively strong magnetic fields to become permanently magnetized and to reverse or erase the magnetization. They are most appropriate for digital data storage
    - Soft magnetic media require relatively weak magnetic fields to become magnetized. They are more appropriate for analog audio and video recording.

Common materials used for magnetic tape

type	bias	material	comments
I	"normal"	gamma ferric oxide (γ-Fe_2O_3)	first commercially manufactured in 1937
II	"high"	chromium dioxide (CrO_2)	later replaced by layers of ferric oxide (Fe_2O_3) and cobalt (Co) with similar magnetic characteristics
III		ferric chrome (FeCr)	quickly became obsolete
IV	"metal"	finely ground metallic iron	later replaced by mixtures of finely ground iron and cobalt
n/a		barium ferrite ($BaFe_{12}O_{19}$)	magnetic stripes on bank and credit cards, high coercivity, less susceptible to accidental erasure

transition temperatures

The Curie temperature is named for the French physicist Pierre Curie (1859–1906), who discovered the laws that relate some magnetic properties to change in temperature in 1895.

The antiferromagnetic equivalent of the Curie Temperature is called the Néel Temperature in honor of the French physicist Louis Néel (1904–2000), who successfully explained antiferromagnetism in 1936.

Curie temperatures of selected ferromagnetic materials

elements	T_C (K)
iron	1043
cobalt	1404
nickel	628
gadolinium	289
erbium	32
dysprosium	155
ferrous compounds	**T_C (K)**
barium ferrite	720
strontium ferrite	720
Alnico	1160
Alumel	436
Mutamel	659
Permalloy	869
Trafoperm	1027
NdFeB	580
$SmCo_5$	990
Sm_2Co_{17}	1070
nonferrous compounds	**T_C (K)**
CrO_2	390
$CuAlMn_3$	?
$La_xCa_{1-x}B_6$	900
MnAs	318
MnBi	633
MnSb	587
polymerized C_{60}	~500

Néel temperatures of selected antiferromagnetic materials

material	T_N (K)
$CoCl_2$	25
CoF_2	38
CoO	291
chromium	475
Cr_2O_3	307
erbium	80
$FeCl_2$	70
FeF_2	79–90
FeO	198
FeMn	490
α-Fe_2O_3	953
MnF_2	72–75
MnO	122
MnSe	173
MnTe	310–323
$NiCl_2$	50
NiF_2	78–83
NiFeO	180
NiO	533–650
$TiCl_3$	100
UCu_5	15
V_2O_3	170

animal magnetism (magnetotaxis?)

- creepy crawlies
  - magnetotactic bacteria
  - flatworms (*Platyhelminthes*)
  - honey bees?
- fish
  - chinook salmon (*Oncorhynchus tshawytscha*)
  - yellowfin tuna (*Thunnus albacares*)
- amphibians
  - red-spotted newt (*Notophthalmus viridescens viridescens*)
- reptiles
  - loggerhead sea turtle (Caretta caretta)? or is it some other variety ?
- birds
  - rock pigeon (*Columba livia*)
  - bobolink (*Dolichonyx oryzivorus*)
- mammals
  - naked mole rat (*Heterocephalus glaber*)
  - Siberian hamster (*Phodopus sungorus*) ? or is it some other variety ?
  - brown bat (*Eptesicus fuscus*)

health and safety

text

Magnetic field exposure when using various devices

device	B (μT)
color tv/computer crt display	500
electric stove	1000
hair dryer	1000
maglev train	100

text

Average daily exposure to magnetic fields

location		median (μT)	range (μT)
earth's surface		45	40-60
workplace:	clerical worker w/o computer	0.05	0.02-0.20
	clerical worker w/computer	0.12	0.05-0.45
	machinist	0.19	0.06-2.76
	electrical line worker	0.25	0.05-3.48
	electrician	0.54	0.08-3.40
	welder	0.82	0.17-9.60
home:	typical US home	0.09	0.03-0.37

mri

magnetic resonance imaging (nuclear magnetic resonance)

- atoms in a magnetic field will absorb and then release energy as radio waves
- each atom that's visible to MRI has its own radio frequency (each atom is its own radio tower)
- All nuclei that contain odd numbers of nucleons have an intrinsic magnetic moment and angular momentum
- What atoms can MRI see (nmr frequencies at 1 T)?
    - (42.38 MHz) hydrogen 1
    - (40.05 MHz) fluorine 19 (in a lot of medications)
    - (16.33 MHz) lithium 7 (not a lot in our body, but found in drugs for treating bipolar disorder)
    - sodium 23 (used by neurons to make electric signals)
    - (17.25 MHz) phosphorous 31 (involved in energy containing compounds)
    - (10.71 MHz) carbon 13
    - potassium (used by neurons to make electric signals)
- The same atoms in different molecules absorb and emit radio waves at slightly different frequencies