Electricity and Magnetism

Personal

Henk Polinder
At EE TUDelft:

- 86-92 Ir
- 92-98 PhD
- 96-?? U(H)D
- 09-11 theology
- 08 ABB – fault tolerant generator systems
- 02/04/06/14 Visiting professor in Newcastle, Quebec, Edinburgh, Itajuba
- 98-99 Lagerweij – design of a 750 kW direct drive generator

Objectives

- Objectives
  - Knowing the basic theory of electricity and magnetism
  - Use the theory to solve problems
- Lectures cover theory
- Instructions Mastering Physics: solve problems
- Physics: basic of (electrical) engineering

Contents

Overview Magnetism

- 28-5: Introduction, magnetism: field and force
- 1-6: Magnetism: Biot-Savart, Ampere
- 4-6: Electromagnetic induction
- 8-6: Electromagnetic induction
- 11-6: Maxwell’s equations and electromagnetic waves
- 15-6: Local laws for the magnetostatic field, local laws for the electromagnetic field, magnetic field intensity H
- 18-6: available for answering questions, exercises

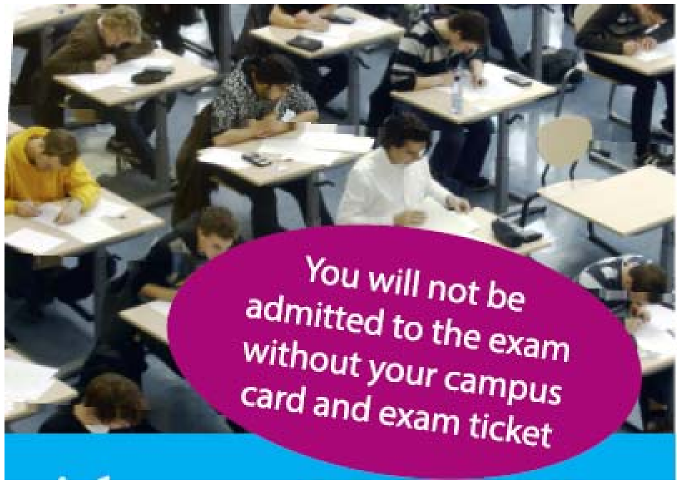
Organisation

- Electricity and magnetism 5 ECTS – 140 hours
  - Contact 54 hours
  - Self-study 86 hours
- Information: blackboard
- Lecturer: dr.ir. Henk Polinder
  - room number LB03.610
  - e-mail: h.polinder@tudelft.nl
- Feedback
  - Appreciate feedback
  - I am joining instructions
  - Small group of students?

Taking exams?

register = ticket = entry = exam

- The date of the exam for this course is: 01-07-2015
- The final exam registration date for this course is: ??-??-????
- Don’t forget to register in time. Bring your exam ticket and your campus card to the exam!



Facts about studying

- Studying is an activity of students, not of lecturers. So, you have to do it yourself.
- The objective of a lecture is not that the lecturer can tell his story without interruption.
- Most lecturers like questions (I do).
- Stupid questions are rarely asked.
- Asking a stupid question does not mean that you are stupid.
- Following lectures in an inactive way is not a good way of studying
- Preparing lectures is an effective way of studying.

Lectures

Therefore, I will try to help your study process by

- discussing important and difficult points (not everything)
- giving background information
- discussing applications
- showing slides
- doing some exercises in the lectures
- giving demonstrations
- answering your questions
- asking questions
- giving you the opportunity to prepare the lectures
- developing curiosity about phenomena
    - www.youtube.com/watch?v=zOdboRYf1hM
    - demo copper disc and magnets

Study styles

- Studying theory
- Solving problems
- Discussing with others
- Experiment with applications

- Find out for yourself!

Scientific method

- Laws of nature:
  - Observation of phenomena
  - Formulation of hypothesis
  - Validation by means of observations

- Derivation of mathematical equations describing the physical aspect of reality
  - Modelling
  - Predicting
  - Designing

- Understand why?
- Reduction of reality, reality has more aspects!!

Magnetism: force and field

- Learning objectives
- Magnetic field and magnetic forces
- Charged particles in magnetic fields
- Magnetic force on current
- Origin of the magnetic field
- Magnetic dipoles
- Magnetic matter
- Ampere’s law

In this lecture you'll learn to

- Describe magnetism in relation to electric charge
- Calculate magnetic forces on charges and currents
  - Describe the trajectories of charged particles in magnetic fields
- Explain the origin of magnetic fields
  - Calculate the magnetic fields of simple current distributions
- Describe the effects of magnetism in matter

Magnetism: force and field

- Learning objectives
- Magnetic field and magnetic forces
- Charged particles in magnetic fields
- Magnetic force on current
- Origin of the magnetic field
- Magnetic dipoles
- Magnetic matter
- Ampere’s law

Magnetic field

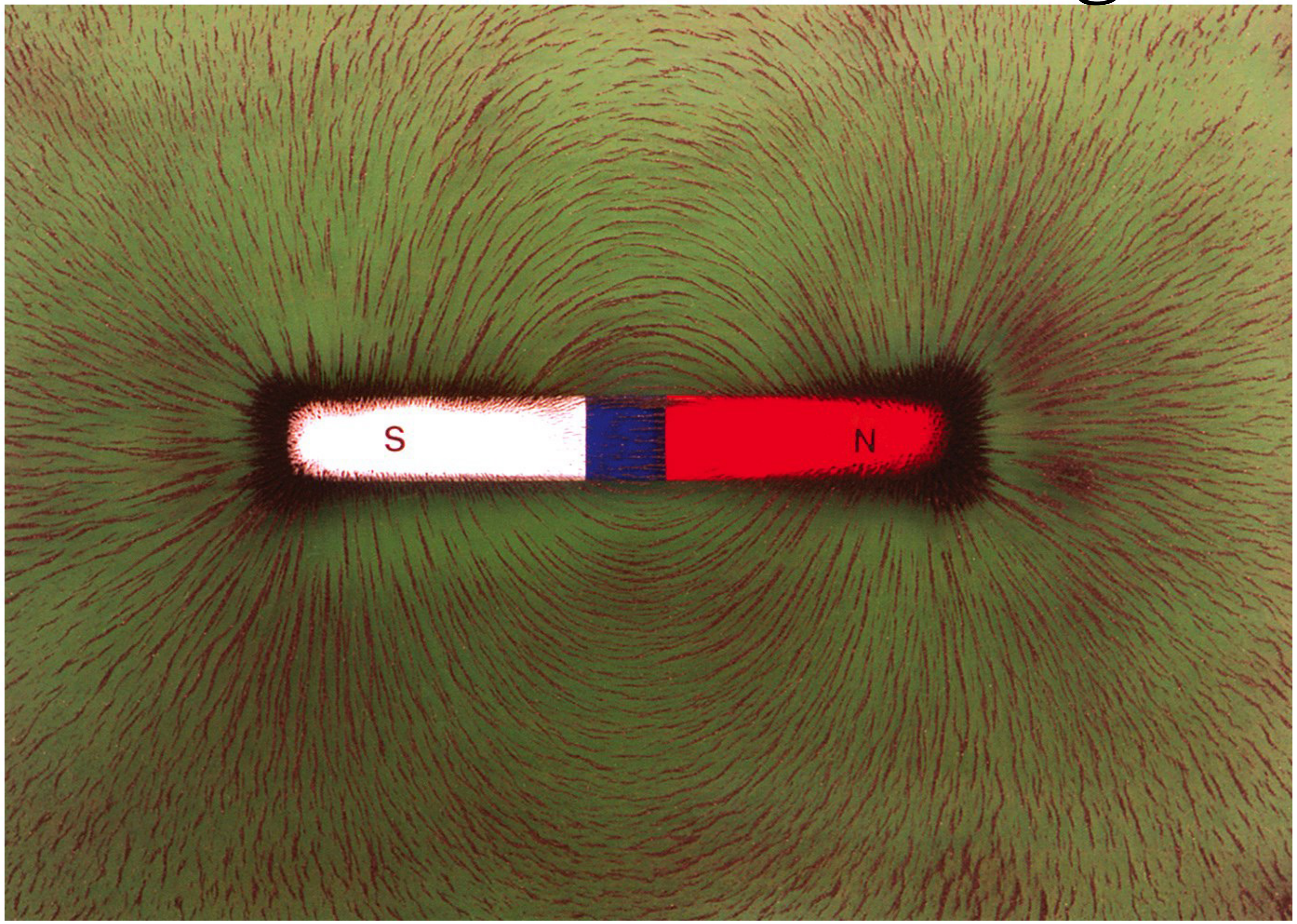
- Where can you find magnetism?

- What is a magnetic field?

- Imagine you have three identical blocks:
  - One permanent magnet
  - One of magnetic steel (iron)
  - One of non-magnetic steel (copper or aluminium)
- How could you identify which is which?

The magnetic field of a magnet

The magnetic field of a magnet visualised with iron filings



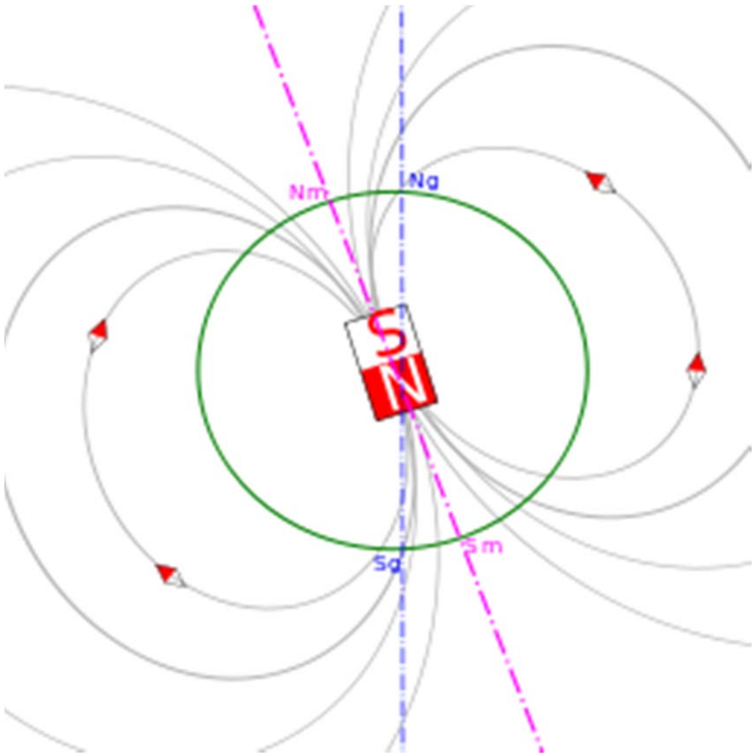
Question

- Does the needle of a compass point to the geographic north pole of the earth?

A. Yes
B. No
C. Nearly, there is a 11.3 degrees shift

Magnetic north pole of the earth

- SI-unit of magnetic flux density T=N s/(C m)
- Other unit Gauss 1 G = 0.1 mT



Magnetism: force and field

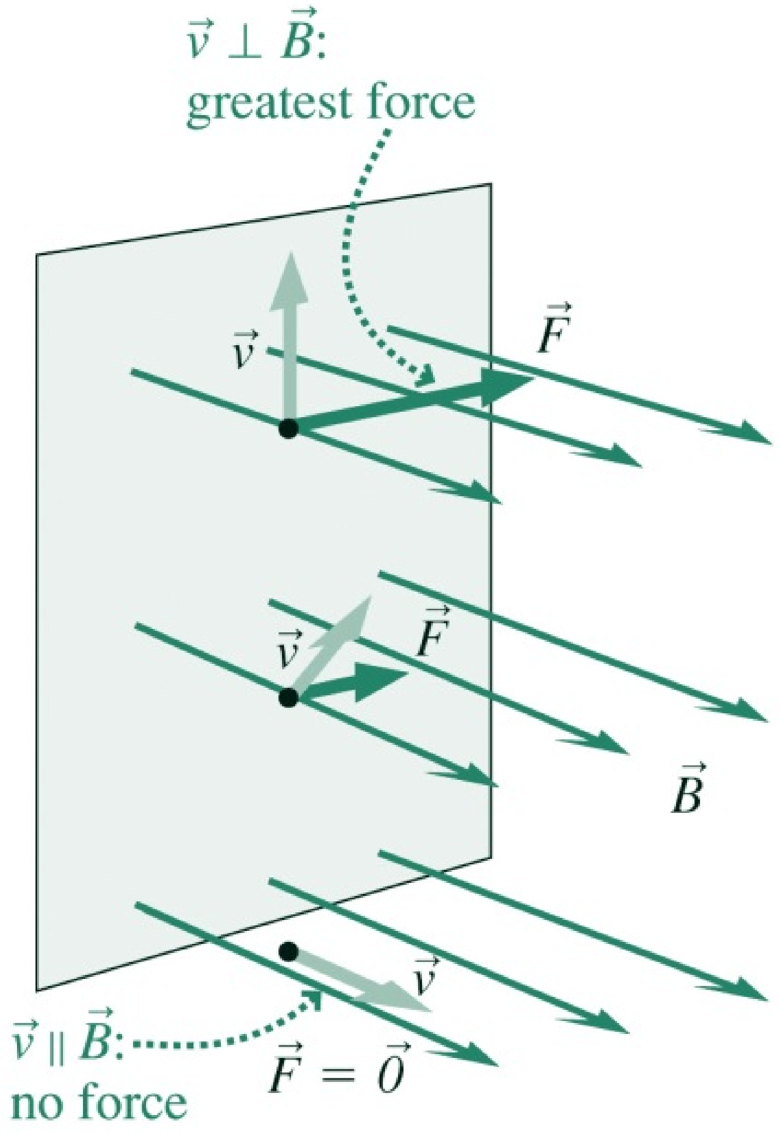
- Learning objectives
- Magnetic field
- Charged particles in magnetic fields
- Magnetic force on current
- Origin of the magnetic field
- Magnetic dipoles
- Magnetic matter
- Ampere’s law

Magnetic field and magnetic force

- B : magnetic field
- q : charge in free space (vacuum)
- v : speed

$$\vec{F} = q\vec{v} \times \vec{B}$$

$$F = qvB\sin\theta$$

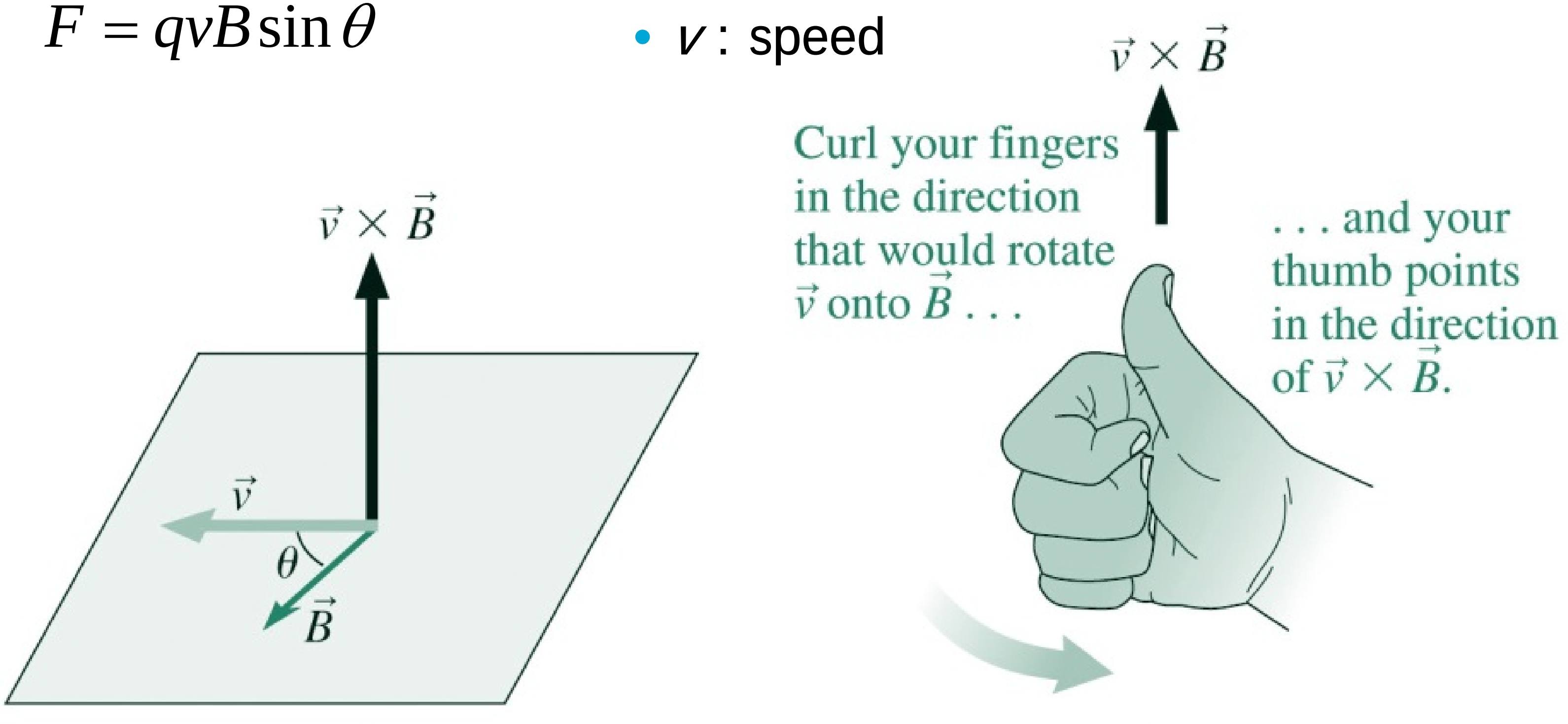


Magnetic field and magnetic force

$$\vec{F} = q\vec{v} \times \vec{B}$$

$$F = qvB\sin\theta$$

- B : magnetic field, magnetic flux density
- q : charge in free space (vacuum)
- v : speed

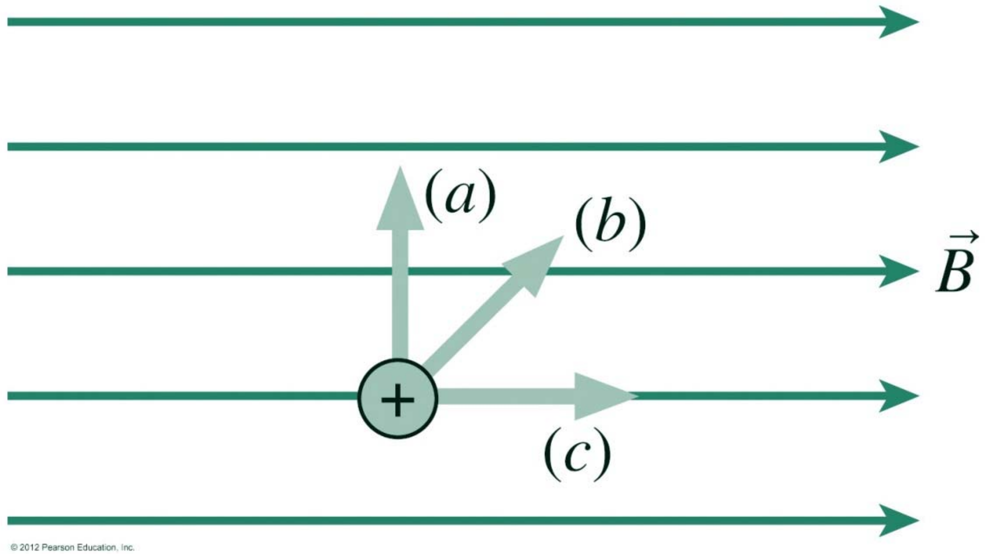


(a) (b)

Clicker question 1

- The figure shows a proton moving in a magnetic field. What will the direction of the magnetic force on the proton be in all cases?

A. Parallel to B
B. Into the page
C. Out of the page
D. Zero



Charged particles in magnetic fields

- What is the form of the curve of a moving electric charge in a uniform magnetic field perpendicular to the speed?

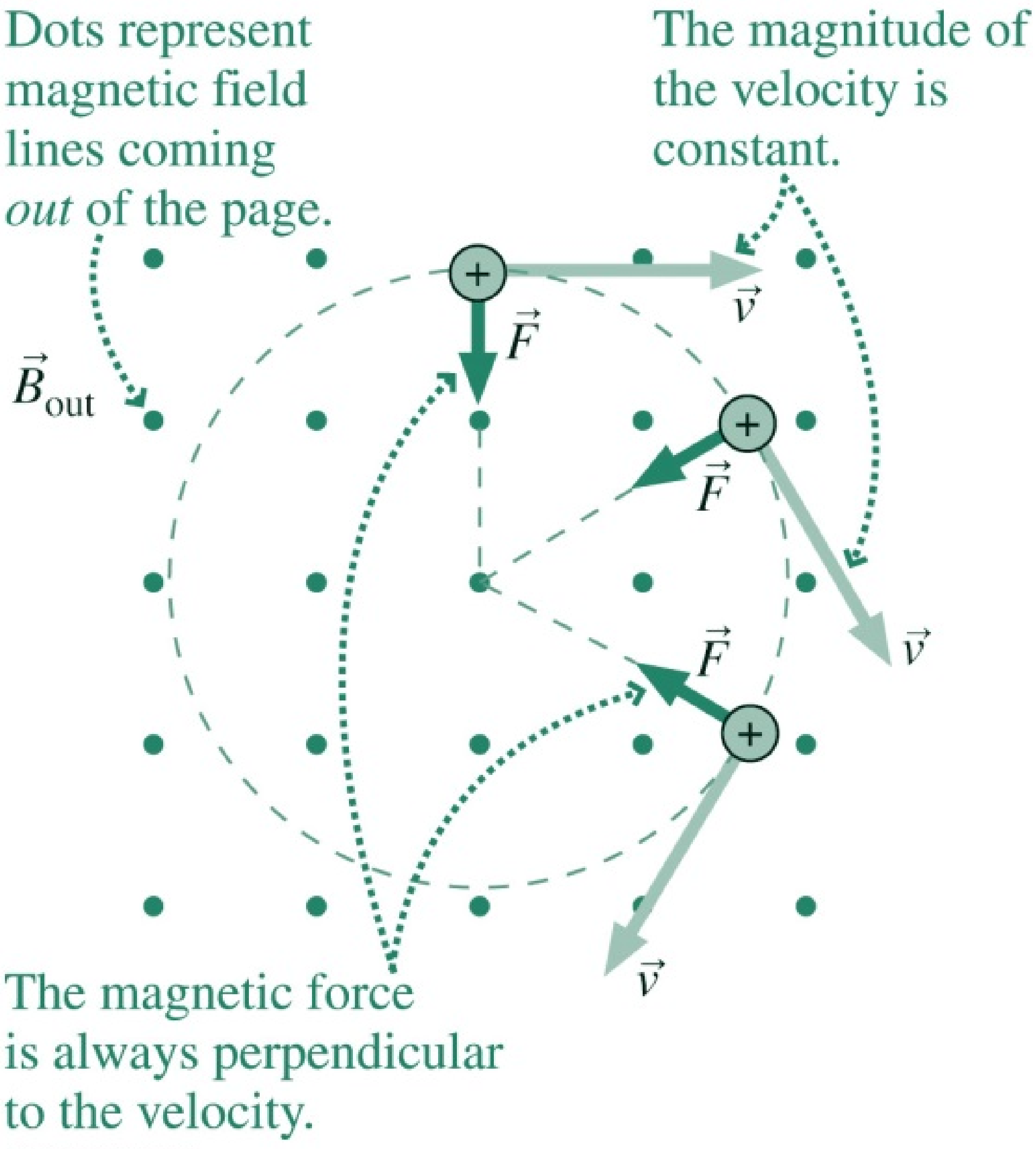
Circular motion

$$\begin{bmatrix} x \\ y \end{bmatrix} = \begin{bmatrix} r\cos(\omega t) \\ r\sin(\omega t) \end{bmatrix}$$

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} -r\omega\sin(\omega t) \\ r\omega\cos(\omega t) \end{bmatrix}$$

$$\begin{bmatrix} a_x \\ a_y \end{bmatrix} = \begin{bmatrix} -r\omega^2\cos(\omega t) \\ -r\omega^2\sin(\omega t) \end{bmatrix}$$

$$\begin{bmatrix} F_x \\ F_y \end{bmatrix} = \begin{bmatrix} -mr\omega^2\cos(\omega t) \\ -mr\omega^2\sin(\omega t) \end{bmatrix}$$



Charged particles in magnetic fields

$$\vec{F} = q\vec{v} \times \vec{B}$$

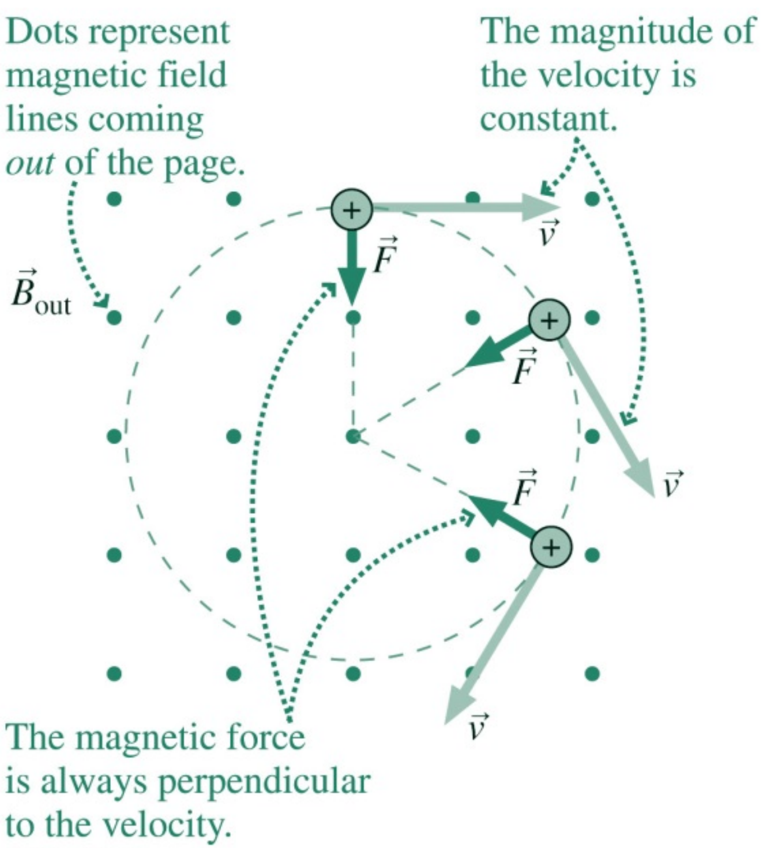
- Magnetic force perpendicular to a charged particle's velocity
- A particle moving in a plane perpendicular to the field undergoes uniform circular motion:

$$F = mr\omega^2 = \frac{mv^2}{r} = qvB \quad \Rightarrow \quad r = \frac{mv}{qB}$$

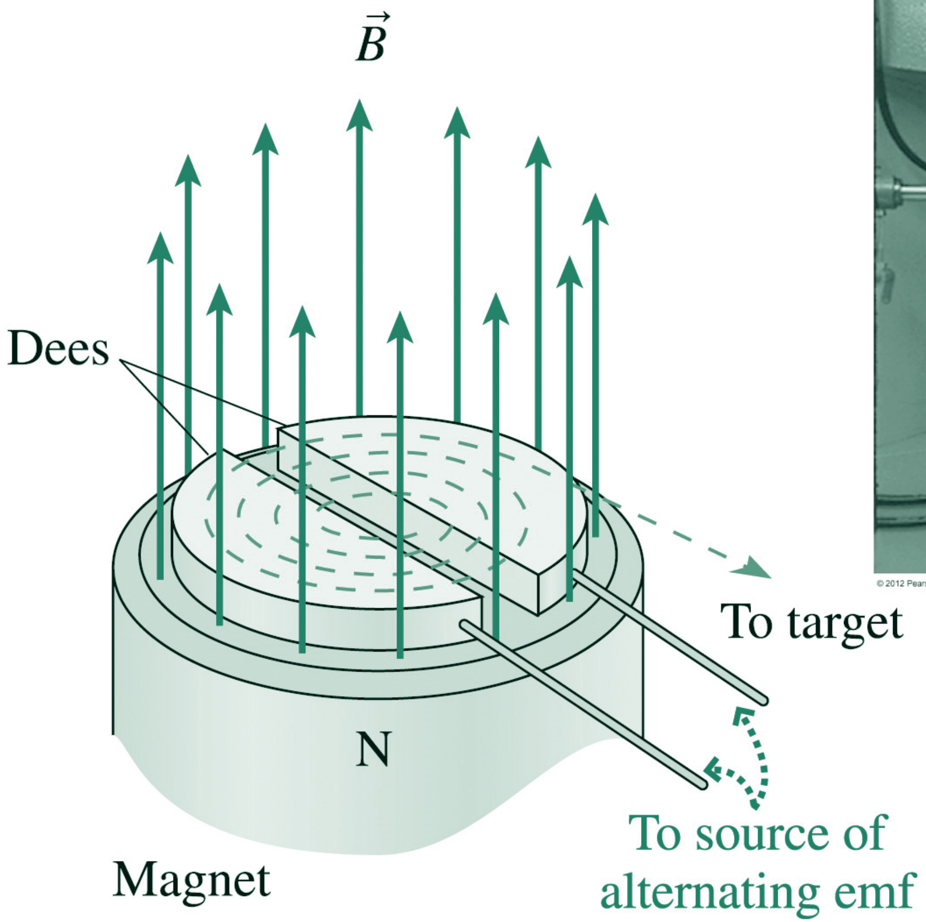
- The angular frequency is

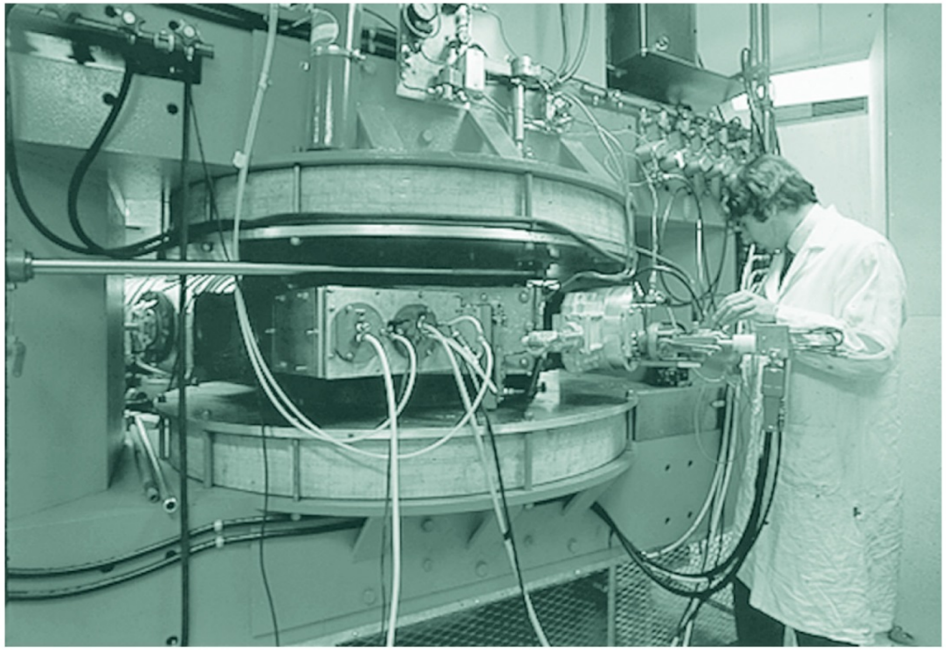
$$F = mr\omega^2 = qvB = qr\omega B \quad \Rightarrow \quad \omega = \frac{qB}{m}$$

independent of the particle's speed!



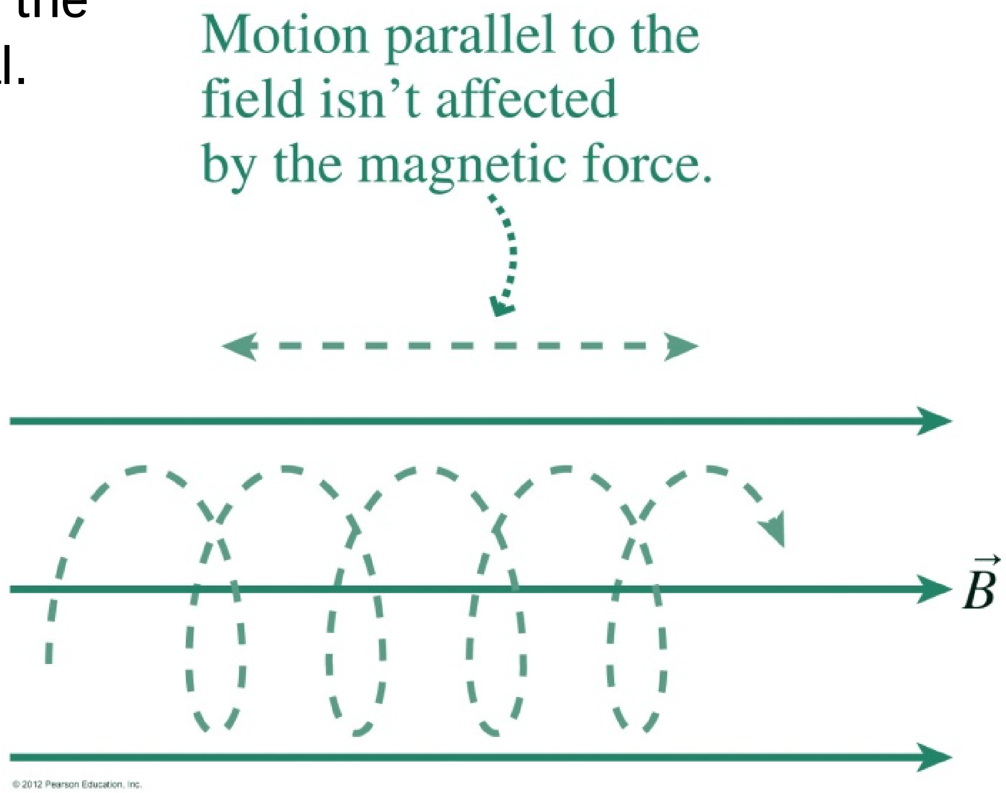
Cyclotron: particle accelerator





Charged particles in magnetic fields

- When the particle has a component of motion along the field, its trajectory is a spiral.



Clicker question 6

- A uniform magnetic field points out of this page. An electron that's moving in the plane of the page will circle _______________ as viewed from above the page.

A. clockwise
B. counterclockwise

Magnetism: force and field

- Learning objectives
- Magnetic field and magnetic forces
- Charged particles in magnetic fields
- Magnetic force on current
- Origin of the magnetic field
- Magnetic dipoles
- Magnetic matter
- Ampere’s law

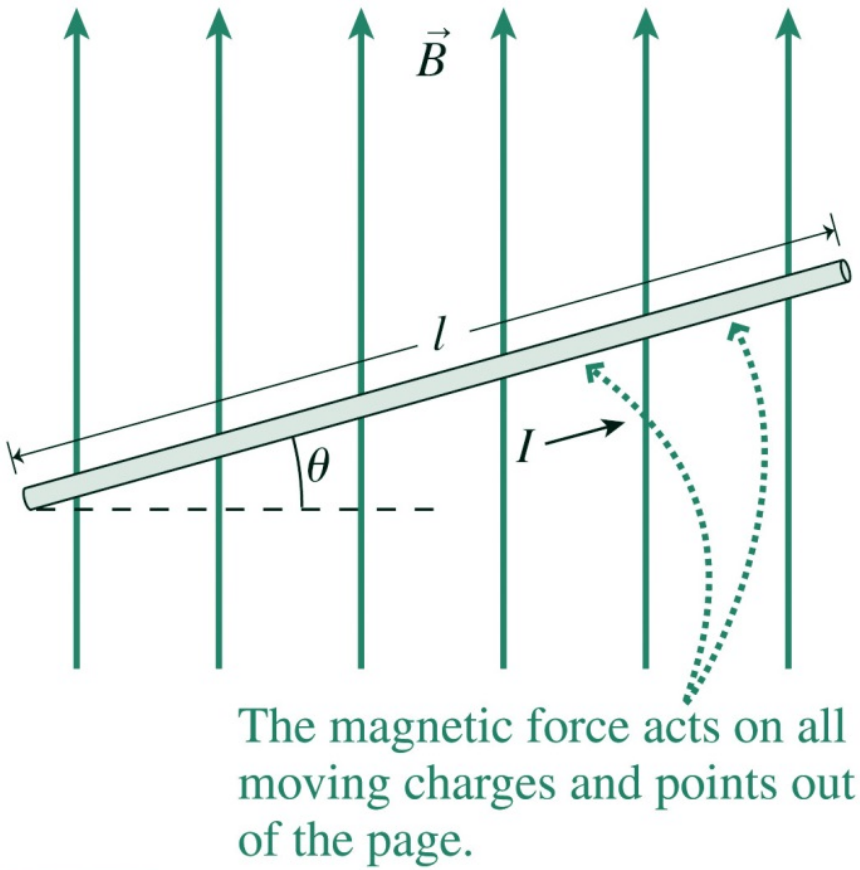
Magnetic force on current

$$\vec{F} = nALq\vec{v}_d \times \vec{B}$$

$$\vec{F} = I\vec{L} \times \vec{B}$$

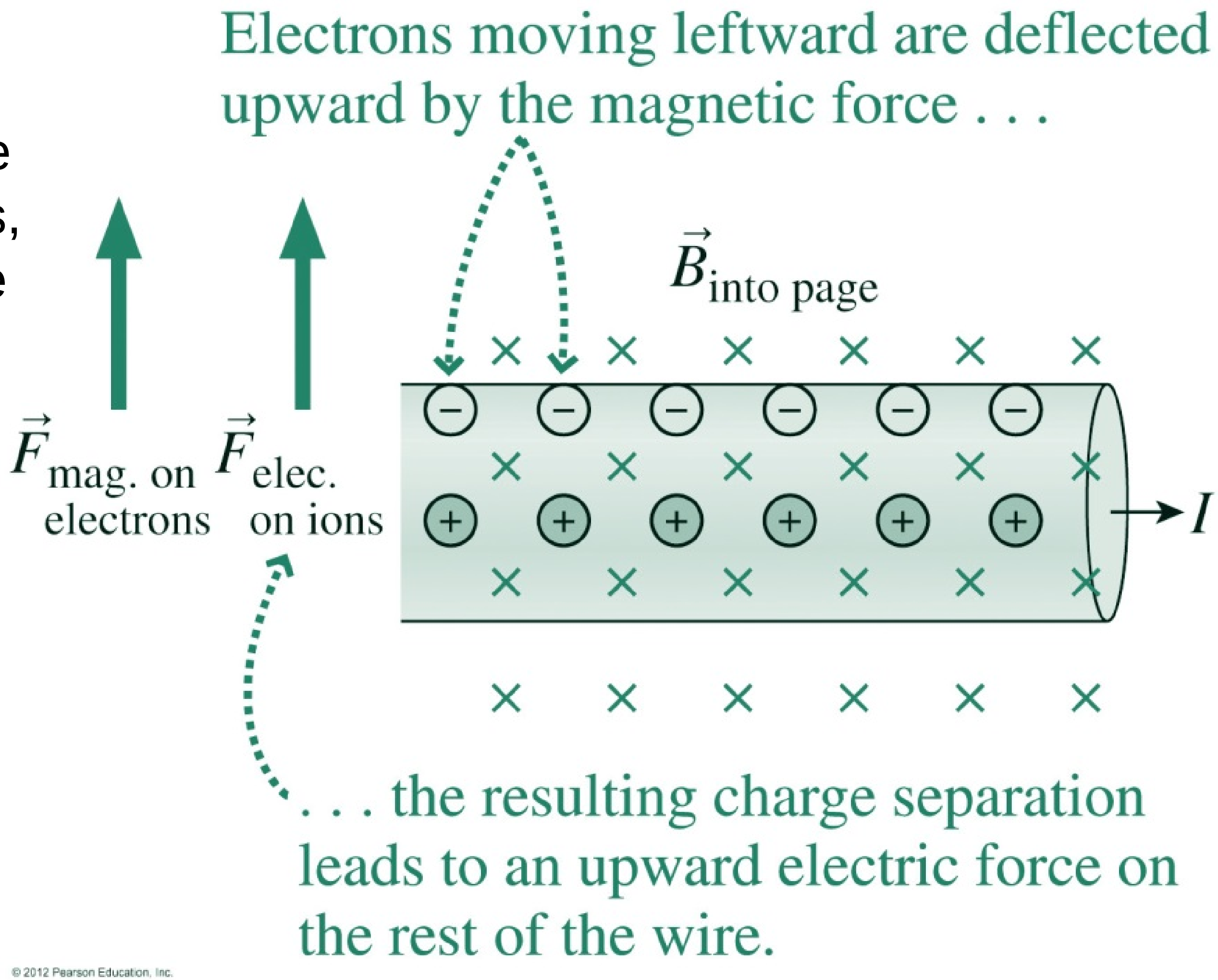
$$F = ILB\sin(\tfrac{1}{2}\pi - \theta)$$

- B : magnetic field
- q : charge
- v_d : drift velocity (average!)
- A : conductor cross section
- L : conductor length
- I : current
- n : charges per volume

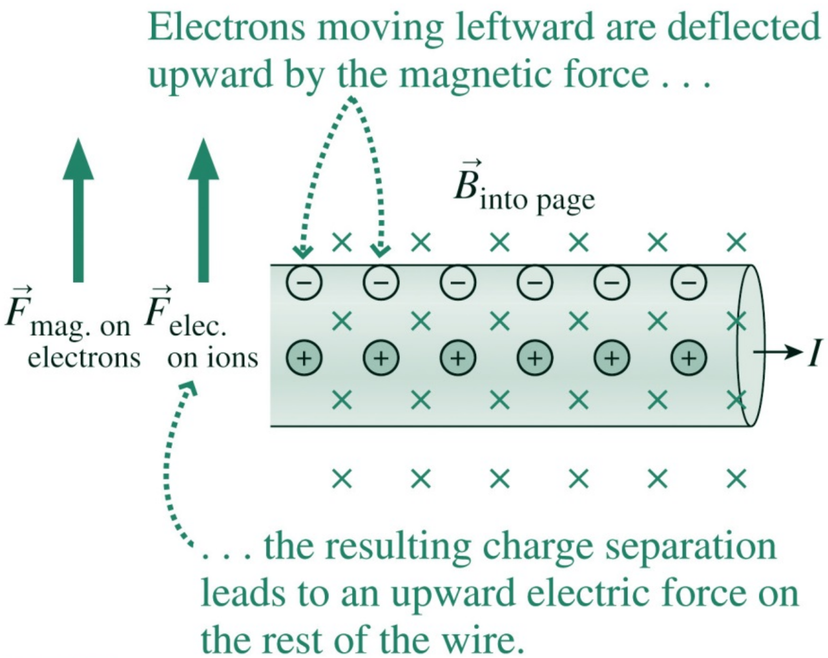


Magnetic force on a current

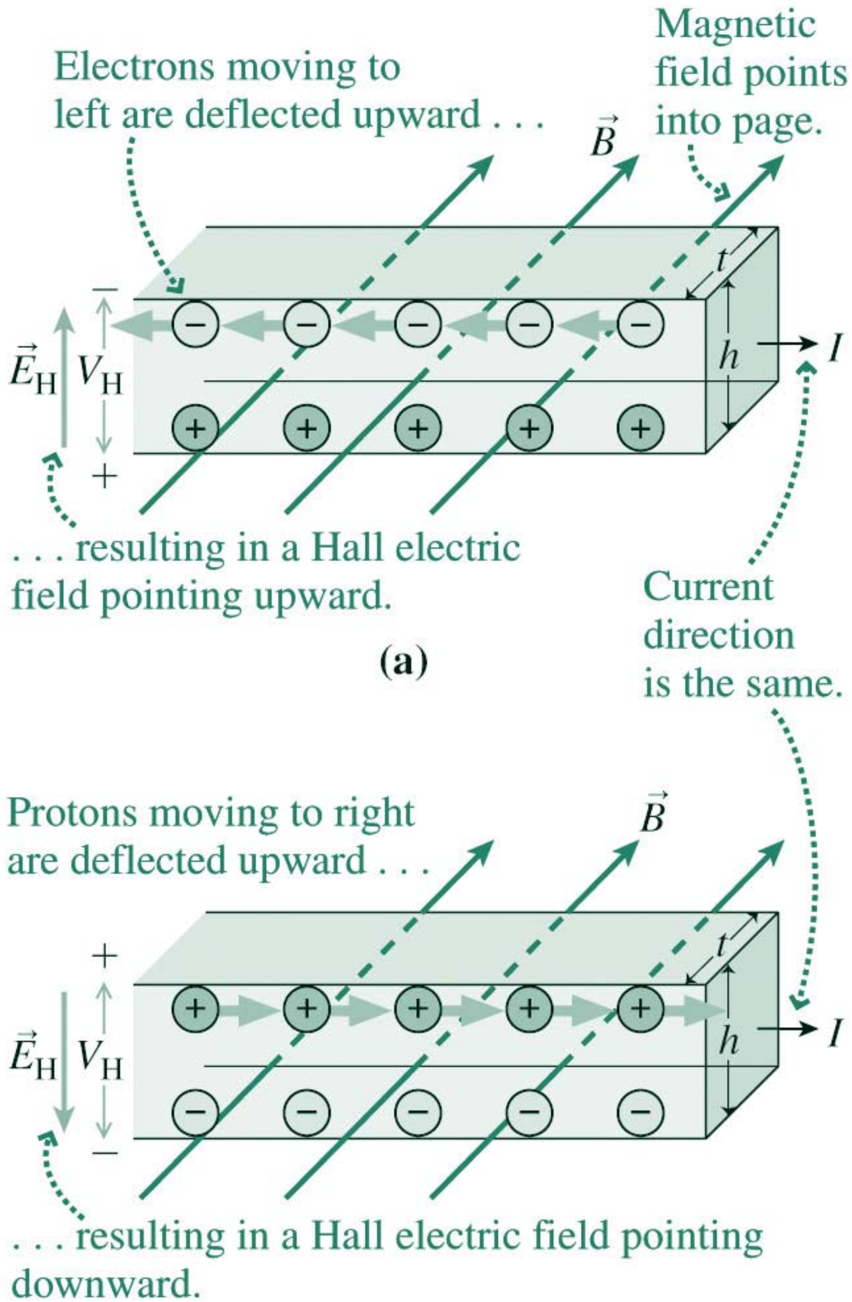
- Electrons move in all directions, but on average to left



Hall effect



Electrons moving leftward are deflected upward by the magnetic force . . .
$\vec{B}_{\text{into page}}$
$\vec{F}_{\text{mag. on electrons}}$
$\vec{F}_{\text{elec. on ions}}$
I
. . . the resulting charge separation leads to an upward electric force on the rest of the wire.



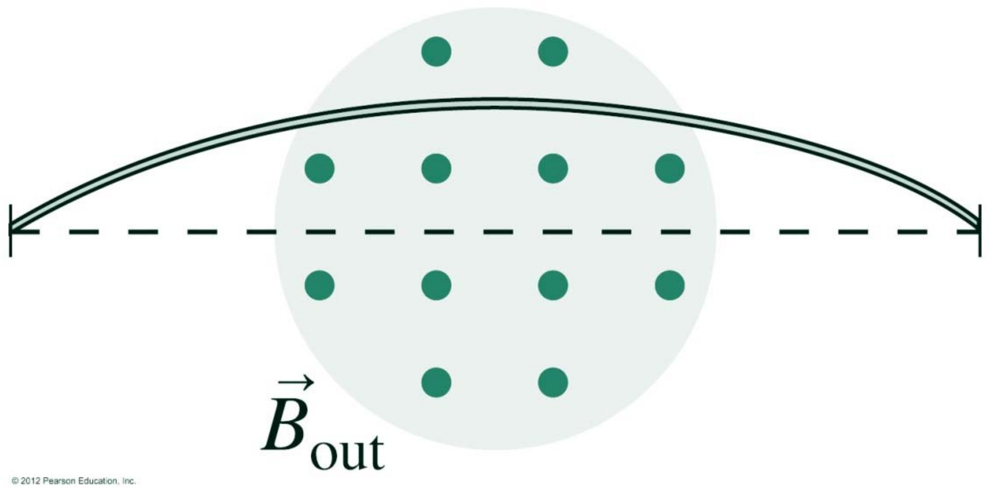
Electrons moving to left are deflected upward . . .
Magnetic field points into page.
$\vec{B}$
t
h
I
$\vec{E}_H$
V_H
. . . resulting in a Hall electric field pointing upward.
(a)
Current direction is the same.
Protons moving to right are deflected upward . . .
. . . resulting in a Hall electric field pointing downward.

Clicker question 2

- The figure shows a flexible conducting wire passing through a magnetic field that points out of the page. The wire is deflected upward, as shown. In which direction is current flowing in the wire?

A. To the left

B. To the right



Magnetism: force and field

- Learning objectives
- Magnetic field and magnetic forces
- Charged particles in magnetic fields
- Magnetic force on current
- Origin of the magnetic field
- Magnetic dipoles
- Magnetic matter
- Ampere’s law

Origin of the magnetic field

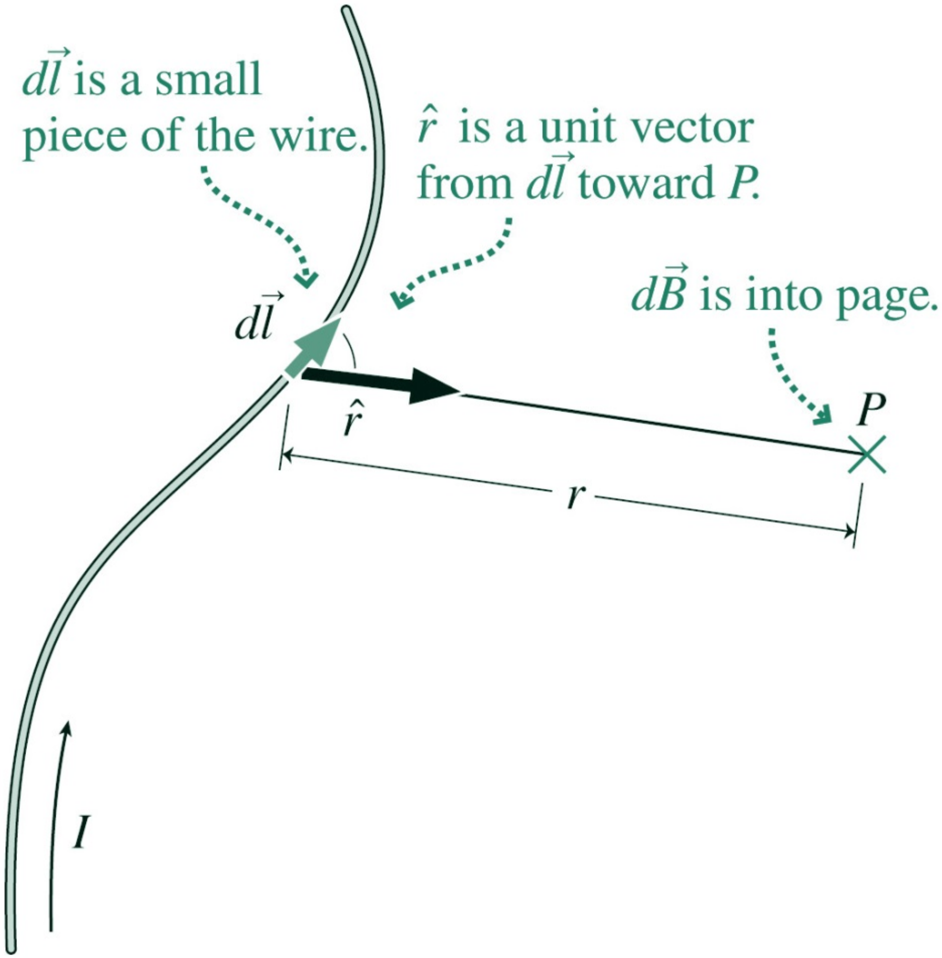
- Magnetic field
  - produces forces on moving electric charges,
  - arises from moving electric charge.
- Biot-Savart:

$$d\vec{B} = \frac{\mu_0}{4\pi}\frac{I\,d\vec{L}\times\hat{r}}{r^2}$$

- Therefore:

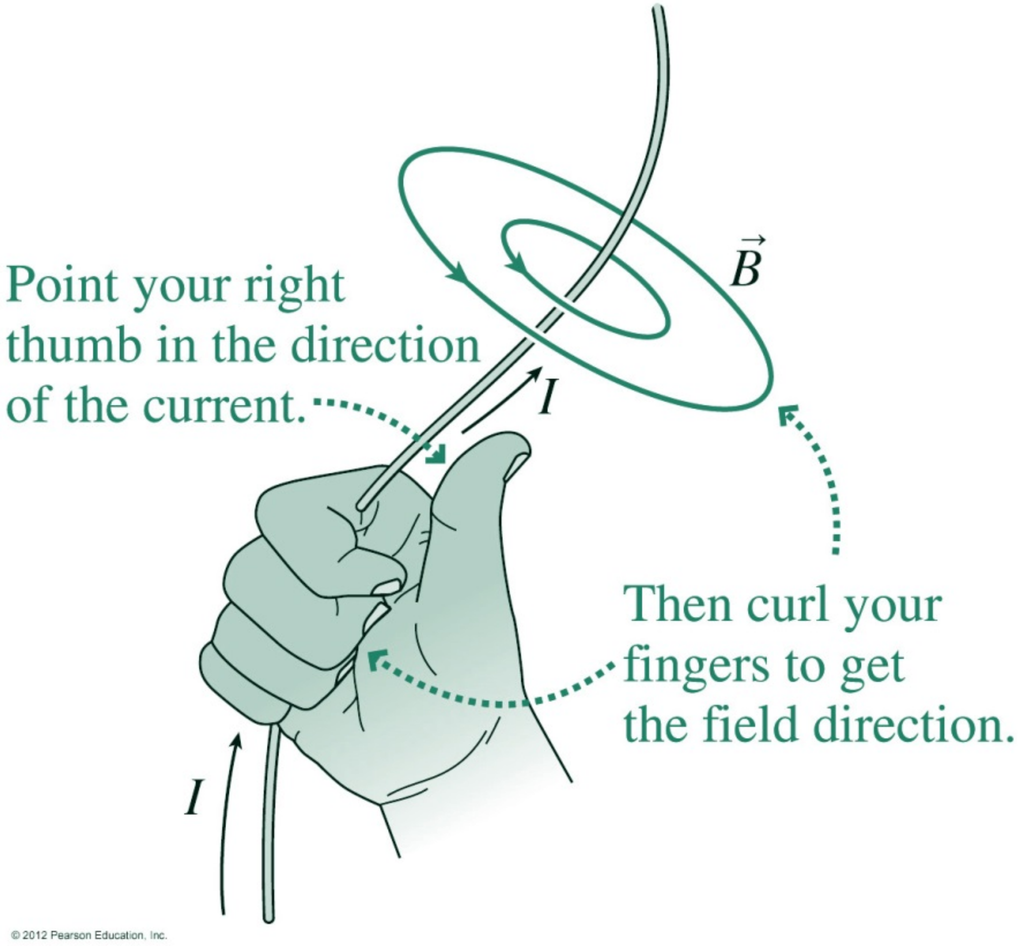
$$\vec{B} = \int d\vec{B} = \int \frac{\mu_0}{4\pi}\frac{I\,d\vec{L}\times\hat{r}}{r^2}$$

- $\mu_0 = 4\pi \times 10^{-7}$ N/A^2 is the permeability constant.



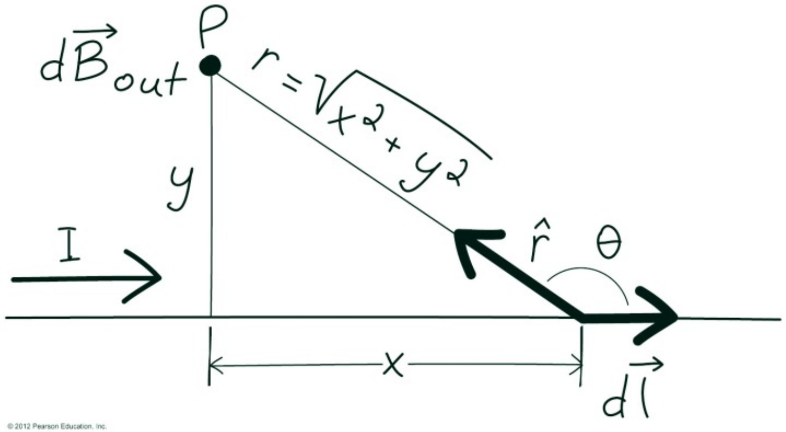
Behavior of magnetic field lines

- Magnetic fields originate in moving charge.
- Unlike static electric fields, (field lines begin and end on charges) magnetic field lines don't begin or end on the moving charges and currents.
- Magnetic field lines encircle moving charges or currents.
- Direction follows from the right-hand rule.
- In special cases, field lines may extend to infinity, but they don't begin or end.



Using Biot-Savart: a line current

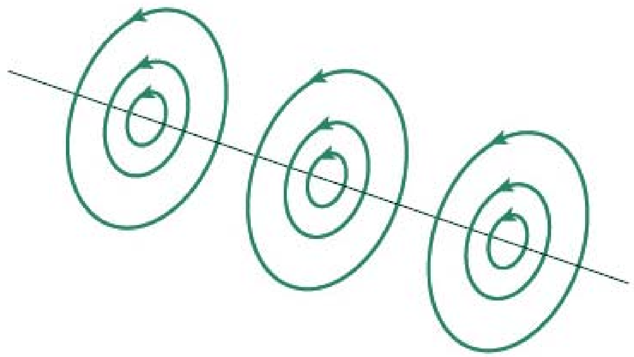
- The field contribution from a current element $I\mathrm{d}L = I\,\mathrm{d}x$ is



$$dB = \frac{\mu_0}{4\pi}\frac{I\,dL\sin\theta}{r^2} = \frac{\mu_0 I}{4\pi}\frac{y\,dx}{(x^2+y^2)^{3/2}}$$

- Integrating along an infinite line gives

$$B = \int dB = \frac{\mu_0 I y}{4\pi}\int_{-\infty}^{\infty}\frac{dx}{(x^2+y^2)^{3/2}} = \frac{\mu_0 I}{2\pi y}$$

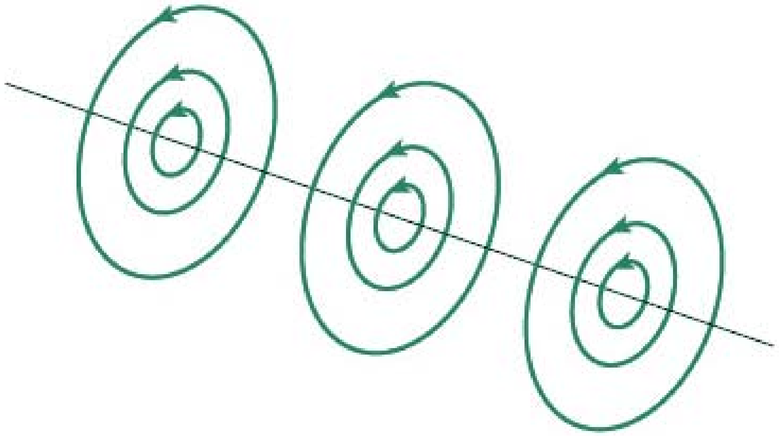


  - The field falls off as the inverse of the distance y from the wire.
  - The field encircles the current.

Force between two conductors

$$B = \int dB = \frac{\mu_0 I y}{4\pi} \int_{-\infty}^{\infty} \frac{dx}{(x^2 + y^2)^{3/2}} = \frac{\mu_0 I}{2\pi y}$$

- Two parallel wires experience forces from each other's magnetic field
- What is the direction of the force if the currents have the same direction?
  - Attract
  - Repel

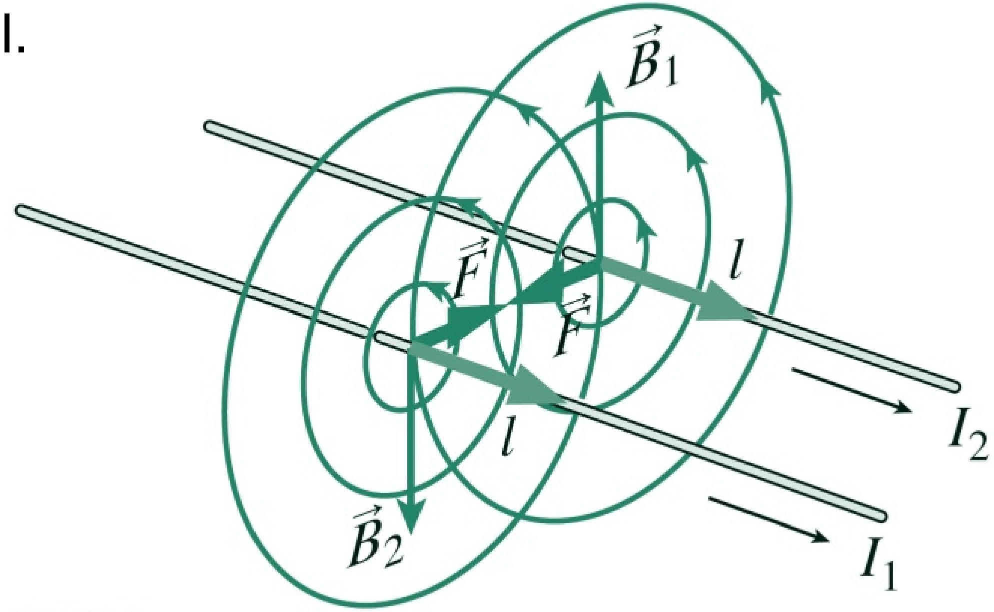


Force between two conductors

- Two parallel wires experience forces from each other's magnetic field:

$$F = \frac{\mu_0 I_1 I_2 L}{2\pi d}$$

  - Parallel currents attract.
  - Antiparallel currents repel.

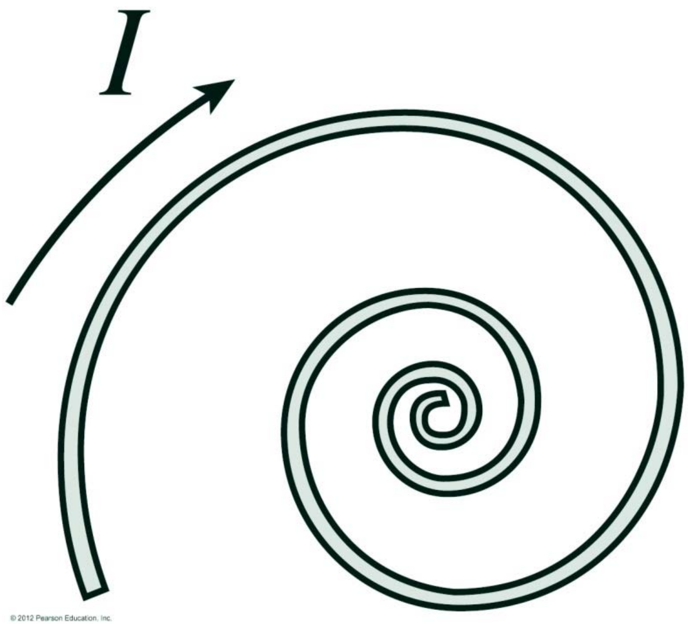


Clicker question 3

- A flexible wire is wound into a flat spiral as shown in the figure. If a current flows in the direction shown, will the coil tighten or loosen?

A. The coil will tighten.

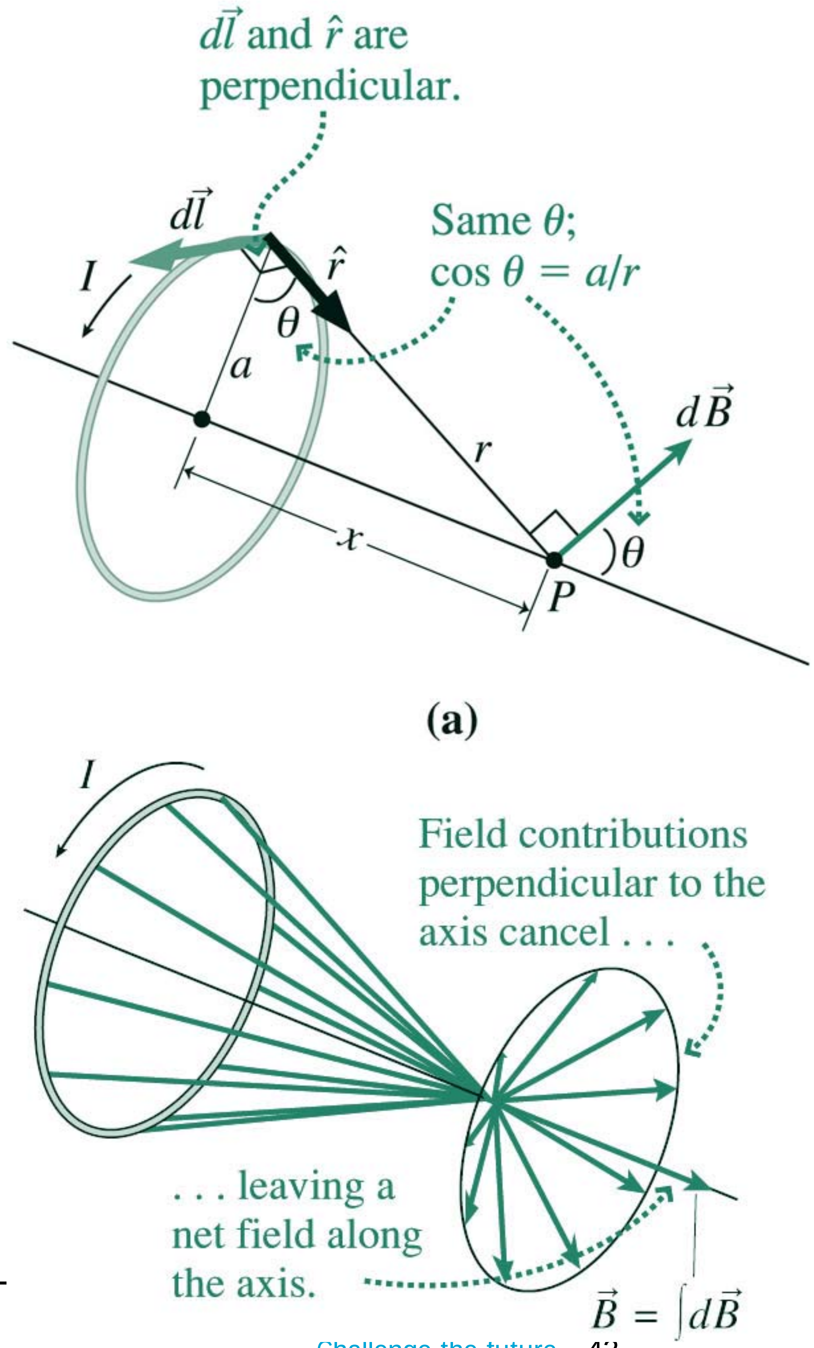
B. The coil will loosen.



Using Biot-Savart: current loop

- The field contribution from a current element $I\mathrm{d}L = I\,\mathrm{d}x$ is

$$dB_x = \frac{\mu_0 I}{4\pi}\frac{dL}{x^2+a^2}\frac{a}{\sqrt{x^2+a^2}}$$



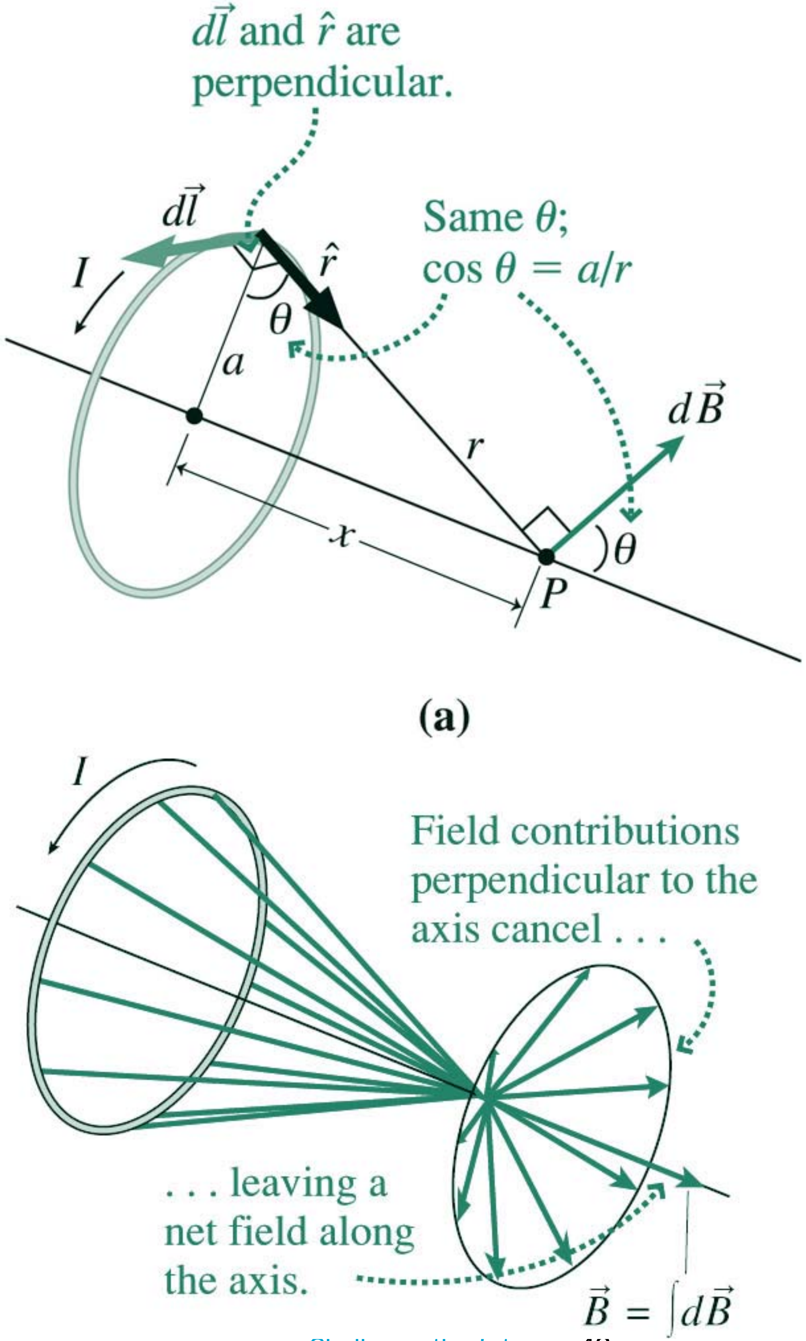
Using Biot-Savart: current loop

- Integrating the contributions along the circular current loop gives a field on the axis that depends on the distance *x* :

$$B=\int dB_x=\frac{\mu_0 Ia}{4\pi(x^2+a^2)^{3/2}}\int_{\text{loop}} dl$$

$$B=\frac{\mu_0 Ia^2}{2(x^2+a^2)^{3/2}}$$

- For large distances (*x* >> *a*), this reduces to $B=\dfrac{\mu_0 Ia^2}{2x^3}$



Magnetism: force and field

- Learning objectives
- Magnetic field and magnetic forces
- Charged particles in magnetic fields
- Magnetic force on current
- Origin of the magnetic field
- Magnetic dipoles
- Magnetic matter
- Ampere's law