

External Field of a Bar Magnet and Inverse Square Law

BACKGROUND: Since early times the existence of magnetic force has been known; certain kinds of rocks called 'lodestone' would attract pieces of iron. Also, forces of attraction and repulsion between two pieces of lodestone were observed to depend on their relative orientation. A freely suspended lodestone would always point in the same direction; the end which pointed toward the geographic North was labeled the North (or N) pole and that pointing toward the geographic South was labeled the South (or S) pole. It therefore would appear that the earth acts like a giant bar magnet with its South magnetic pole in the Northern hemisphere and its North magnetic pole in the Southern hemisphere since opposite magnetic poles attract each other.

A single modern concept of a magnetic field always accompanies an electric current or a moving charge. A circulating electric current in an atom and its electronic spin will produce a magnetic field. Permanent magnets, such as a bar magnet made from iron alloys (ferromagnetic materials), have small clusters of adjacent atoms, called magnetic domains. The unpaired spins in the atoms of a magnetic domain are aligned to produce a sizeable magnetic field. In an unmagnetized piece of a magnetic material, these domains are randomly oriented and their magnetic fields well-nigh cancel each other out. However, under the influence of a sufficiently strong external magnetic field, the domains become generally aligned in the direction opposite of that of the external field. Now the magnetic fields of the individual domains add up to produce a magnetic field, as in a bar magnet.

OBJECT: To investigate the magnetic field about a bar magnet and to show that it varies inversely as the square of the distance from an isolated magnetic pole.

APPARATUS: Long bar magnet, drawing board, compass (one small and one large, if possible), aluminum plate guide for bar magnets, iron filings, and paper.

THEORY: The magnetic field is a vector field since its strength or intensity may be defined as the force on a unit North pole. Somewhat analogous to electric fields, magnetic fields can be represented by lines so that the strength of the field is represented by the density of lines and its direction represented by a tangent to these lines. We illustrate below the magnetic field of a bar magnet in Fig. 5.1 and an expanded view near the North pole of a long bar magnet in Fig. 5.2.

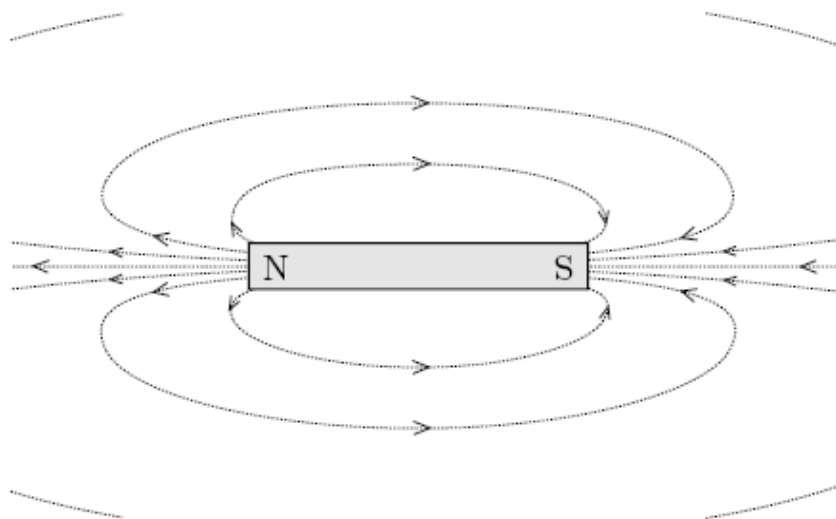


Figure 5.1: Magnetic Field of a Permanent Bar Magnet.

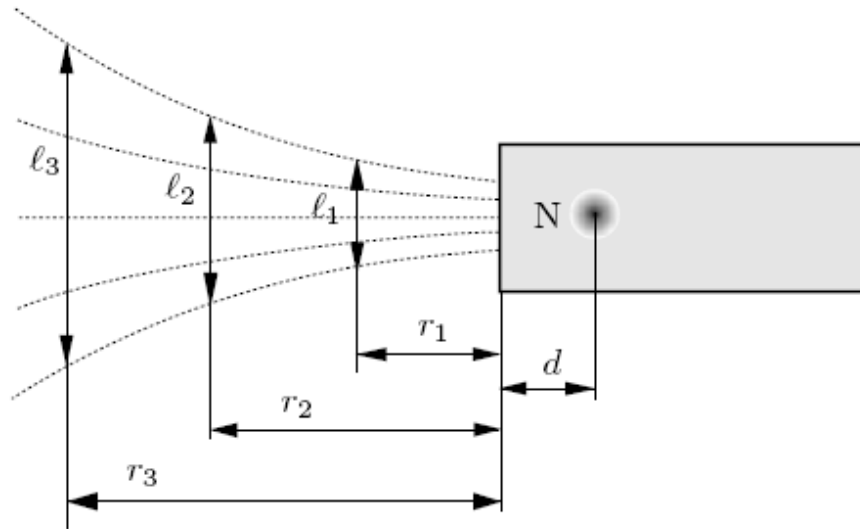


Figure 5.2: The Magnetic Field Near the North Pole of a Bar Magnet.

It is seen from Fig. 5.1 that the magnetic lines of force always form closed loops. The location of the poles is generally uncertain and we will suppose that the pole is situated inside the magnet at a distance d from the end of the magnet.

In Fig. 5.2, the same number of lines thread through the lengths ℓ_1 , ℓ_2 and ℓ_3 which are located at r_1 , r_2 , and r_3 from the end of the magnet. The strength of the magnetic field at a point is described by the number of lines per unit area crossing a small area perpendicular to the field at that point. The magnetic field is inversely proportional to the square of the distance from the pole. Together these statements for the average value of B will give:

$$B \propto \frac{1}{r^2}, \text{ and } B \propto \frac{1}{(r + d)^2}, \quad (1)$$

or

$$\ell = c(r + d), \quad (2)$$

where c is the proportionality constant and d is the distance between the pole and edge of the bar magnet. However, bear in mind that the influence of the South pole (visible in the bending of the magnetic lines of force as in Fig. 5.1) renders this relation approximate.

PROCEDURE:

1. Place the bar magnet in the center of the paper with its South pole facing North. A compass needle, in the absence of any external magnetic fields other than that of the Earth, will align itself in the N–S direction. Make sure that it is a strongly magnetized magnet. Draw the magnet outline.
2. Place the small compass near the North pole of the magnet and make a dot on the paper at each end of the compass arrow. Move the compass forward till its South pole is over the dot of the previous North pole location.

3. Plot at least 10 to 12 lines of force by moving the compass, marking arrow positions and repositioning the compass. Take care that these lines originating from the North pole are nearly equally spaced at the starting point.
4. Draw a smooth curve through the series of dots and place arrows indicating that these lines emanate from the North pole.
5. Locate the points where the compass needle has no tendency to turn in any direction. These points are called neutral points and should indicate where the magnetic field of the Earth and that of the magnet are equal and opposite to each other.
6. To further visualize the magnetic field of a bar magnet, position the bar magnet beneath a sheet of paper. Sprinkle iron filings above the paper and magnet and tap the box slightly so that the filings will align along the magnetic field lines.

CALCULATIONS:

1. Measure several ℓ 's (ℓ_1, ℓ_2, \dots), keeping them much smaller than the length of the bar magnet, and the corresponding r 's (r_1, r_2, \dots). The closer (as compared to the length of the bar magnet) you are to the pole for these measurements, the better your results will be since the magnetic field will more closely resemble that of an isolated magnetic pole, for which Eq. (1) applies.
2. Plot ℓ versus r using the computer. The linearity of this plot, implied by Eq. (1), is only approximate because Eq. (1) itself holds only approximately as explained above. (This is the reason for keeping the ℓ 's as small as possible compared to the length of the bar magnet.) Determine the value of d from the intercept with the axis displaying r in the ℓ - r plot.