

A new description and a fresh technique for explaining the attraction and repulsion of magnet poles)..

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In this article, we first present an overview of the theory of magnetic fields and the identification of their N and S poles, even in free space. We then discuss the net force exerted on closed current loops in the presence of a magnetic field. A representative and highly practical example is introduced for the force acting on current carrying loops in magnetic fields that appear to be uniform but are in fact nonuniform. The results are then used to explain the magnetic force between two interacting magnets.

I. INTRODUCTION

As we know, one of the well-known types of fields in electromagnetism is the magnetic field^{1–2}. In the static case (with no time dependence), the lines of magnetic field strength are represented as shown in Figure 1.

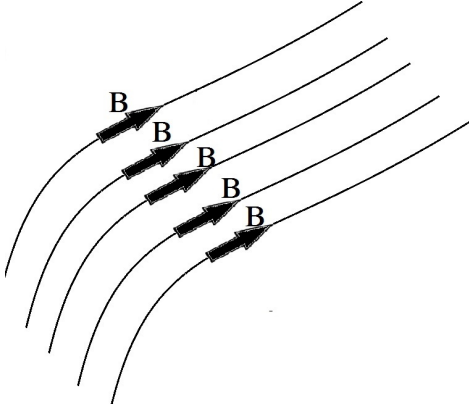


FIG. 1. The representation of magnetic field lines in space, in which the concepts of N and S exist simultaneously at every point in space..

Unlike other well-known fields such as gravitational and electric fields, since magnetic monopoles cannot be found at ordinary energy scales, the concept of magnetic S and N poles is introduced. The labeling and identification of N and S poles for magnetic fields strongly depend on the region under consideration. If we are asked to determine the magnetic poles within an arbitrarily selected region, as shown in Figure 2, we must examine that region more closely, as illustrated in Figure 3.

By enlarging it, we can see from which side the field lines exit (the N pole) and from which side they enter (the S pole). As another example, in each of Figures 4a, 4b, and 4c—where three types of magnetic-field-generating systems are shown—an arbitrary region has been selected in the lower row of these figures, and we aim to identify the

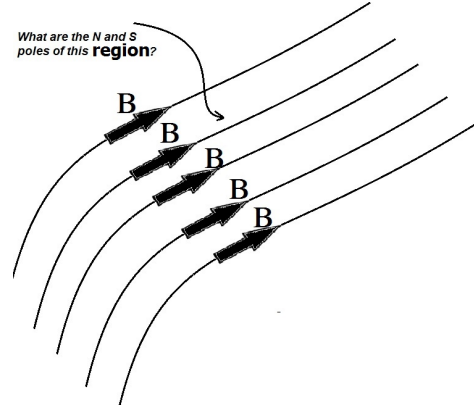


FIG. 2. The request to determine the N and S poles for a small region or a volume element.

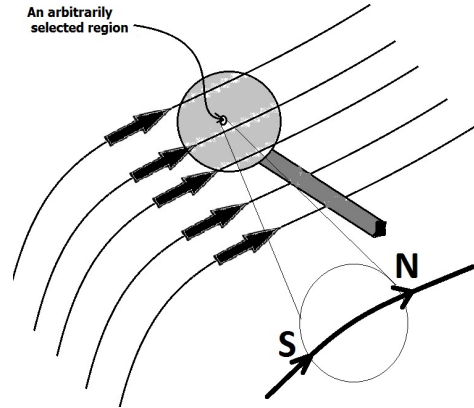


FIG. 3. Magnifying the region to identify the N and S poles: the side from which the field lines emerge is the N pole, and the part of the region where the field lines enter is the S pole.

magnetic poles associated with that region. The point explained through Figures 1, 2, 3, and 4 is closely related to the main subject of this study, namely the description of magnetic attraction and repulsion, which we will address in the following sections.

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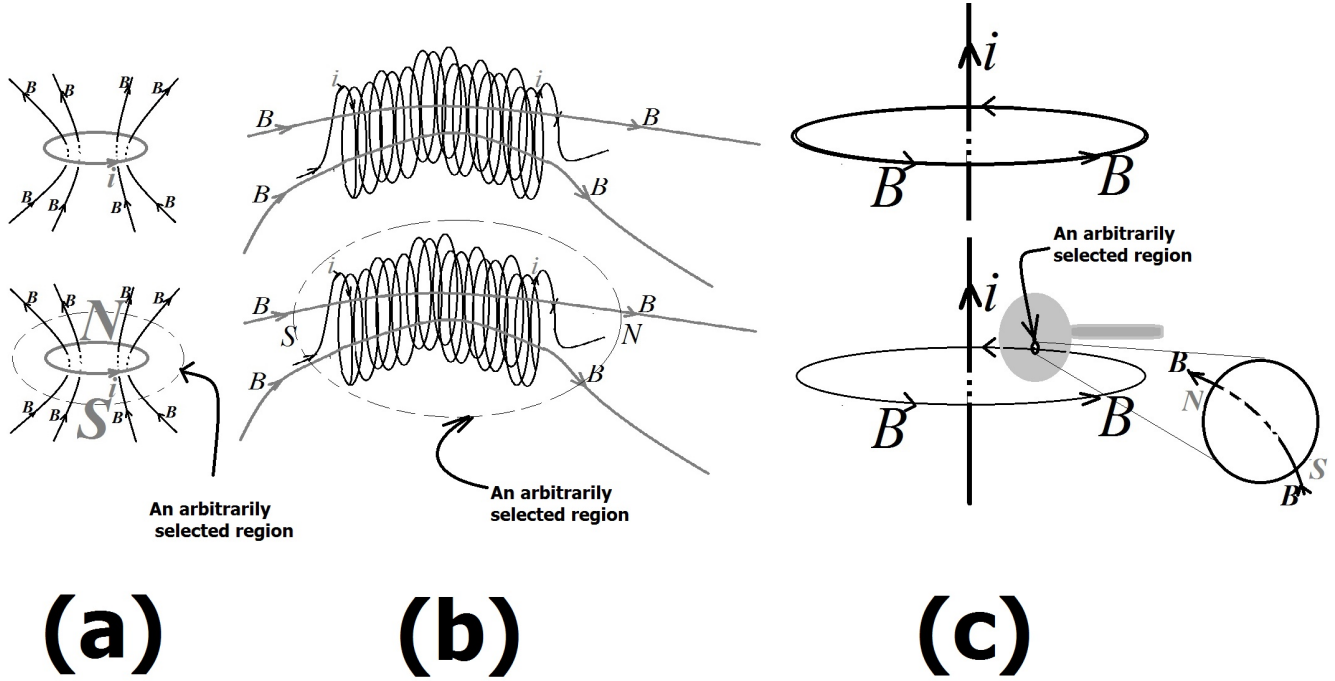


FIG. 4. Representation of three magnetic field sources and selecting a region of space that contains the sources in order to determine the magnetic poles of those regions: 4-a) A circular loop carrying a current i . 4-b) A non-straight, non-standard coil carrying a current i . 4-c) A straight wire carrying a current i

II. THE NET FORCE ACTING ON CLOSED CURRENT PATHS IN THE PRESENCE OF AN EXTERNAL MAGNETIC FIELD

As is usually discussed in introductory magnetism, the force exerted on a closed current-carrying loop with current i in an external magnetic field such as B can be calculated using the following relation,

$$\vec{F} = i \oint_{\text{loop}} d\vec{l} \times \vec{B}$$

where $d\vec{l}$ is the differential length vector along the loop in the direction of the current. Undoubtedly, if a closed loop carrying current i is placed in a completely uniform magnetic field (constant in both magnitude and direction), the net force acting on it becomes zero because[1-2]

$$\vec{F} = i \oint_{\text{loop}} d\vec{l} \times \vec{B} = i \left(\underbrace{\oint_{\text{loop}} d\vec{l}}_0 \right) \times \vec{B} = 0$$

In the above relation, the magnetic field B could be taken outside the integral because it was assumed that the loop is placed in a completely uniform (constant) magnetic field. But does this hold true for a magnetic field shaped in space as shown in Figure 5?

The magnetic field depicted in Figure 5 is modeled as a conical field in space. For example, at a fixed height, the magnetic field magnitude is constant at B_0 , but it always makes a fixed angle α with the vertical direction. While the magnitude is constant, its direction varies at each point, though the angle with the vertical remains fixed. Is this magnetic field truly uniform (constant in both magnitude and direction)? The answer is negative; although the magnitude of this field is constant, its direction changes, so it cannot be considered a completely uniform and constant field. For example, as shown in Figure 6, if a loop of radius R carrying current i is placed in this field, a net force is exerted on the loop downward. The details and the calculation method are illustrated in Figure 6, as you can see. As can be seen, this current carrying ring experiences a net force from the field, and this force is directed opposite to the z -axis. Therefore, a more precise definition of a uniform magnetic field must be provided, because this trumpet-shaped magnetic field

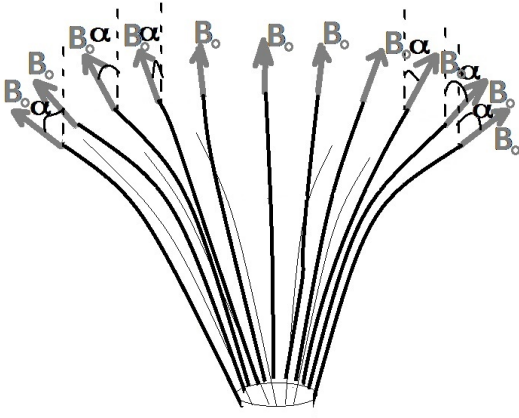


FIG. 5. A type of magnetic field distribution in space (similar to a trumpet-shaped opening) in which the field magnitude is constant at a fixed height, but it is symmetrically distributed about a fixed axis, and its direction always makes an angle α with the vertical..

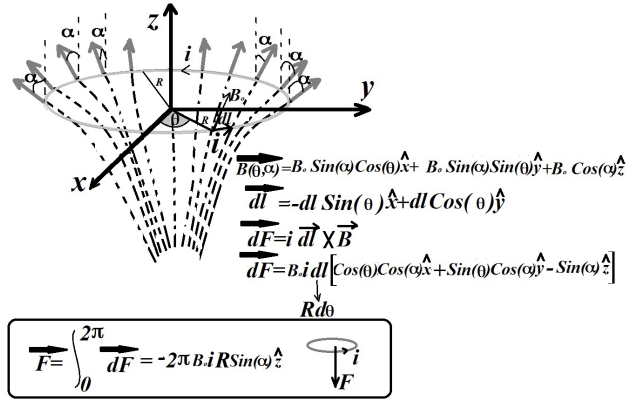


FIG. 6. A current-carrying loop placed in a non-uniform magnetic field and the detailed calculation of the net force on the loop, which causes the loop to be pulled downward..

is not truly constant the direction of the field continuously changes in space.

An important point that can be inferred from the expression of the force obtained in Fig. 6 is that if closed circuits are placed in non-uniform magnetic fields, they will experience a net force. However, if we look more carefully at the components shown in Fig. 6, we realize that the circular loop itself acts as a source of magnetic fields, and in Fig. 7 we have precisely illustrated its poles.

Figure 7 practically provides the answer to the question of what structure can create a trumpet-shaped magnetic field in space. Yes, as shown in Fig. 7, a single N pole from another magnet is sufficient to produce this field in space.

In other words, this can be considered as the reason for the attraction between unlike poles in magnets. More simply, when we place the opposite poles of two magnets

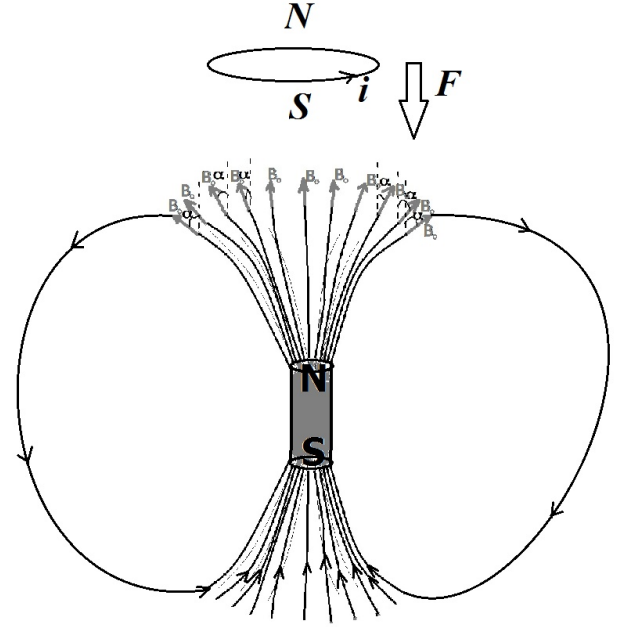


FIG. 7. Identifying the object that can generate a trumpet-shaped magnetic field in space, which is the N pole of a magnet. This magnet is attracting a current-carrying loop whose S pole is positioned opposite the N pole of the main structure..

near each other, one magnet produces non-uniform magnetic fields inside the other magnet, and the very small current carrying loops formed either by the spin motion of electrons around themselves or by their orbital motion around the nucleus experience forces that can be described in exactly the same way as the forces on loops placed in a non-uniform magnetic field. In fact, as shown in Fig. 8, the lower magnet creates non-uniform magnetic fields inside the second magnet, and the tiny loops within the second magnet (the upper magnet in Fig. 8) each experience a net force.

Essentially, the first magnet is pulling and attracting the current loops in the second magnet, which is what we perceive. It is up to the student to demonstrate that if the direction of the current in the loop shown in Fig. 6 is reversed, the resulting force will act along the positive z-axis, causing the loop to be repelled providing a clear explanation of the repulsion between like poles. Of course, in more advanced topics of electromagnetism, the concept of when a net force appears on closed current-carrying paths placed in a magnetic field is expressed by the following equation³⁻⁴.

$$\vec{F} = -\vec{\nabla} (U_P) = -\vec{\nabla} \left(-\vec{m} \cdot \vec{B}_{\text{ext}} \right)$$

In the above equation, U_P is the potential energy function, $\vec{m}$ is the magnetic dipole moment of the loop, and $\vec{B}_{\text{ext}}$ is the external magnetic field in which the loop is placed.

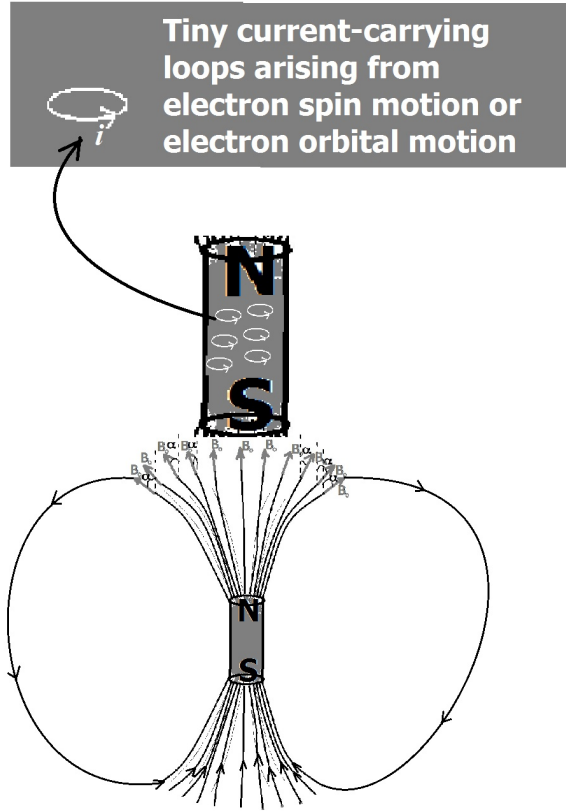


FIG. 8. The magnetic field of the lower magnet penetrates in a non-homogeneous and non-uniform manner, leading to the attraction of current loops in the upper magnet.

Since $\vec{m}$ for a loop is a fixed vector and does not depend on position, the only way for the gradient operation to yield a nonzero result is for the magnetic field to be position dependent, that is, non-uniform, which means $\vec{B}_{ext} = \vec{B}_{ext}(r)$

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