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Beyond the Right-Hand Rule, Describing the Magnetic Field around an Electrical Current Using a Recent Scalar Magnetic Field Definition

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Abstract

An electrical current running through a wire generates a surrounding magnetic field which is detectable by a compass. The right-hand is used to determine, at each position, the direction of this magnetic field. This direction is clearly in agreement with the direction given by the compass. Even if this rule is accepted today, the objective of this article is to rewrite our knowledge of the magnetic field in the case of two or more electrical wires.

Keywords

Wire With Electromagnetic Field, Right-Hand Rule for Magnetism, Scalar Magnetic Field, Biot-Savart Law

1. Introduction

The discovery of the effect of an electrical current on a compass was observed by Oersted in 1820 [1]. He had communicated its observations to Ampère who repeated the experiments [2]. Ampere explained the effect by the formation of a magnetic field around the wire carrying the current. He also proposed representing this field with an oriented vector, which direction could be found thanks to the right-hand rule [3]-[5]. Shortly after, Biot and Savart used a cross product of two vectors to evaluate the field direction and its value around an electrical segment [6]. The theory of magnetic field vector has evolved from there, notably differing from the electrostatic scalar field, despite both fields originating from electrons. My research aims at unifying electrostatic and magnetic fields. I have hence in previous articles proposed replacing the classical point charge used in electrostatic field into a linear charge. To do so, I had suggested a re-evaluation involving a scalar field around both the electrostatic and magnetic source [7] based on the classical scalar field definition [8]. This idea was evaluated using parallel and crossing long wires [9] [10]. Unfortunately, at that time, I had not linked my work in the article using the scalar field model to the right-hand rule [9]. The objective of the present article is to repair this missing part of magnetism by studying the results of the right-hand rule to the proposed scalar field model.

In recent articles, I had tried to use Biot-Savart law to calculate the field around a short electrical segment [6]. I have found that this Biot-Savart law contradicts a physical law, by stating strong field modifications between two nearby points, is impossible. This strong modification is obtained when the field is evaluated either aligned to the segment or perpendicularly to the segment. Thus, I had proposed clarifying the Biot-Savart law by using first a scalar field value and second to associate this field value to three orthogonal vectors having this length [11].

In present paper, I propose my approach using three orthogonal vectors, to the right-hand rule proposed by Ampère and currently accepted [4]. It will be shown that there is not always a good correspondence between both.

This article starts by describing the differences between my scalar magnetic field model and the right-hand rule. To reconcile both approaches, it is followed by a specific mixture of the scalar model and the right-hand rule. In the following, this mixture is applied to various magnetic configurations. In the discussion, mathematical formulas of both models are compared.

Units used in this paper are meters (m) for distances, Amperes (A) for electrical-current in wires, and Ampere/meter (A/m) for field values and vector lengths at a point placed everywhere out of the wires. To reduce data complexity, the value of vacuum permittivity is chosen equal to one.

Software and websites used in this article are Mathematica [12], Gimp [13] and Wikipedia [14].

In 3D figures of this article, colorations of vectors and surfaces have importance. For vectors which all are in the same physical space, and identical physical function have the same color. For surfaces, colors are as in topographic maps depending on their altitudes (z axes).

2. Two Methods to Calculate the Magnetic Field Induced by Current Flowing through Wires

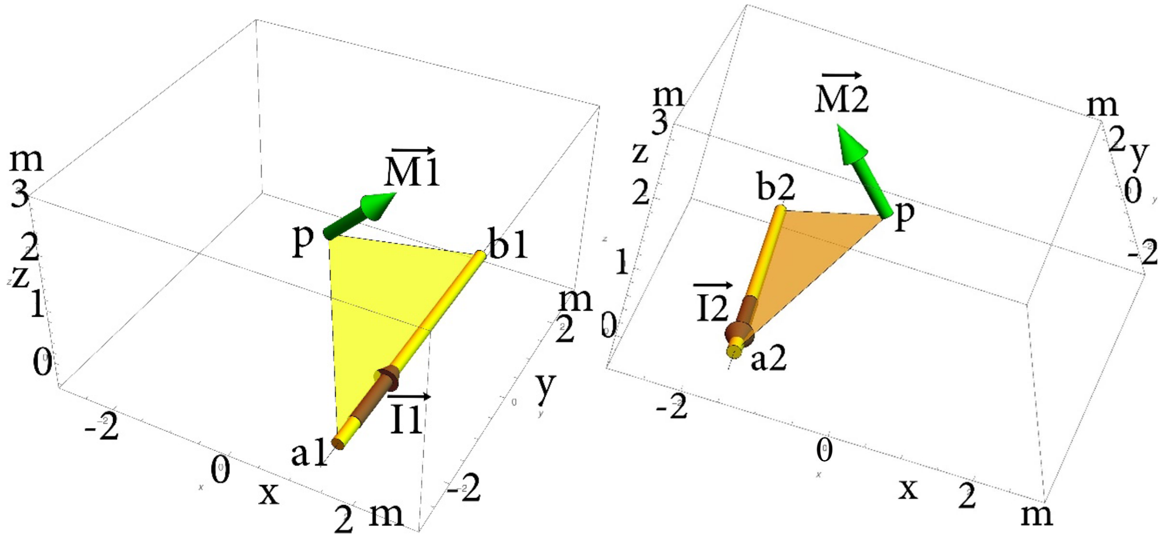
The objective of this chapter is to demonstrate how the scalar field method seems to better deal with fields resulting from the superposition of several magnetic fields induced by current flowing through wires. Taking the case of two opposing magnetic fields, there should be a point where fields cancel each other. The classical theory, however, cannot point to the location while the proposed method finds the middle point between both sources of the fields.

The objective of this Paragraph is to demonstrate that when two magnetic fields are opposed, the classical total field is non-zero at the middle between the two wires, and zero at this position in the proposed theory.

The opening paragraph describes how classical theory and the right-hand rule deal with superposition of opposing fields. The following section introduces the scalar field model and finds the location where opposing fields cancel. Gauss's law is then recalled and helps defining field lines with zero field magnitude. Last, the scalar field model is applied to a more generic case of two wires.

2.1. Classical Theory and Addition of Two Magnetic Fields

In this chapter the right-hand rule is used to describe the direction of the magnetic field around one current-carrying wire, then used to evaluate the direction of the field between two wires.



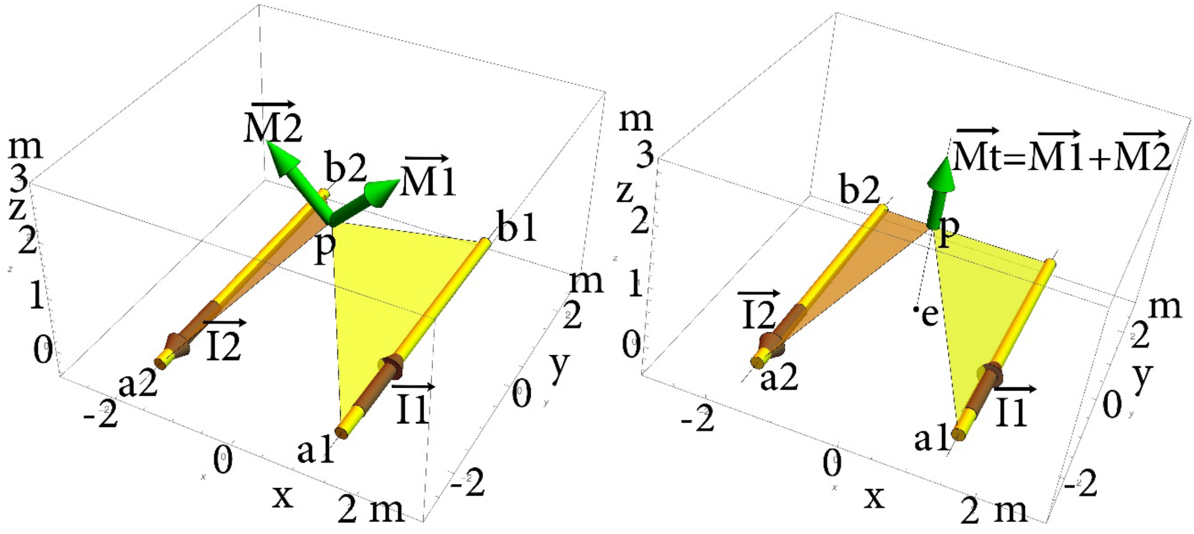
(a) (b)

Figure 1. Two magnetic field vectors in the vicinity of different conducting wires with opposite electrical current directions. In (a) current flows from a1 to b1. In (b), current flows from b2 to a2. Magnetic vectors M1 and M2 follow the right-hand rule in which the palm of the right-hand corresponds to yellow or brown triangles a, b, p. In the right-hand rule, the thumb follows the current direction in both images, and fingers give the field direction.

Figure 1(a) (current flows from a1 to b1) and **Figure 1(b)** (current flows from b2 to a2) show that when the current direction changes, the field direction also changes. The magnitude of the field decreases proportionally to the electrical current.

The right-hand rule imposes our thumb to be aligned with the wire, pointing in the same direction as the electrical current flowing through the wire. If the palm of the hand is aligned with the colored triangle between points a, b and p, then, our fingers, placed perpendicularly to the palm hand, indicates the direction as the magnetic field (noted as vector M1 in **Figure 1(a)** and M2 in **Figure 1(b)**).

Let us now observe what happens if both magnetic fields are superposed.



(a)

(b)

Figure 2. Superposing two magnetic fields induced by two parallel wires with same magnitude and opposite current flows. Left (a) The green arrows are magnetic field vectors induced by each wire. Colored triangles represent the hand palm in the right-hand rule. Right (b) the green vector is the addition of the two vectors of a) and as such the resulting magnetic field vector of the conjugated effect of both magnetic fields. This vector Mt is perpendicular to the plane including both wires.

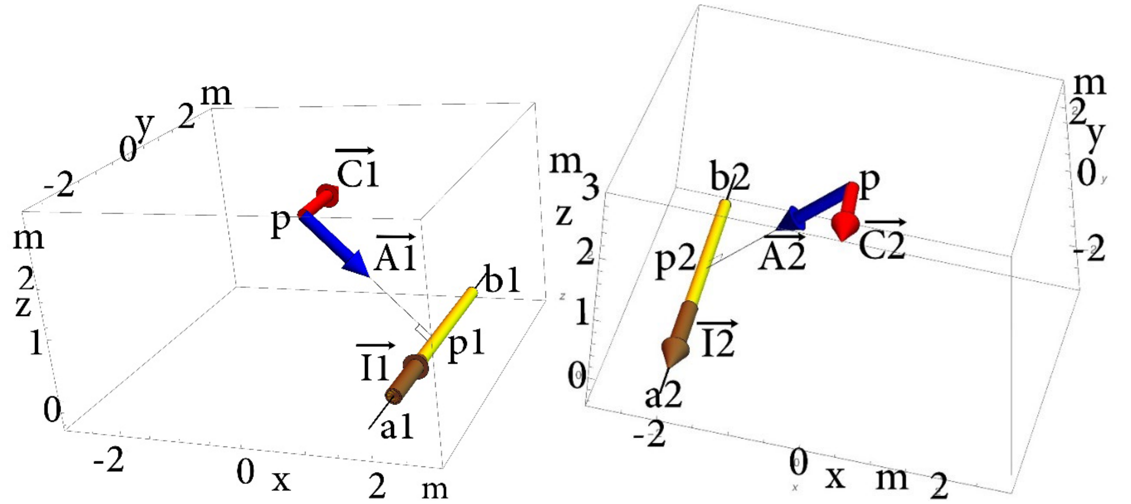
Two current-carrying wires, induce each a magnetic field at all locations in their surroundings. The magnetic field at all points is the addition of both magnetic fields. At any location, the magnetic field vector is the addition of magnetic field vectors of each field. Figure 2(a) and Figure 2(b) illustrate the example of two parallel wires through which an electrical current flows, with the same magnitude and opposite directions. At equal distances to both wires, the magnetic field is the addition of both fields (M1 and M2 gives in Figure 2(b) the vector Mt) which direction is perpendicular to the plane defined by both wires. The magnitude of the resulting magnetic field decreases further away from the wires and is maximum at the closest to the wires.

2.2. Scalar Field Model Apply to Specific Field Positions

The scalar field model [7] can be described at any point around one or several electrical wires. The magnetic field value is calculated thanks to three vectors named A for attraction, C for current and M for magnetism. In the following Figure 3 and Figure 4 in next page, vector M is not represented but derived from A and C. Mt, the total field resulting from both fields, will be more precisely described in paragraph 2.4.

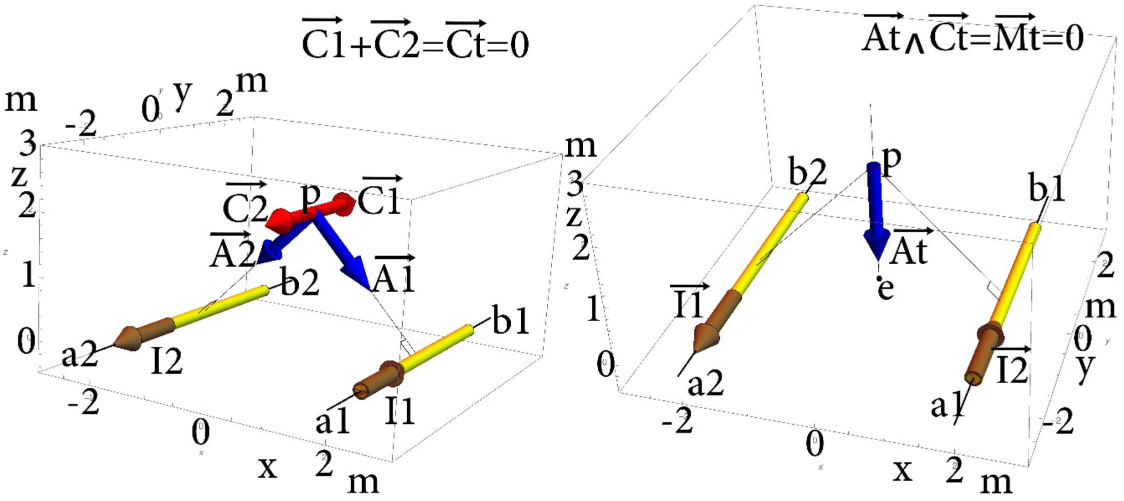
In Figure 3(a) and Figure 3(b), the same parallel wires with same currents as in Figure 2 are described. At any point around the wire, vector C points in the same direction as the electrical current while vector A points to the wire. Magnetic vector M has the direction of the cross-product of vectors A and C.

If both wires are placed in the same zone, the direction of the magnetic field can be deduced in the same way from A and C. Figure 4 illustrates the situation.



(a) (b)

Figure 3. Drawings vectors of the scalar field model which determine the vector lengths. Vector A (attraction) starts at point p in the direction of the wire. Vector C originates at point p, has the direction of the electrical current in the wire. Magnetic vector M, not drawn here, has the direction of the cross-product of vectors A and C.



(a) (b)

Figure 4. Illustration depicting the calculated vectors At and Ct, at point p at equidistance from both wires which have current flows in opposite direction. Vectors A1 and A2, point to the wires (A1 to I1 and A2 to I2). Vectors C1 and C2, are parallel to the wires (C1 with I1 and C2 with I2), and are in opposite current direction. Then, the sum of C1 with C2 gives Ct vector equal to zero. Vector Mt (not represented) is equal to the cross product of vector At with vector Ct which is zero, then vector Mt is also null, it cannot be drawn.

At an equal distance of each wire, since wires are parallel and with opposite currents, vectors C1 and C2 are also in opposite directions. The current magnitudes being also the same, the resulting current-vector Ct size is equal to zero. The cross product of vector At with vector Ct means in turn that the magnetic vector Mt is also equal to zero, which means that the magnetic field is null at this location. The same can be said for all points at equal distance between the wires, and to infinity.

In the scalar field model, the straight line at equal distance from both wires, corresponds to a field line up to infinity with a constant zero-field value.

2.3. Gauss' Law for Magnetism

In magnetism induced by current, Gauss described field lines as lines along which the magnetic field has a constant value. These lines have neither a beginning nor an end: they either form a close loop, wind around or extend to infinity [15].

If lines are straight and infinite, they can only indicate a field value of zero (A/m) [16] [17].

It has been shown above that in the classical theory, the magnetic field magnitude varies along the straight line at equal distance, but perpendicular to two wires through which opposite but equally intense currents flow.

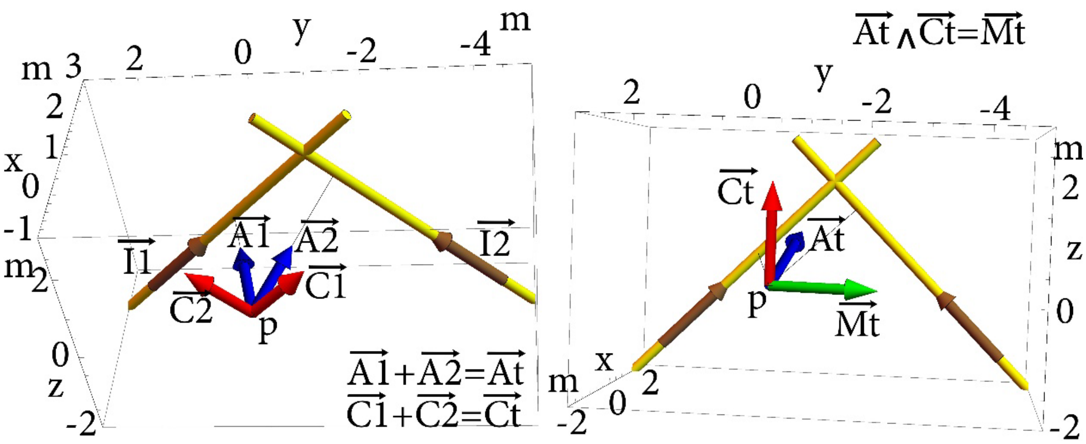
In the scalar field approach, the magnitude of the magnetic field is constant and equal to zero along any infinite field line.

Due to that property, the author proposes to use a scalar field model for every magnetic point around wires [7].

2.4. Theory of Scalar Field Model with Two Crossing Wires

The main principle of the scalar field model is first that the magnetic field value in A/m is a non-vector value, and second, that magnetic vector M can be derived from an attraction vector A and a current vector C.

In **Figure 5(a)** and **Figure 5(b)**, two infinite wires with two attraction vectors A and two current vectors C are shown. Their addition followed by their cross-product gives the total magnetic vector Mt, as illustrated in **Figure 5(b)**.



(a) (b)

Figure 5. Scalar field model with three vectors: attraction vector A in blue; current vector C in red and parallel to the electrical current. Using the cross-product of At with Ct, both sums of individual vectors A and vectors C, the green vector Mt gives the direction of the magnetic field vector at point p.

The attraction vector resulting from the superposition of two magnetic fields is the addition of the different attraction vectors induced by each magnetic field source. In the same way, the current vector is the addition of each current vector. The direction of the magnetic vector is that of the cross-product of the total attraction vector with the total current vector. Even if resulting attraction vectors and current vectors are not necessarily perpendicular, the total magnetic vector is orthogonal to both other vectors.

Using this method, the field direction, that is the resulting magnetic vector direction, is determined for all points in the area.

Note: When a point is located close enough to one wire and away from the others, it is possible to evaluate the magnetic field direction either with the right-hand rule or with the three vectors of the scalar field model.

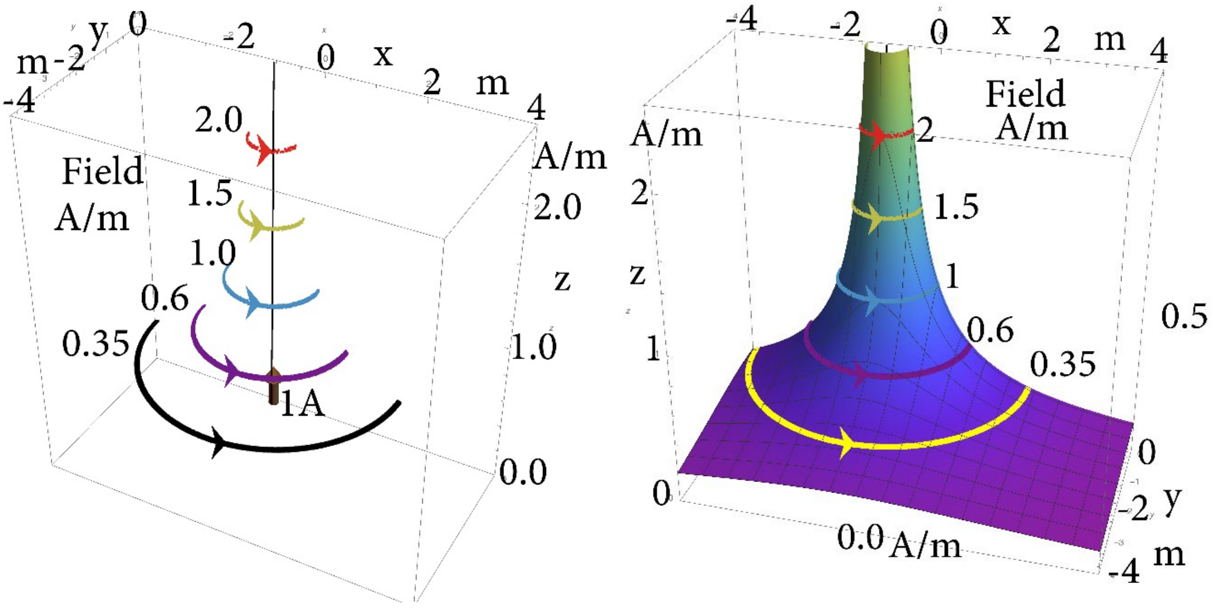
The present article focuses mostly on two wires in the following. However, the same reasoning can be applied (and it will be) at the end on three parallel wires.

3. Applications and Limits between Magnetic Domains

Using now the scalar field model, magnetic field values are calculated and drawn as maps, and field lines are drawn at selected constant field values. With the help of the vector procedure, field directions are evaluated and compared to directions given by the right-hand rule. This chapter focuses on parallel infinite wires with various electrical current configurations. In every case the field lines at zero field value will be identified, showing the limit between magnetic domains.

The following figures use one, two and three infinite electrical wires.

3.1. One Wire



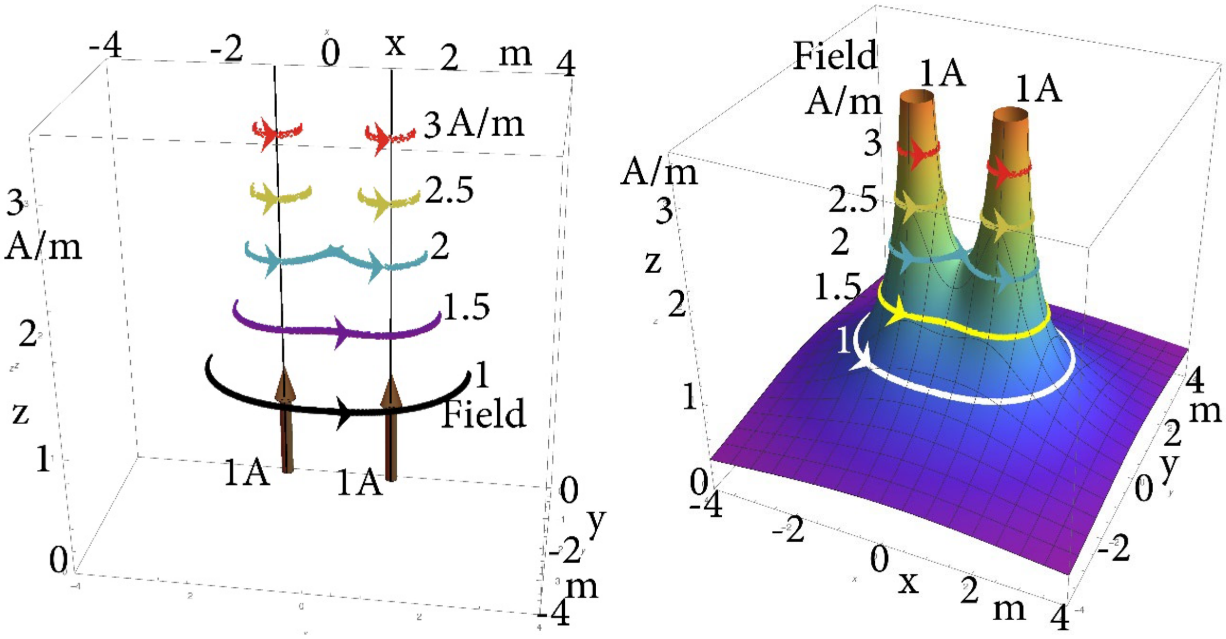
(a) (b)

Figure 6. Magnetic field lines around one infinite electrical wire, left without magnetic surface magnitude and right with a surface showing magnitude continuity. Each magnetic field line is at a constant magnetic field value. The wire carries a current of 1A, and the magnetic value is equal to I/r, where r represents the distance to the wire. The field value is zero A/m only at an infinite distance from the wire.

In **Figure 6**, pictures show only half of the field to have a better view of the magnetic field map, and of the arrows indicating the field orientation. It follows the right-hand rule, but it is also in agreement with the cross-products of vectors A and C as defined in **Figure 4(a)** and **Figure 4(b)**.

As expected by Gauss' law, magnetic field lines never cross.

3.2. Two Parallel Wires with Same Current Flowing Direction



(a) (b)

Figure 7. Magnetic field curves and magnetic height around two parallel electrical wires, left a) without the magnetic field magnitude height and right b) with its magnitude. Below the field value of 2A/m, field curves are around both wires. At the value of 2A/m, the green field curve is crossing itself. At higher field values, each wire is surrounded by their own field curves.

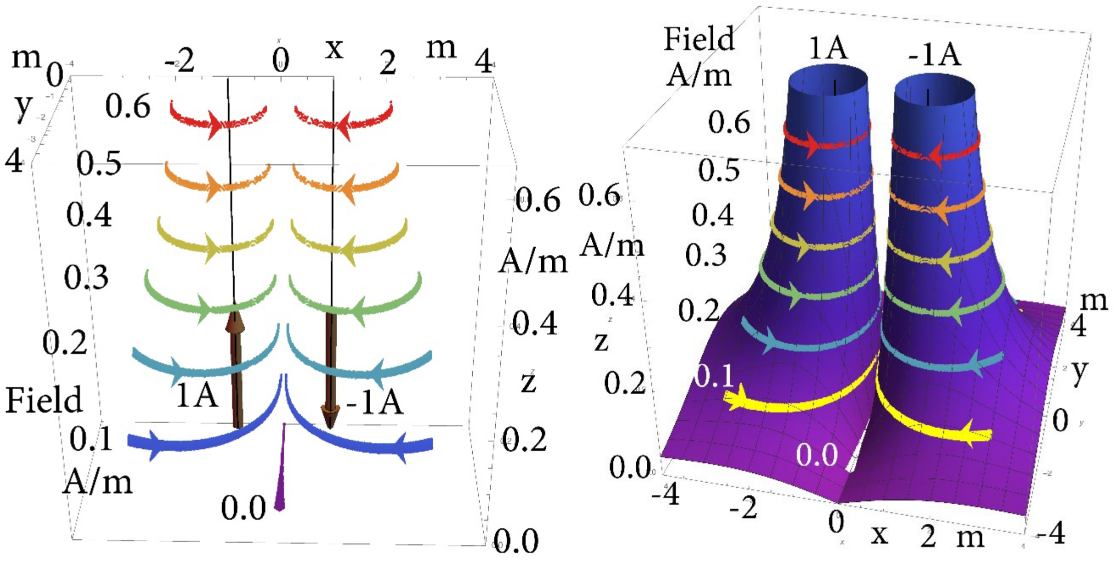
In the case of two parallel wires in which currents flow in the same direction, as illustrated in **Figure 7** with currents of 1 A, the magnetic field direction is the same around each wire. This is fully compatible with the right-hand rule.

Using the scalar field model, it becomes possible to calculate a distance at which the field lines merge to become one ring around both wires. At the merging, the field line draws the figure of an eight, as if the line would cross itself. This effect can be explained with the equal and opposite directions of attraction vectors A at this point, which results in zero value to the cross-product of At with Ct. At that point, the total magnetic vector, resulting from this cross-product, does not exist.

In classical theory, the magnetic field at equal distance between both lines must be 0 A/m. This is the addition of both fields which are in opposite directions according to the right-hand rule.

An illustration of this opposite current is available in [18]. The author said "Dans ce cas, le champ magnétique est nul pour un point situé exactement au milieu des deux fils, "est faible de manière générale dans cette zone". This is directly different in **Figure 7**.

3.3. Two Wires with Equal Current Value and Opposite Orientations



(a) (b)

Figure 8. Magnetic field curves around two parallel, and opposite flowing current wires, shown without (left a) and with (right b) the magnetic potential height. Current intensity is +1A at position x = −1 and −1A at position x = +1. The zero field straight line in black color (left) and in white (right), is a border between field domains. This border is linear, up to infinity in both directions.

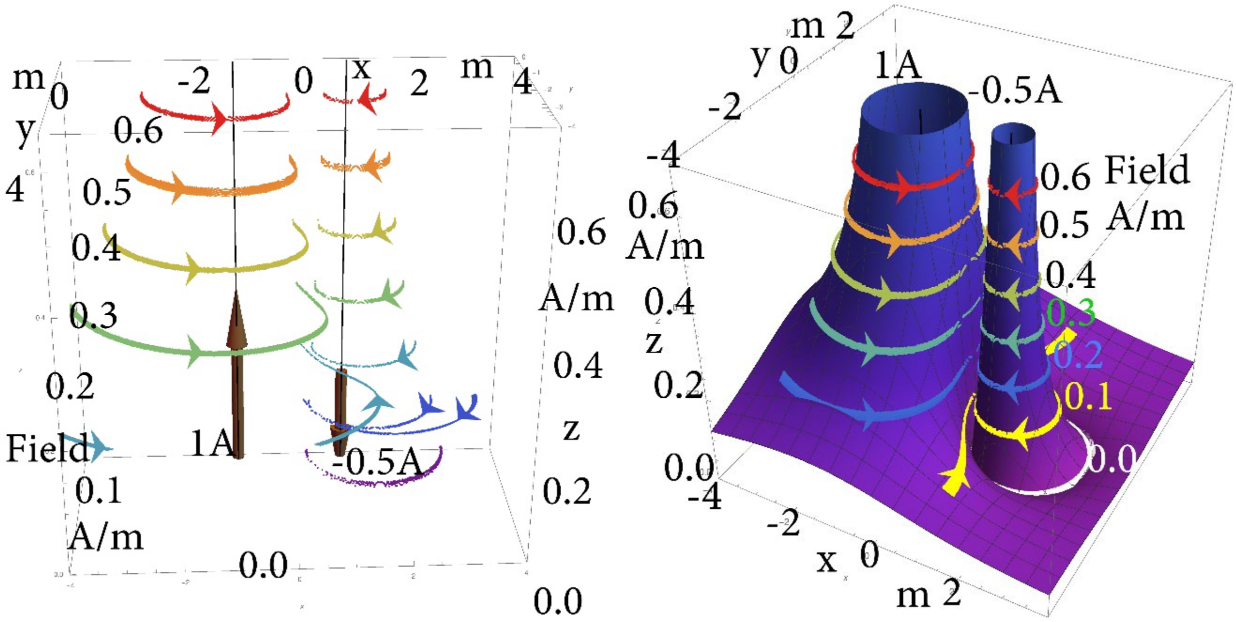
In the case of two parallel wires in which currents flow in opposite directions, as illustrated in **Figure 8** with currents of 1 A, field lines around the wires have opposite directions.

In this configuration, the scalar field model reveals a straight field line at a magnetic field magnitude of zero. This line is a limit between the influences of each wire and forms a border between two domains. This magnetic null field line is specific among all field lines: it has no direction. It marks the limit between one domain with field lines revolving in one direction and the other with field lines revolving in the opposite direction. When both currents have the same intensity, the line is straight and extends to infinity. On both sides of the null field line, the magnetic field value is always positive independently from the electrical current direction.

The ability of the scalar magnetic field model to pin the exact location of the magnetic null field line is one interest of the scalar magnetic model that we will explore in the following. This field line cannot be inferred from the classical field theory.

3.4. Two Wires with Different Electrical Directions and Values

When a wire with a small electrical current is positioned near a wire through which a high electrical current is flowing, a small magnetic domain (as defined in the previous paragraph) is formed only if they have opposite current direction. An example of this is shown in **Figure 9**. In this case, a magnetic null field line forms around the wire with the smallest current intensity. It makes a finite loop and has no field direction.



(a) (b)

Figure 9. Magnetic field curves and magnetic height around two parallel electrical wires, through which currents of different magnitude and opposite directions flow. Left without magnetic field height and right with their magnetic height. The left-side wire has an upside-oriented current of 1A, and the right-side wire has a downside current of −0.5A. Field oriented curves surround their wire at all height, except for the white curves at zero field strength, forming a border between domains of each wire.

As in 3.3, the null magnetic field line marks the limit between two magnetic domains, but it is here finite and not infinite.

3.5. Zero Field Curves for Two and Three Wires at Various Electrical Currents

For wires through which opposite currents flow, the previous paragraphs have led to observe that the null magnetic field line is straight when current intensities are identical and circular when current intensities are different. This paragraph explores the evolution of the shape and position of the null magnetic field line.

Figure 10 shows changes occurring with changes in step of 0.2 A in one of the current-carrying wires. The bigger the difference in current intensity the smaller the circle drawn by the field line. When the current intensities equalize, the line is straight and extends to infinity. When the difference in intensities reverses, the field line circles the other wire.

In Figure 10, the right-side wire has a current below 1A and circles stay around it. When this current increases above 1A, the circular zero border will move on the left to stay around the left-side wire.

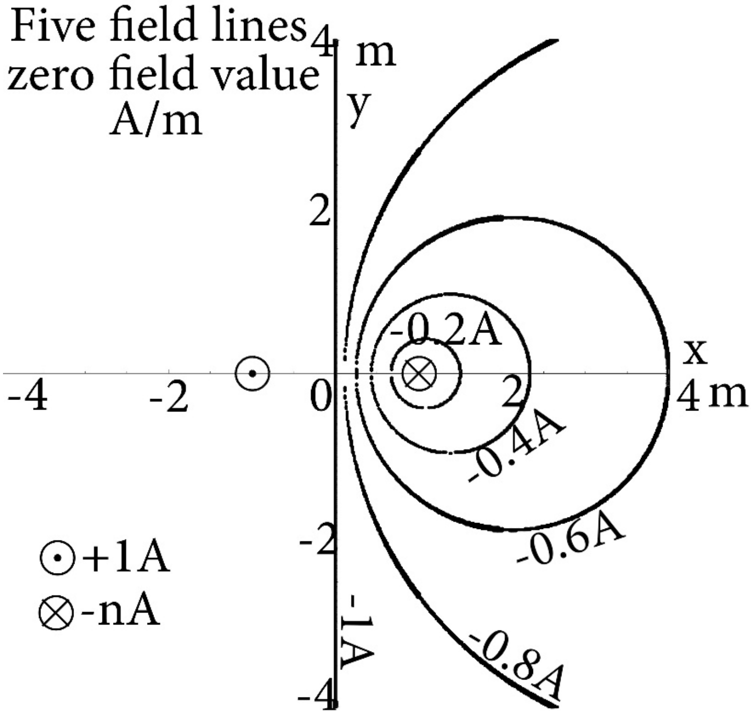


Figure 10. Zero field curves *i.e.* null magnetic field lines are mathematically circular around the low current wire: Current of 1A (left) and several negative currents (right). Field lines are resolved with polynomial equations: two variables x and y and two constants for electrical currents are used. The 1A wire is pointing to the reader at (x = −1,0) position. Each wire with negative current is going away from the reader at (x = +1,0) position. These zero field curves do not have any field direction. Field lines curling around on the left side are not shown. They will appear on the left only when the electrical current is below −1A. For example, at a −10A current, the circle will be very closed to position x = −1 and around the left side wire.

Note that these circular borders do not follow Ampere's right-hand rule since they do not have directions and mark the zero-field value.

Figure 10 uses only two wires, but the same mathematical procedure can be used with a higher number of wires. This is shown in Figure 11 with three wires.

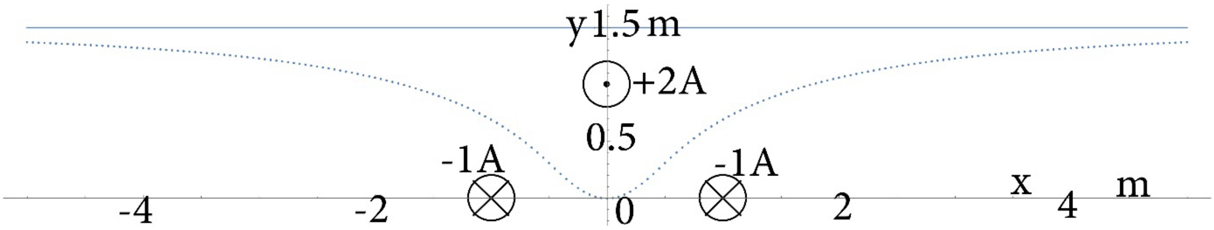


Figure 11. Infinite magnetic curve at zero field value around three wires: one upside of 2A at position (x = 0 m, y = 1 m) and two down-side of −1A each at position (x = −1 m, y = 0) and (x = +1 m, y = 0). The horizontal line y = 1.5 m is tangent to the magnetic curve at infinite x position positive or negative.

With three wires, as depicted in Figure 11, the null magnetic field line is not a straight line. It marks the limit between two domains: one belonging to the up-side wire and the other belonging to both down-side wires. One can observe in this specific configuration that the null magnetic field line is infinite only when both domains have the same total opposite electrical current.

4. Discussion

4.1. Focusing on Some Mathematical Differences between Cross Product Definitions

This is shown in **Formula (1a)** and **Formula (1b)**.

$$\sum_i \left(\overrightarrow{A_i} \wedge \overrightarrow{B_i} \right) = \overrightarrow{M1} \tag{1a}$$

$$\sum_i \overrightarrow{A_i} \wedge \sum_i \overrightarrow{B_i} = \overrightarrow{M2} \tag{1b}$$

The classic additivity of magnetic vectors is shown in (1a), whereas in (1b), the additivity of vectors Ai is in the cross product with the additivity of vectors Bi to form the single magnetic vector M2 of the scalar field model.

These mathematical formulas are applied in Figure 2 for the classical model and in Figure 4 for the scalar model presented by the author.

In the case of a single wire, both formulas give the same field value for vector M.

4.2. Classical Electromagnetism

This article describes electromagentism properties in steady state. The fields interactions described here are valid for current flowing steadily. Therefore, this article is far away from recent article published by G. Rousseaux [19] about the relation of the electromagnetic field with field propagation using well known Maxwell Equations.

4.3. Evolution of Topologic 3D View of Magnetic Value

In our previous article [9], the field value was dependent on the electrical current direction in electrical wires. Then when current was going up, the field values were positive, and negative for current going down. Then all magnetic field space is used for electron moving in wires. Unfortunately, if electrical charge is changed with positive charges, the field value cannot be drawn in this space. For that reason, in this article, the space around electrons moving in electrical wires, is always positive. The field value will become negative when protons are moving. This is not actually possible with our metallic wires.

4.4. Physical Superposition Process

The superposition process is applied when several field vectors are at one point of a field. In electrostatic field, this rule is currently applicable due to the unicity of the electrostatic field around several charges. Unfortunately, in the Biot-Savart law, three vectors do not have the same physical units, and their addition is difficult. Most of the time, only the magnetic form vector is used with this rule. In the proposed model of this article, the scalar field has one physical dimension for their three vectors. The superposition process is more complex. In Figure 4 and Figure 5, vectors A are added together. The same thing occurs with vectors C. This is not applicable to vectors M which is calculated by a specific formula shown in **Formula (1b)** in paragraph 4.1.

4.5. Recent Magnetic Field Analysis with Classical Model

At that time of the present work, several classical magnetic field images have been published. In these images, vectors illustrate magnetic field. For example, 3-D field of magnetic vectors between parallels having the same electrical direction and different intensity written by Dave Nero are available [20]. To do so, Biot and Savard law is not necessary.

5. Conclusion

This article compares the classical right-hand rule which determines the direction of a magnetic curve around a wire with the scalar field model which easily can evaluate orientation of field curves around several wires. For a single wire, the right-hand rule is easier to use compared to the calculation used by the scalar field model. The scalar field model allows us to describe magnetic areas which are limited by borders having a zero field values not described by the right-hand rule. The scalar field model for magnetism is now describing the magnetic field around various numbers of wires. The author plans to soon apply the scalar field model using several segments.

Acknowledgement

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Conflicts of Interest

The author declares no conflicts of interest regarding the publication of this paper.

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