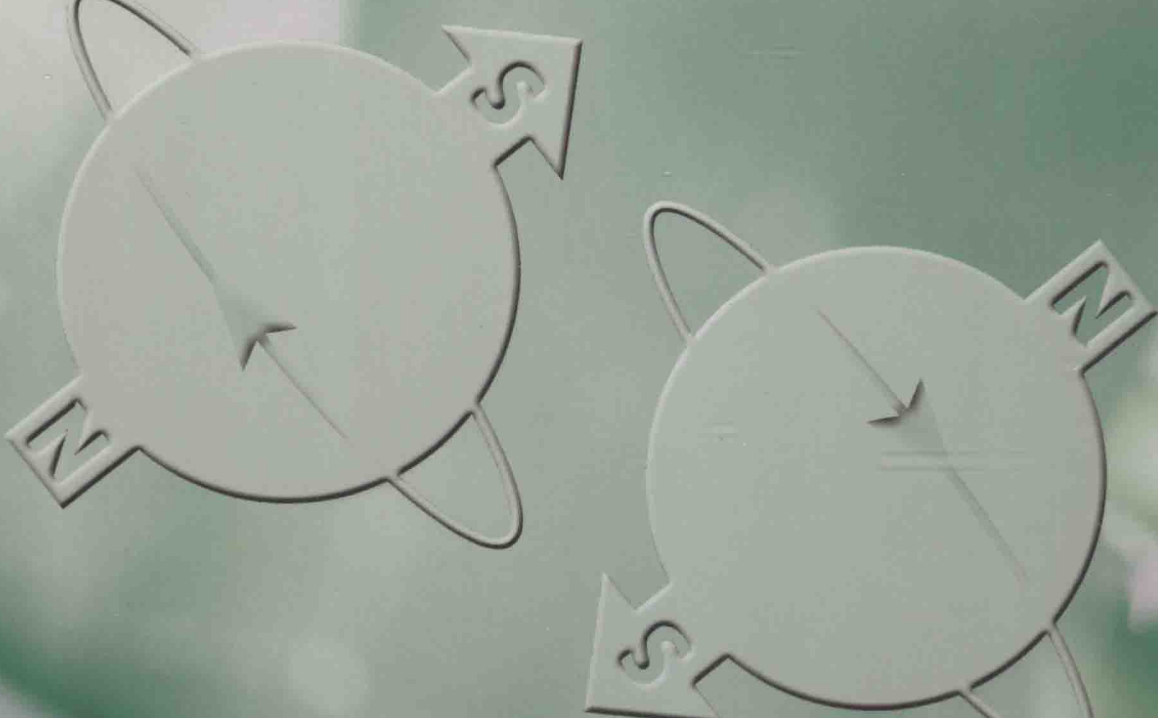
Second edition

Magnetic Materials

Fundamentals and Applications

Nicola A. Spaldin



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NICOLA A. SPALDIN
University of California, Santa Barbara

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MAGNETIC MATERIALS

Fundamentals and Applications

Magnetic Materials is an excellent introduction to the basics of magnetism, magnetic materials, and their applications in modern device technologies. Retaining the concise style of the original, this edition has been thoroughly revised to address significant developments in the field, including the improved understanding of basic magnetic phenomena, new classes of materials, and changes to device paradigms. With homework problems, solutions to selected problems, and a detailed list of references, *Magnetic Materials* continues to be the ideal book for a one-semester course and as a self-study guide for researchers new to the field.

New to this edition:

- Entirely new chapters on exchange-bias coupling, multiferroic and magnetoelectric materials, and magnetic insulators
- Revised throughout, with substantial updates to the chapters on magnetic recording and magnetic semiconductors, incorporating the latest advances in the field
- New example problems with worked solutions

NICOLA A. SPALDIN is a Professor in the Materials Department at the University of California, Santa Barbara. She is an enthusiastic and effective teacher, with experience ranging from developing and managing the UCSB Integrative Graduate Training Program to answering elementary school students' questions online. Particularly renowned for her research in multiferroics and magnetoelectrics, her current research focuses on using electronic structure methods to design and understand materials that combine magnetism with additional functionalities. She was recently awarded the American Physical Society's McGroddy Prize for New Materials for this work. She is also active in research administration, directing the UCSB/National Science Foundation International Center for Materials Research.

Magnus magnes ipse est globus terrestris.
William Gilbert, *De Magnete*. 1600.

Acknowledgments

This book has been tested on human subjects during a course on Magnetic Materials that I have taught at UC Santa Barbara for the last decade. I am immensely grateful to each class of students for suggesting improvements, hunting for errors, and letting me know when I am being boring. I hope that their enthusiasm is contagious.

Nicola Spaldin

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Part I

Basics

1

Review of basic magnetostatics

> Mention magnetics and an image arises of musty physics labs peopled by old codgers with iron filings under their fingernails.
>
> John Simonds, Magnetoelectronics today and tomorrow, *Physics Today*, April 1995

Before we can begin our discussion of magnetic materials we need to understand some of the basic concepts of magnetism, such as what causes magnetic fields, and what effects magnetic fields have on their surroundings. These fundamental issues are the subject of this first chapter. Unfortunately, we are going to immediately run into a complication. There are two complementary ways of developing the theory and definitions of magnetism. The "physicist's way" is in terms of circulating currents, and the "engineer's way" is in terms of magnetic poles (such as we find at the ends of a bar magnet). The two developments lead to different views of which interactions are more fundamental, to slightly different-looking equations, and (to really confuse things) to two different sets of units. Most books that you'll read choose one convention or the other and stick with it. Instead, throughout this book we are going to follow what happens in "real life" (or at least at scientific conferences on magnetism) and use whichever convention is most appropriate to the particular problem. We'll see that it makes most sense to use Système International d'Unités (SI) units when we talk in terms of circulating currents, and centimeter–gram–second (cgs) units for describing interactions between magnetic poles.

To avoid total confusion later, we will give our definitions in this chapter and the next from *both* viewpoints, and provide a conversion chart for units and equations at the end of Chapter 2. Reference [1] provides an excellent light-hearted discussion of the unit systems used in describing magnetism.

1.1 Magnetic field

1.1.1 Magnetic poles

So let's begin by defining the magnetic field, $\boldsymbol{H}$, in terms of magnetic poles. This is the order in which things happened historically – the law of interaction between magnetic poles was discovered by Michell in England in 1750, and by Coulomb in France in 1785, a few decades before magnetism was linked to the flow of electric current. These gentlemen found empirically that the force between two magnetic poles is proportional to the product of their pole strengths, p, and inversely proportional to the square of the distance between them,

$$F \propto \frac{p_1 p_2}{r^2}. \tag{1.1}$$

This is analogous to Coulomb's law for electric charges, with one important difference – scientists believe that single magnetic poles (magnetic monopoles) do not exist. They can, however, be approximated by one end of a very long bar magnet, which is how the experiments were carried out. By convention, the end of a freely suspended bar magnet which points towards magnetic north is called the north pole, and the opposite end is called the south pole.[1] In cgs units, the constant of proportionality is unity, so

$$F = \frac{p_1 p_2}{r^2} \qquad \text{(cgs)}, \tag{1.2}$$

where r is in centimeters and F is in dynes. Turning Eq. (1.2) around gives us the definition of pole strength:

A pole of unit strength is one which exerts a force of 1 dyne on another unit pole located at a distance of 1 centimeter.

The unit of pole strength does not have a name in the cgs system.

In SI units, the constant of proportionality in Eq. (1.1) is $\mu_0/4\pi$, so

$$F = \frac{\mu_0}{4\pi}\frac{p_1 p_2}{r^2} \qquad \text{(SI)}, \tag{1.3}$$

where μ_0 is called the permeability of free space, and has the value $4\pi \times 10^{-7}$ weber/(ampere meter) (Wb/(A m)). In SI, the pole strength is measured in ampere meters (A m), the unit of force is of course the newton (N), and 1 newton $= 10^5$ dyne (dyn).

[1] Note, however, that if we think of the earth's magnetic field as originating from a bar magnet, then the *south* pole of the earth's "bar magnet" is actually at the magnetic north pole!

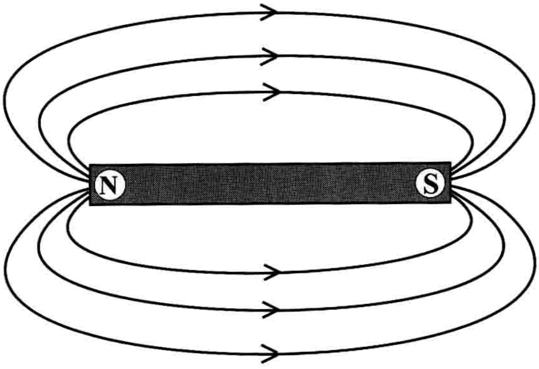

Figure 1.1 Field lines around a bar magnet. By convention, the lines originate at the north pole and end at the south pole.

To understand what causes the force, we can think of the first pole generating a magnetic field, $\boldsymbol{H}$, which in turn exerts a force on the second pole. So

$$F = \left(\frac{p_1}{r^2}\right) p_2 = \boldsymbol{H} p_2, \tag{1.4}$$

giving, by definition,

$$\boldsymbol{H} = \frac{p_1}{r^2}. \tag{1.5}$$

So:

A field of unit strength is one which exerts a force of 1 dyne on a unit pole.

By convention, the north pole is the *source* of the magnetic field, and the south pole is the *sink*, so we can sketch the magnetic field lines around a bar magnet as shown in Fig. 1.1.

The units of magnetic field are oersteds (Oe) in cgs units, so a field of unit strength has an intensity of 1 oersted. In the SI system, the analogous equation for the force one pole exerts on another is

$$F = \frac{\mu_0}{4\pi} \left(\frac{p_1}{r^2}\right) p_2 = \frac{\mu_0}{\boldsymbol{H}} p_2, \tag{1.6}$$

yielding the expression for $\boldsymbol{H} = \frac{1}{4\pi} \frac{p_1}{r^2}$ in units of amperes per meter (A/m); $1\ \mathrm{Oe} = (1000/4\pi)\ \mathrm{A/m}$.

The earth's magnetic field has an intensity of around one-tenth of an oersted, and the field at the end of a typical kindergarten toy bar magnet is around 5000 Oe.