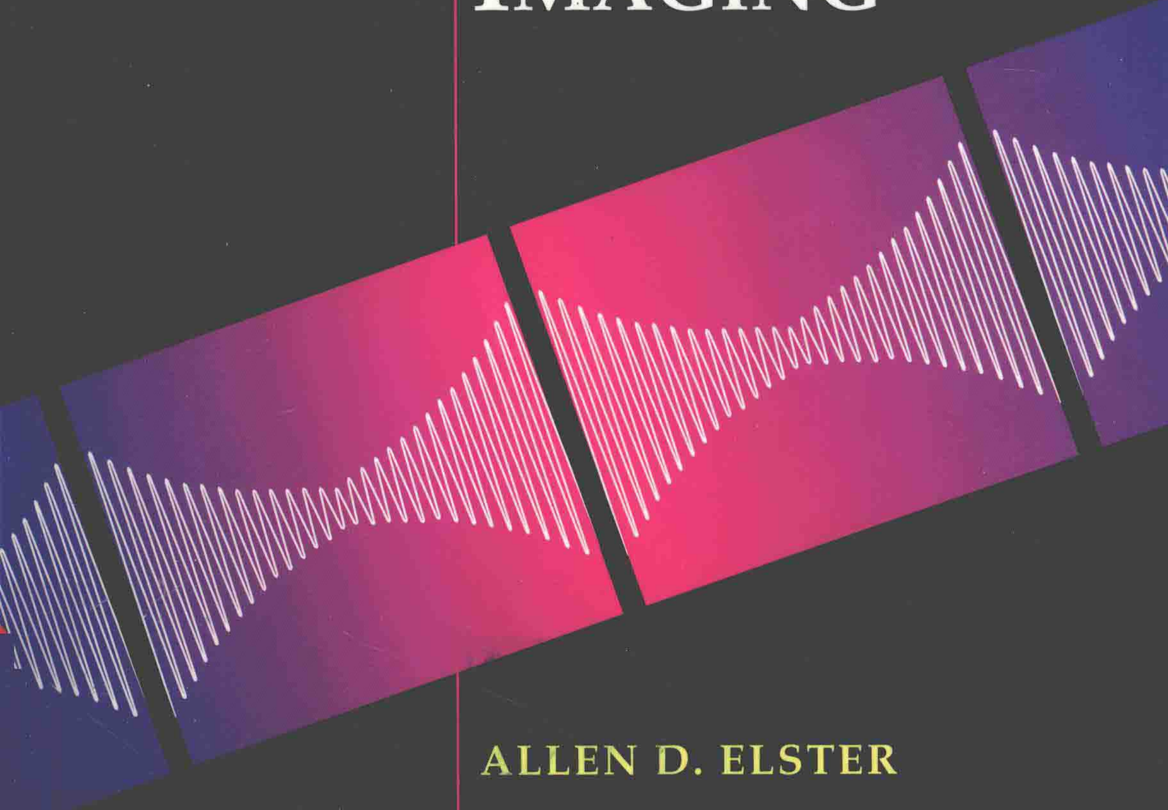
Questions and Answers in

Magnetic Resonance Imaging



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Questions and Answers in

Magnetic Resonance Imaging

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Questions and Answers in Magnetic Resonance Imaging

To Allen, Elizabeth, Martha, and Patricia—

Keep asking those questions.

Preface

Over the last 6 years, I have had the pleasure of teaching the physical principles of magnetic resonance (MR) imaging to hundreds of technologists, residents, fellows, and visiting physicians who have participated in educational programs sponsored by the Bowman Gray School of Medicine. Like experienced teachers in other disciplines, I came to realize that each group of students struggled with many of the same conceptual problems year after year. Because I was being asked many of the same questions over and over again, I found myself repeatedly giving the same lectures and explanations to each group of new students. Eventually I developed a series of handouts and drawings that I would distribute and discuss when certain common questions arose. As these handouts became more numerous and sophisticated, they began to form the basis for the book you are now reading, *Questions and Answers in Magnetic Resonance Imaging*.

At least three quarters of the questions in this book were at one time directly posed to me by students, being retained in their original (and sometimes awkward) form as best I can remember them. The remaining 25% of questions are of my own construction; these are questions that I often ask students in order to reinforce their basic understanding of MR physics and to force them to reflect more critically on certain key concepts.

Since the mid 1980s, when I published the first whole-body MR atlas* and first textbook devoted exclusively to cranial MR imaging,† numerous other MR books and teaching aids have become available. *Questions and*

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*Elster AD: Magnetic resonance imaging. A reference guide and atlas, Philadelphia, 1986, Lippincott.
†Elster AD: Cranial magnetic resonance imaging, New York, 1987, Churchill Livingstone.

Answers in Magnetic Resonance Imaging is intended to supplement, not replace, these larger texts. Each answer is purposefully limited to a few paragraphs, and only a pertinent reference or two from the literature are cited. For the most part, I have included material that is highly practical and immediately applicable to clinical MR imaging. Occasionally, however, I will delve into topics that are principally of historical interest or represent a future direction for MR. Hopefully, these excursions into the past and future will add some color and spirit to MR physics that I try to convey to students in my live lectures.

The book is primarily intended for readers with some clinical knowledge of MR imaging who desire to know more about the physical basis of what they see. While MR specialists may already know the answers to many of these questions, I daresay even they will benefit from a few points scattered throughout this text. Just to be sure, I have included a few tough questions especially for them!

Good luck to all.

Allen D. Elster

Contents

CHAPTER

1

Basic Principles of Electricity and Magnetism

To understand the more complex aspects of magnetic resonance (MR) physics, it is first necessary to review some basic principles of electricity and magnetism you may have forgotten (or never learned) in high school or college. Although most of the individual equations presented in this chapter are *not* important, the basic concepts and definitions *are*.

Part of the confusion with electromagnetic terminology in many MR textbooks arises from two different systems of measurement often being intermixed: the older *centimeter-gram-second (CGS)*, or *gaussian, system* and the more modern *meter-kilogram-second-ampere (MKSA) system*, also called the *Système International d'Unités (SI)*. These two systems differ not only in their nomenclature and units of measurement but also in their definitions of several fundamental electromagnetic quantities. For interested and advanced students, some of these subtle distinctions are addressed in Q 1.07.

Q 1.01 **The field strength of our MR scanner is said to be 1.5 tesla. How large is a tesla, and what exactly does this mean?**

The strength of a magnetic field is operationally defined in terms of the deflecting force the field exerts on a current or electrical charge moving through it. With reference to Fig. 1-1, consider a hypothetical wire stretched across the bore of an MR scanner whose magnetic field lines

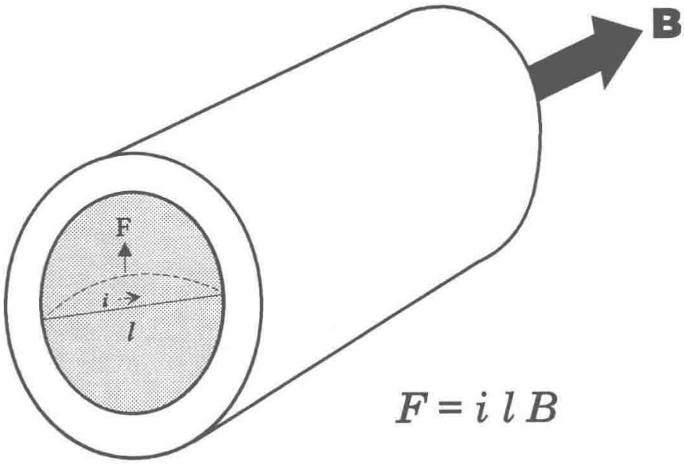

Fig. 1-1. Definition of magnetic strength *(B)*. A hypothetical wire of length *l* carrying a current *i* perpendicular to *B* experiences a force *F* given by the equation $F = i\,l\,B$.

are directed along the bore. When a current is passed through this wire, a magnetically generated force deflects the wire upward. The magnitude of this force (*F*) is proportional to the current (*i*), the length of the wire (*l*), and the strength of the magnetic field (*B*). If the wire is exactly perpendicular to the lines of the magnetic field, the force is maximal and is given by

$$F = i\,l\,B$$

We see from this equation that *B* should be expressed in units of force ÷ (current × distance). The SI units for *B* are therefore newtons per ampere-meter, or *tesla (T)*. In other words, an ideal wire carrying a current of 1 ampere perpendicular to a magnetic field of 1 T experiences a deflecting force of 1 newton along each meter of its length.

In the older CGS system, *B* is measured in *gauss (G)*. For conversion, 1 T equals 10,000 G. Because the tesla is a relatively large unit, it is most suitably used to define the strength of the *main* magnetic field of an MR scanner. *Subsystems* (such as gradient coils) within the MR imager generate much smaller fields more conveniently measured in gauss.

The reader should realize that we have defined only the *magnitude* (*B*) of the field at a given point. If the field is perfectly uniform, *B* is the same at all points within the field. In general, however, the structure of the magnetic field is more complex, and *B* may have different values and directions of action at different points in space. A magnetic field is therefore formally defined to be an array of vectors (denoted by the boldfaced letter **B**) whose size and direction at each point in space define how the field will act on a charge moving at that location.

Reference

Weidner RT, Sells RL. Elementary classical physics, 2nd ed. Boston: Allyn and Bacon, 1973, pp 572-598. (A similar discussion can be found in most college-level physics texts.)

Q 1.02 **I still don't have a clear idea of how large a 1.5-tesla magnetic field really is. How much stronger is it than a refrigerator magnet or the big magnet in a junkyard that picks up cars?**

Although a 1.5 T scanner is considered "high field" compared with other *imaging* devices, this field strength is actually "midrange" when judged against other experimental and commercial applications of magnets. High-resolution nuclear magnetic resonance (NMR) spectrometers used in chemistry laboratories typically possess much higher fields than clinical MR imagers, usually in the 2 T to 11 T range; a few research sites have specially constructed NMR spectrometers operating at up to 14 T. The large electromagnets that pick up junk cars and scrap metal have fields of 1.5 T to 2.0 T, but they are extremely inhomogeneous (nonuniform). By comparison, a household refrigerator magnet generates a field of less than 10 millitesla (mT) (100 G). The Earth's magnetic field is even smaller, varying from about 30 microtesla (μT) (0.3 G) at the equator to about 70 μT (0.7 G) at the poles.

Q 1.03 **What is the orientation of the main magnetic field within an MR scanner?**

Commercially available MR scanners have either horizontally or vertically oriented main magnetic fields (Fig. 1-2). All superconducting and most resistive scanners are of solenoidal design, and their main magnetic fields are directed along the bore of the magnet. In some lower-field permanent and resistive scanners, however, the magnetic fields are oriented vertically.

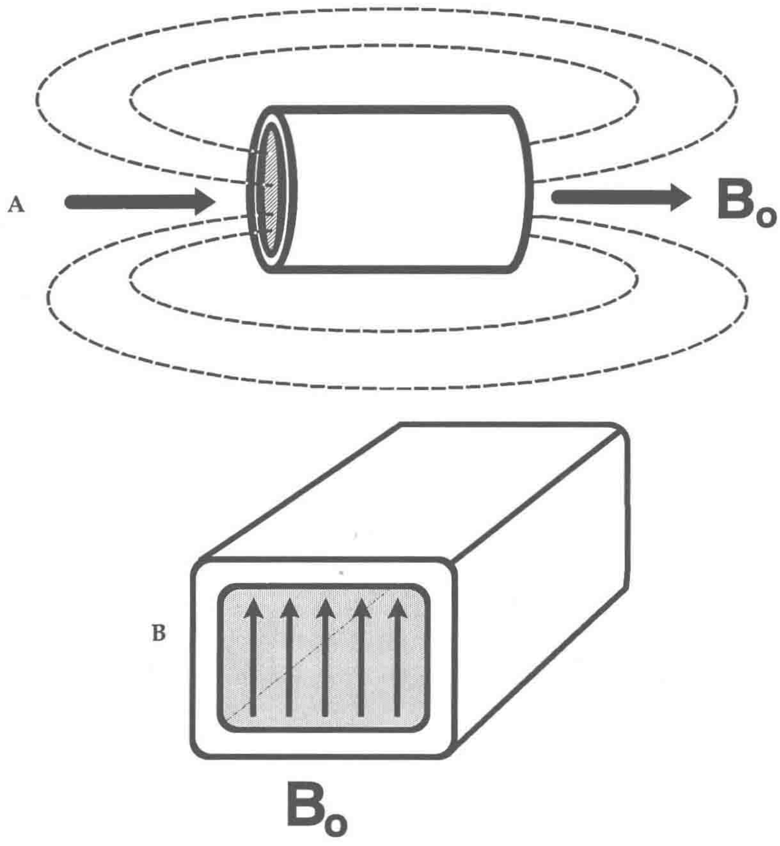

Fig. 1-2. **A,** Most resistive and superconducting MR imagers have their main magnetic fields **(B_o)** directed along the scanner bores. **B,** A few permanent magnet scanners have a vertical orientation of their fields.

Q 1.04

Does it matter which end of an MR scanner is the north or south pole?

For a single scanner the answer is "no"; the actual field direction (from front to back or back to front) is irrelevant. When two or more scanners are sited near each other, however, the answer is "yes," and some consideration should be given to polarity of each magnet. In general, magnetic fringe fields and interactions are minimized by configuring the magnets so that the unlike poles face each other.

Q 1.05 What is meant by a magnetic field gradient?

When the strength or direction of a magnetic field differs between two points in space, a *magnetic field gradient* is said to exist. This gradient is defined as the rate at which magnetic field strength changes with position. For example, if a magnetic field increases in magnitude by 0.001 T over a distance of 1 meter (m), the magnetic field gradient would be 0.001 T/m or 1 mT/m in that direction.

By definition, an ideal, perfectly homogeneous magnetic field contains no gradients. In any real field, however, inhomogeneities (and thus magnetic field gradients) must occur. These magnetic gradients may result from (1) intrinsic imperfections in the field itself, known as *static field inhomogeneities*, (2) the presence of matter within the field, whose charged particles interact with the field to create *susceptibility gradients*, or (3) the purposeful activation of specialized gradient coils that create predictable distortions of the main magnetic field and allow spatial encoding of the MR signal. Static field inhomogeneities are discussed in Chapter 2 and susceptibility effects in Q 1.06 to Q 1.10. In this section I address the purposeful type of magnetic field gradients used for imaging.

Imaging gradients are produced by special electrical windings, known as *gradient coils*, that are housed within the body of the MR imager. When energized with electricity, these coils create additional small magnetic fields that distort the main magnetic field as a function of position within the scanner. Typically, there are three sets of such coils (x-, y-, and z-) corresponding to the cardinal directions within the scanner. By convention, the z-axis is usually taken to coincide with the direction of the main magnetic field ($\mathbf{B_o}$), which may be either parallel or perpendicular to the gantry, depending on scanner design (see Q 1.03 and Fig. 1-2).

When a certain gradient is turned on, it creates a predictable distortion of the magnitude, *but not the direction*, of $\mathbf{B_o}$ along that axis. In other words, the magnetic field lines always retain their original orientations (parallel to the z-axis) even when the x-gradient or y-gradient coils are energized. It is thus only the magnitude of $\mathbf{B_o}$ in the z-direction that varies spatially according to position along the x- or y-axis. (In mathematical terms, the x-, y-, and z-gradients are altering $\partial B_z/\partial x$, $\partial B_z/\partial y$, and $\partial B_z/\partial z$, respectively.) These concepts are illustrated graphically in Fig. 1-3.

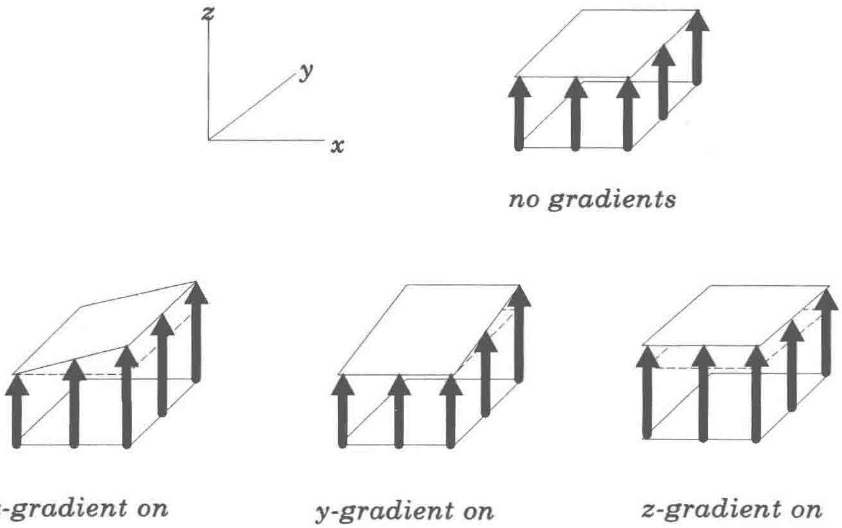

Fig. 1-3. Magnetic field gradients along each of the cardinal scanner directions (x, y, and z).

Q 1.06

In some textbooks I've seen two different designations for the magnetic field, *B* and *H*. What's the difference between them?

This relatively advanced question is sometimes raised by MR fellows who have encountered these two magnetic field designations in their readings. Novice students of MR should feel free to skip the moderately technical answer to this question and proceed directly to Q 1.07. For students who are interested, the difference between **B** and **H** fields is discussed in the following paragraphs, with the hope that this explanation clarifies some confusing concepts about SI and CGS units as well.

The magnetic field (**B**) defined in Q 1.01 is also known as the *magnetic induction field*, *magnetic induction*, or *magnetic flux density*. However, another type of magnetic field, denoted by **H**, is called the *magnetic field intensity*. **H** and **B** have different units and a different physical significance. **H** may be thought of as an externally applied *"magnetizing force,"* whereas **B** represents the actual magnetic field *induced* within a region of space. It is necessary to distinguish between **H** and **B** because the electromagnetic field at a given point in space depends not only on the distribution of electrical currents giving rise to that field (reflected in **H**) but also on the type of matter occupying the region (reflected in **B**).

When no matter is present (i.e., in a vacuum), **B** and **H** are essentially equivalent, except for a factor μ_o to adjust units of measurement. Thus, we can write: $\mathbf{B}_{\mathbf{vac}} = \mu_o\mathbf{H}$. The factor μ_o is called the *permeability of free space* and has the value $4\pi \times 10^{-7}$ newtons/ampere^2 in SI units. Since **B** is measured in tesla (newtons per ampere-meter), the SI units for **H** must therefore be amperes per meter. In the CGS system, however, μ_o is dimensionless and is assigned the value 1. In the CGS system, therefore, both **B** and **H** are measured in the same units (gauss), although they continue to have a different physical significance. (To complicate matters even more, sometimes the CGS unit for **H** has been called the oersted [Oe]; however, since 1 Oe = 1 G, there seems to be little point in perpetuating this even older nomenclature.)

Whenever matter is present within a given region of space, the induced field (**B**) is generally not equal to the applied field (**H**). When **H** encounters matter, various electromagnetic interactions occur that can be thought of as tending to "concentrate" or "disperse" the magnetic lines of force. This phenomenon results primarily from the action of unpaired orbital and delocalized electrons, which set up circulating currents and secondarily induce an internal *magnetization* ($\mathbf{M_i}$) within the matter that serves either to augment or to oppose the applied field (**H**).

In matter, therefore, the relationship between **B** and **H** is quite complex but can be approximated by the relationship

$$\mathbf{B} = \mu_o \, \mu \, \mathbf{H}$$

where μ is a dimensionless factor known as the *relative magnetic permeability* of the material. When $\mu > 1$ the magnetic field can be thought of as "concentrated" relative to that in a vacuum. When $\mu < 1$ the field can be considered relatively "thinned" or "dispersed" within the matter. Substances with $\mu > 1$ are called *paramagnetic*; those with $\mu < 1$ are called *diamagnetic*. These concepts are discussed in greater detail in Q 1.07.

The relative permeability of a material, μ, is closely related to another dimensionless property known as *magnetic susceptibility*. The defining formulae and symbols used in the SI system differ slightly from those used in the CGS system, as follows:

$$\mu = 1 + \kappa \text{ (SI)} \quad \text{and} \quad \mu = 1 + 4\pi\chi \text{ (CGS)}$$

where κ in the SI system and χ in the CGS system are termed *volume magnetic susceptibilities*. For purposes of conversion between the SI and CGS systems, $\kappa = 4\pi\chi$. Under this alternative formulation, paramagnetic substances are said to have positive susceptibilities, and diamagnetic substances have negative susceptibilities.

We may further define the induced *magnetization* ($\mathbf{M_i}$) per unit volume of a substance as

$$\mathbf{M_i} = \kappa\, \mathbf{H} \text{ (SI) and } \mathbf{M_i} = \chi\, \mathbf{H} \text{ (CGS)}$$

For paramagnetic substances (κ, $\chi > 0$), $\mathbf{M_i}$ points in the same direction as **H**, and the "effective field" is thus augmented. For diamagnetic substances (κ, $\chi > 0$), $\mathbf{M_i}$ and **H** point in opposite directions, and the effective field is thus diminished.

Some chemistry textbooks and MR articles do not report κ and χ in their volumetric (dimensionless) forms but rather as *mass susceptibilities* (κ_m or χ_m) or *molar susceptibilities* (κ_M or χ_M), which *do* have dimensions (cubic centimeters per gram and cubic centimeters per mole, respectively). Additionally, $\mathbf{M_i}$ is sometimes defined *per unit mass or mole* and therefore has different dimensions from those used here. One need not memorize a dozen different equations and definitions; the important point is that these quantities and concepts are expressed in different ways in different textbooks and articles. I will continue to use the more widely accepted dimensionless forms of κ and χ throughout this book and urge other authors to do the same.

The relationships among **B**, $\mathbf{M_i}$, and **H** in the SI and CGS systems can now be formally expressed by combining the previous equations:

$$\mathbf{B} = \mu_o\, \mu\, \mathbf{H} = \mu_o\, (1 + \kappa)\, \mathbf{H} = \mu_o\, (\mathbf{H} + \kappa\mathbf{H}) = \mu_o\, (\mathbf{H} + \mathbf{M_i}) \text{ (SI)}$$

$$\mathbf{B} = \mu_o\, \mu\, \mathbf{H} = 1 \cdot (1 + 4\pi\chi)\, \mathbf{H} = \mathbf{H} + 4\pi\chi\mathbf{H} = \mathbf{H} + 4\pi\mathbf{M_i} \text{ (CGS)}$$

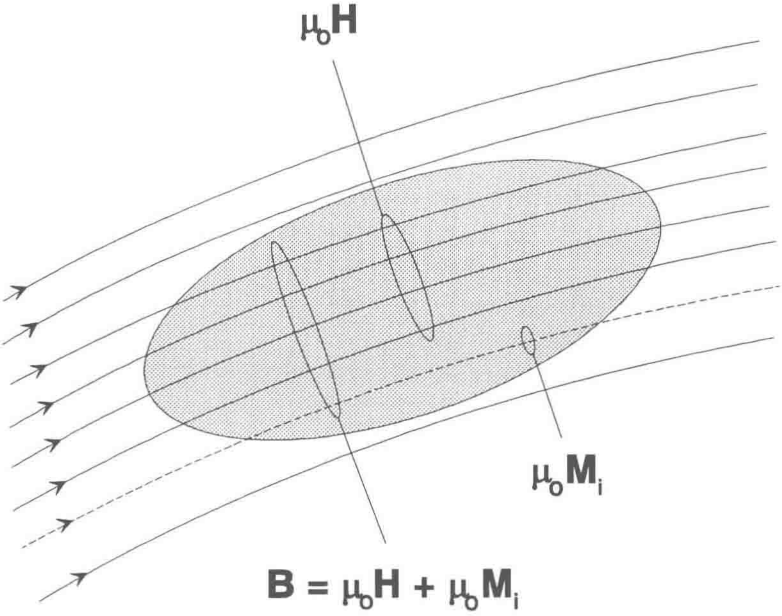

Fig. 1-4. Relationship between **B** and **H** fields in matter *(gray oval)*. See Q 1.06 for details.

TABLE 1-1. Fundamental Units of Electromagnetism

Property	Symbol	SI Units	CGS Units
Magnetic induction field (flux density)	B	Tesla	Gauss
Magnetic field intensity	H	Ampere per meter	Gauss (oersted)
Magnetization	M_i	Ampere per meter	Gauss
Permeability of free space	μ_o	$4\pi \times 10^{-7}$ newtons/ampere^2	1 (dimensionless)
Relative magnetic permeability	μ	Dimensionless	Dimensionless
Volume magnetic susceptibility	κ, X	Dimensionless	Dimensionless

These relationships among **B**, $\mathbf{M_i}$, and **H** are illustrated graphically in Fig. 1-4. The names and units of several fundamental magnetic properties in the SI and CGS systems are summarized in Table 1-1.

Reference

Lentner C (ed). Geigy scientific tables, 8th ed. Vol 1. Units of measurement, body fluids, composition of the body, nutrition. Summit, NJ: Ciba-Geigy, 1981, pp 9-28.

Q 1.07 What is magnetic susceptibility?

Magnetic susceptibility is a measure of the extent to which a substance becomes magnetized when it is placed in an external magnetic field. Magnetic susceptibility is therefore sometimes referred to as *magnetizability*.

Whenever matter is placed in a magnetic field, electromagnetic interactions take place between the matter and the field. These interactions "concentrate" or "disperse" the lines of the magnetic field (Fig. 1-5). This phenomenon results principally from the action within the matter of orbital and delocalized electrons, which set up circulating currents in response to the externally applied field. These circulating currents, in turn, induce within the matter an internal magnetization ($\mathbf{M_i}$) that either augments or opposes the external field. When the direction of $\mathbf{M_i}$ is the same as that of the external field, effective field within the object is enhanced. This magnetic field enhancement phenomenon is known as *paramagnetism*.