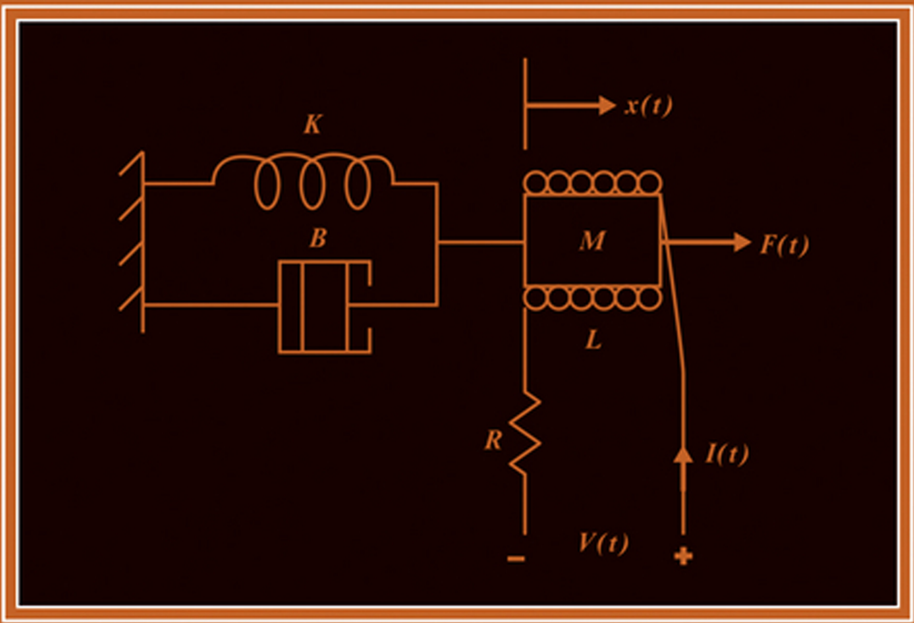
Second Edition

Magnetic Actuators and Sensors



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SECOND EDITION

John R. Brauer

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PREFACE

Since the publication of this book 7 years ago, I have received hundreds of emails from dozens of readers. I would like to thank all of you for your feedback. Your thoughtful questions, helpful suggestions, and many minor corrections have encouraged me to undertake an improved second edition.

Another important reason for a second edition is that considerable progress has been made over the past 7 years in the analysis and design of magnetic actuators and sensors. Accordingly, this edition has a number of added sections to cover new material. Other changes over the past 7 years include the availability of software products. While the free version of Maxwell software (Maxwell SV, a subset of Maxwell version 9) can no longer be downloaded, the Maxwell files used in both the editions still function in the commercial Maxwell version 16 now sold by ANSYS, Inc. Two free magnetic finite-element software products currently available are mentioned in Chapter 4.

Additions for the second edition are summarized here. In Part I, Chapter 1 has a new section on mechatronics and added figures. Chapter 2 adds magnetization and magnetization curve material. Chapter 3 has a new large figure comparing various types of circuits. Chapter 4 updates available finite-element software. Chapter 5 has new material on Halbach magnets, and a new section on magnetic volume forces on permeable particles.

In Part II, Chapter 7 has two new sections, one on magnetic bearings and one on magnetic separators. Chapter 9 has its Section 9.3 greatly expanded to begin with Maxwell's equations. It also has a new large section added on magnetic infusion and effusion.

In Part III, Chapter 10 has a new figure on the range of magnetic field magnitudes, new material on encoders and current sensors, and a new section on GMR spin valve sensors. Chapter 11 has four new sections: Chattock coils, SQUID magnetometers, magnetoimpedance and miniature sensors, and MEMS sensors.

In Part IV, Chapter 14 clarifies both its electromagnetic and mechanical sections, and it ends with new material on reciprocating linear actuators. Chapter 15 has a new frequency domain analysis, a new section on actuators for 2D planar motion, and a new final section containing two detailed examples of optimization of magnetic actuators and systems. Chapter 16 adds new sections on optimizing an electrohydraulic system and on digital hydraulic valves. Finally, Appendix A has been expanded and new Appendices B and C have been added. Files for all examples in this book now appear at http://booksupport.wiley.com.

I thank all of my colleagues over many decades for their friendship and help, and I would like to especially thank the following for their contributions to this second edition. Mark Juds has contributed material including the B–H data of Appendix B. Mark Solveson is the first author of the design optimization studies added to Chapters 15 and 16. The reviewers of both editions made many helpful suggestions which I have endeavored to fulfill. Also I would like to thank my wife, Susan, for again reading aloud every word of this edition and suggesting changes for clarity. Finally, this year marks the 100th anniversary of the birth of my mother, Elizabeth, who taught me many good things including her love of books. I hope this book helps the next generation of engineers.

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PREFACE TO THE FIRST EDITION

This book is written for practicing engineers and engineering students involved with the design or application of magnetic actuators and sensors. The reader should have completed at least one basic course in electrical engineering and/or mechanical engineering. This book is suitable for engineering college juniors, seniors, and graduate students.

IEEE societies whose members will be interested in this book include the Magnetics Society, Computer Society, Power Engineering Society, Industry Applications Society, and Control System Society. Readers of the *IEEE/ASME Transactions on Mechatronics,* sponsored by the IEEE Industrial Electronics Society, may also want to read this book. Many members of the Society of Automotive Engineers (SAE) might also be very interested in this book because the magnetic devices discussed here are commonly used in automobiles and aircraft.

This book is a suitable text for upper-level engineering undergraduates or graduate students in courses with titles such as “Actuators and Sensors” or “Mechatronics.” It can also serve as a supplementary text for courses such as “Electromagnetic Fields,” “Electromechanical Energy Conversion,” or “Feedback Control Systems.” It is also appropriate as a reference book for “Senior Projects” in electrical and mechanical engineering. Its basic material has been used in a 16-hour seminar for industry that I have taught many times at the Milwaukee School of Engineering. More than twice as many class hours, however, will be required to thoroughly cover the contents of this book.

The chapters on magnetic actuators are intended to replace a venerable book by Herbert C. Roters, *Electromagnetic Devices,* published by John Wiley & Sons in 1941. Over the decades since 1941, many technological revolutions have occurred. Perhaps, the most wide-ranging revolution has been the rise of the modern computer. The computer not only uses magnetic actuators and sensors in its disk drives and external interfaces but also enables new ways of analyzing and designing magnetic devices. Hence this book includes the latest computer-aided engineering methods from the most recently published technical papers. The latest software tools are used, especially the electromagnetic finite-element software package Maxwell SV, which are available to students at no charge from Ansoft Corporation, for which I am a part-time consultant. Other software tools used include SPICE, MATLAB, and Simplorer. Simplorer SV, the student version, is also available to students free of charge from Ansoft Corporation. If desired, the reader can work the computational examples and problems with other available software packages, which should yield similar results.

To download Maxwell SV and Simplorer SV along with their example files, please visit the website for this book:

ftp://ftp.wiley.com/public/sci_tech_med/magnetic_actuators/

This book is divided into four parts, each containing several chapters. Part I, on *magnetics,* begins with an introductory chapter defining magnetic actuators and sensors and why they are important. The second chapter is a review of basic electromagnetics, needed because magnetic fields are the key to understanding magnetic actuators and sensors. Chapter 3 is on the reluctance method, a way to approximately calculate magnetic fields by hand. Chapter 4 covers the finite-element method, which calculates magnetic fields very accurately via the computer. Magnetic force is a required output of magnetic actuators and is discussed in Chapter 5, and other magnetic performance parameters are the subject of Chapter 6.

Part II is on *actuators.* Chapter 7 discusses direct current (DC) actuators, while Chapter 8 deals with alternating current (AC) actuators. The last chapter devoted strictly to magnetic actuators is Chapter 9, on their transient operation.

Part III of the book is on *sensors.* Chapter 10 describes in detail the Hall effect and magnetoresistance, and applies these principles to sensing position. Chapter 11 covers many other types of magnetic sensors. However, types of sensors involving quantum effects are not included, because quantum theory is beyond the scope of this book.

Part IV of the book, on *systems,* covers many system aspects common to both magnetic actuators and sensors. Chapter 12 presents coil design and temperature calculations. Electromagnetic compatibility issues common to sensors and actuators are discussed in Chapter 13. Electromechanical performance is analyzed in Chapter 14 using coupled finite elements, while Chapter 15 uses electromechanical system software. Finally, Chapter 16 shows the advantages of electrohydraulic systems that incorporate magnetic actuators and/or sensors. Many examples are presented throughout the book because my teaching experience has shown that they are vital to learning. The examples that are numbered are simple enough to be fully described, solved, and repeated by the reader. In addition, problems at the end of the chapters enable the reader to progress beyond the solved examples.

I would like to thank the many engineers whom I have known for making this book possible. Starting with my father, Robert C. Brauer PE, it has been my great pleasure to work with you for many decades. I thank my wife, Susan McCord Brauer, for her encouragement and advice on writing. Thanks also go to the reviewers of this book for their many excellent suggestions. All of you have taught me many things. This book is my attempt to summarize some of what I have learned and to pass it on.

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January 2006

LIST OF 66 EXAMPLES

PART I

MAGNETICS

CHAPTER 1

Introduction

Magnetic actuators and sensors use magnetic fields to produce and sense motion. Magnetic actuators enable applied electric voltage or current signals to move objects. To sense the motion with an electric signal produced by magnetic fields, magnetic sensors are often used.

Since computers have inputs and outputs that are electrical signals, magnetic actuators and sensors are ideal for computer control of motion. Hence magnetic actuators and sensors are increasing in popularity. Motion control that was in the past accomplished by manual command is now increasingly carried out by computers with magnetic sensors as their input interface and magnetic actuators as their output interface.

Both magnetic actuators and magnetic sensors are energy conversion devices, using the energy stored in static, transient, or low frequency magnetic fields. This book is focused on these magnetic devices, not on devices using electric fields or high frequency electromagnetic fields.

1.1 OVERVIEW OF MAGNETIC ACTUATORS

Figure 1.1 is a block diagram of a magnetic actuator. Input electrical energy in the form of voltage and current is converted to magnetic energy. The magnetic energy creates a magnetic force, which produces mechanical motion over a limited range, typically along a straight line but sometimes rotating over an arc. Thus magnetic actuators convert input electrical energy into output mechanical energy. As mentioned in the caption of Figure 1.1, the blocks are often nonlinear (output not proportional to input), as will be discussed later in this book.

Typical magnetic actuators include the following.

- Contactors, circuit breakers, and relays to control electric motors and circuits.
- Switchgear and relays for electric power transmission and distribution.
- Head positioners for computer disk drives.

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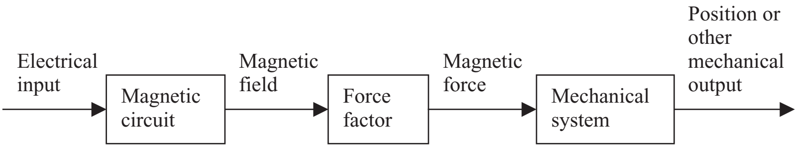

FIGURE 1.1 Block diagram of a magnetic actuator. The blocks are not necessarily linear. Both the magnetic circuit block and the force factor block are often nonlinear. The force factor block often produces a force proportional to the square of the magnetic field.

- Loudspeakers.
- Fuel injectors in engines of automobiles, trucks, and locomotives.
- Electrohydraulic valves in airplanes, tractors, robots, automobiles, and other mobile or stationary equipment.
- Biomedical prosthetic devices for artificial hearts, limbs, ears, and other organs.
- Magnetic separators that produce forces on magnetic objects large and small, including particles smaller than a micron targeted within the human body for tumors, etc.

Since magnetic actuators produce motion over a limited range, other electromechanical energy converters with large ranges of motion are not discussed in this book. Thus electric motors that produce multiple 360° rotations are not covered here. However, "step motors" which produce only a few degrees of rotary motion are classified as magnetic actuators and are included in this book.

1.2 OVERVIEW OF MAGNETIC SENSORS

A magnetic sensor has the block diagram shown in Figure 1.2. Compared to a magnetic actuator, the energy flow is different, and the amount of energy is often much smaller. The main input is now a mechanical parameter such as position or velocity, although electrical and/or magnetic input energy is usually needed as well. Input energy is converted to magnetic field energy. The output of a magnetic sensor

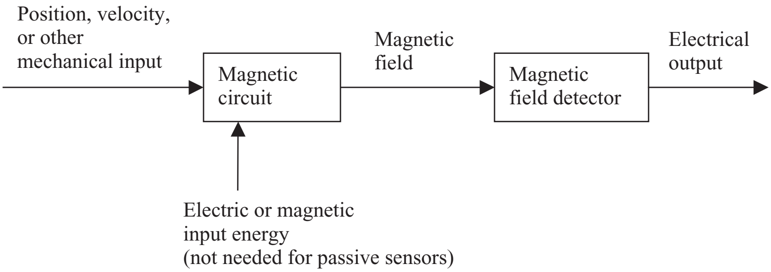

FIGURE 1.2 Block diagram of a magnetic sensor. The blocks are not necessarily linear.

is an electrical signal. In many cases the signal is a voltage with very little current, and thus the output electrical energy is often very small.

Magnetic devices that output large amounts of electrical energy are not normally classified as sensors. Hence typical generators and alternators are not discussed in this book.

Typical magnetic sensors include the following.

- Proximity sensors to determine presence and location of conducting objects for factory automation, bomb or weapon detection, and petroleum exploration.
- Microphones that sense air motion (sound waves).
- Linear variable differential transformers to determine object position.
- Velocity sensors for antilock brakes and stability control in automobiles.
- Hall effect position or velocity sensors.
- Magnetoresistive position or field sensors.

Design of magnetic actuators and sensors involves analysis of their magnetic fields. The actuator or sensor should have geometry and materials that utilize magnetic fields to produce maximum output for minimum size and cost.

1.3 ACTUATORS AND SENSORS IN MOTION CONTROL SYSTEMS

Motion control systems can use nonmagnetic actuators and/or nonmagnetic sensors. For example, electric field devices called *piezoelectrics* are sometimes used as sensors instead of magnetic sensors. Other nonmagnetic sensors include global positioning system (GPS) sensors that use high frequency electromagnetic fields, radio frequency identification (RFID) tags, and optical sensors such as television cameras. Nonmagnetic actuators and sensors are not discussed in this book.

An example of a motion control system that uses both a magnetic actuator and a magnetic sensor is the computer disk drive head assembly shown in Figure 1.3. The head assembly is a magnetic sensor that senses ("reads") not only the computer data magnetically recorded on the hard disk, but also the position (track) on the disk. To position the heads at various radii on the disk, a magnetic actuator called a *voice coil actuator* is used.

Often the best way to control motion is to use a feedback control system as shown in Figure 1.4. Its block diagram contains both an actuator and a sensor. The sensor may be a magnetic sensor measuring position or velocity, while the actuator may be a magnetic actuator producing a magnetic force. It is found that accurate control requires an accurate sensor. Control systems books widely used by electrical and mechanical engineers describe how to analyze and design such control systems [1–4]. The system design requires mathematical models of both actuators and sensors, which will be discussed throughout this book.

Another example of a magnetic actuator and a magnetic sensor is shown in Figure 1.5. It shows a tubular magnetic actuator and a magnetic Hall effect sensor

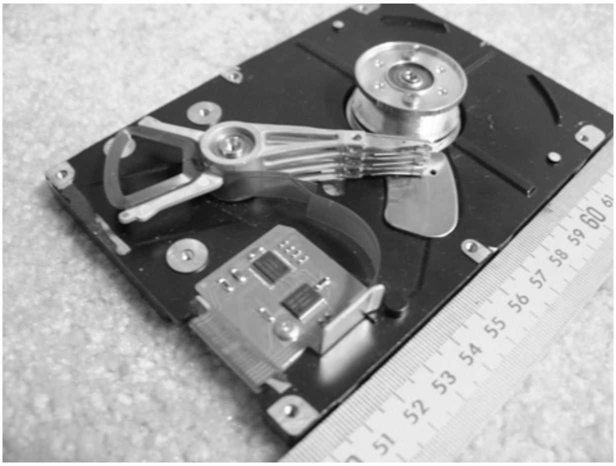

FIGURE 1.3 Typical computer disk drive head assembly. The actuator coil is the rounded triangle in the upper left. The four heads are all moved inward and outward toward the spindle hub by the magnetic force and torque on the actuator coil. Portions of the actuator and all magnetic disks are removed to allow the coil and heads to be seen.

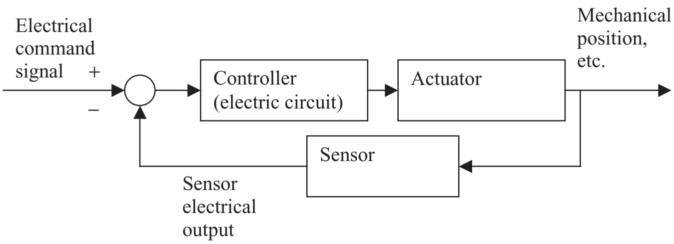

FIGURE 1.4 Basic feedback control system which may use both a magnetic actuator and a magnetic sensor.

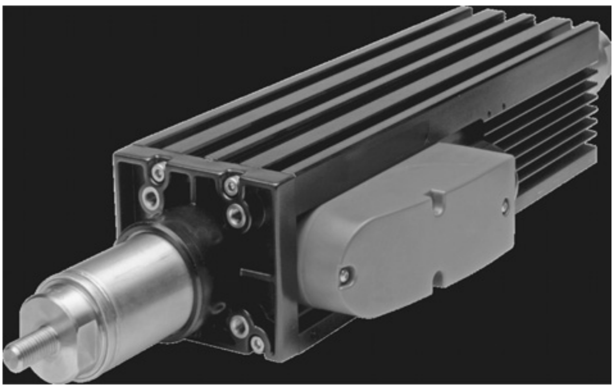

FIGURE 1.5 Magnetic actuator with built-in magnetic sensor, producing straight-line motion along its axis. Figure courtesy of Dunkermotoren Linear Systems.

packaged together to produce and sense motion along a straight line. This linear motion is accomplished without any gears or chains, thus enabling long maintenance-free life with low friction. Associated electronic controls enable precise motion control.

1.4 MAGNETIC ACTUATORS AND SENSORS IN MECHATRONICS

The word "mechatronics" is a blend of the words mechanics and electronics [5]. Mechatronic systems contain both mechanical components and electronics with controlling software. To enable the electronics to control mechanical motion, electromechanical devices are used, often containing magnetic actuators and sensors, as shown in Figures 1.1–1.5.

Figure 1.6 depicts mechatronics as made up of four major overlapping systems [6]. The mechanical systems are controlled by electrical/electronic systems, computer systems, and control systems—all working together. Note all four major systems have overlaps; one overlap area is called electromechanical systems. Magnetic actuators and sensors are important components of electromechanical systems.

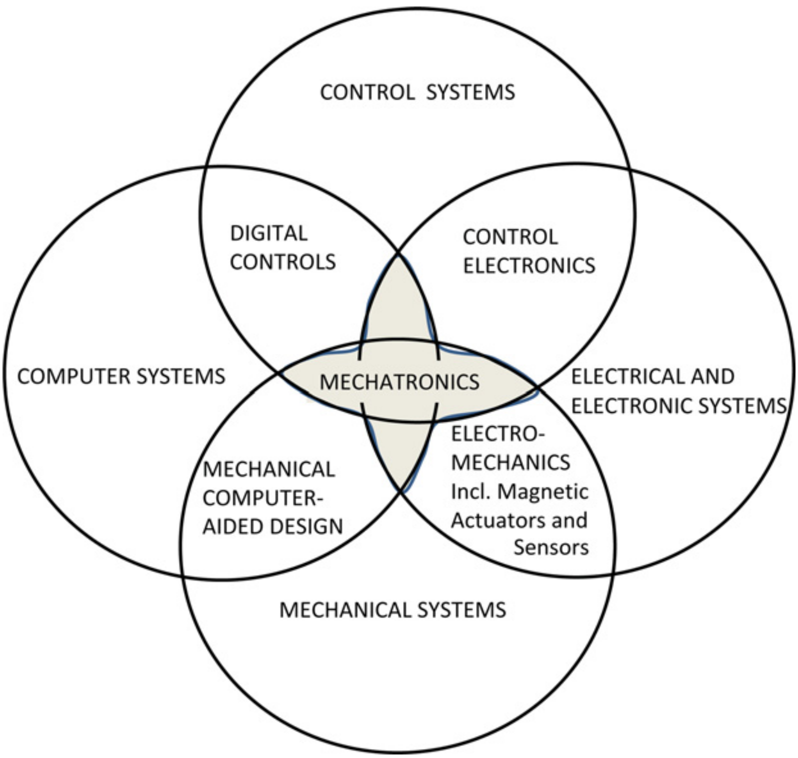

FIGURE 1.6 Venn diagram showing major engineering areas in mechatronics and how they relate to magnetic actuators and sensors.

Figure 1.6 is actually a simplified picture of the overlapping and multidisciplinary or "multiphysics" nature of mechatronics. This book also deals with additional overlaps not explicitly indicated in Figure 1.6, for example, the use of computer software to analyze and design magnetic actuators and sensors. To understand mechatronic systems containing magnetic actuators and sensors, this book is ordered in parts devoted to Magnetics, then Actuators, then Sensors, and finally to the resulting Systems.

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CHAPTER 2

Basic Electromagnetics

Study of magnetic fields provides an explanation of how magnetic actuators and sensors work. Hence this chapter presents the basic principles of *electromagnetics*, a subject that includes magnetic fields.

In reviewing electromagnetic theory, this chapter also introduces various parameters and their symbols. The symbols and notations used in this chapter will be used throughout the book, and most are also listed in Appendix A along with their units.

2.1 VECTORS

Magnetic fields are vectors, and thus it is useful to review mathematical operations involving vectors. A *vector* is defined here as a parameter having both magnitude and direction. Thus it differs from a *scalar*, which has only magnitude (and no direction). In this book, vectors are indicated by **bold** type, and scalars are indicated by italic non-bold type.

To define *direction*, rectangular coordinates are often used. Also called *Cartesian coordinates*, the position and direction are specified in terms of x, y, and z. This book denotes the three rectangular direction unit vectors as $\mathbf{u}_x$, $\mathbf{u}_y$, and $\mathbf{u}_z$; they all have magnitude equal to one.

Common to several vector operations is the "del" operator (also termed "nabla"). It is denoted by an upside down (inverted) delta symbol, and in rectangular coordinates is given by:

$$\nabla = \frac{\partial}{\partial x}\mathbf{u}_x + \frac{\partial}{\partial y}\mathbf{u}_y + \frac{\partial}{\partial z}\mathbf{u}_z \tag{2.1}$$

2.1.1 Gradient

A basic vector operation is *gradient*, also called "grad" for short. It involves the del operator operating on a scalar quantity, for example, temperature T. In rectangular coordinates the gradient of T is expressed as:

$$\nabla T = \frac{\partial T}{\partial x}\mathbf{u}_x + \frac{\partial T}{\partial y}\mathbf{u}_y + \frac{\partial T}{\partial z}\mathbf{u}_z \tag{2.2}$$

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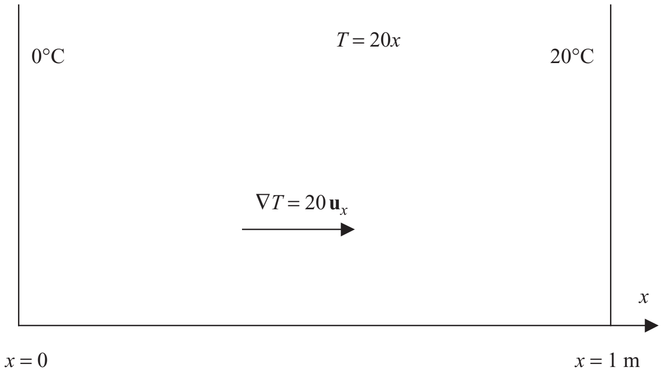

FIGURE 2.1 Temperature distribution and gradient versus position x.

An example of temperature gradient is shown in Figure 2.1. A block of ice is placed to the left of $x = 0$, for position x values less than zero. At $x = 1$ m, a wall of room temperature 20°C is located. Assuming the temperature varies linearly from $x = 0$ to $x = 1$ m, then:

$$T = 20x \tag{2.3}$$

To find the temperature gradient, substitute (2.3) into (2.2), obtaining:

$$\nabla T = 20\,\mathbf{u}_x\,{}^\circ\mathrm{C/m} \tag{2.4}$$

The direction of the gradient is the direction of maximum rate of change of the scalar (here temperature). The magnitude of the gradient equals the maximum rate of change per unit length. Since this book uses the SI (Système International) or metric system of units, all gradients here are per meter.

Two other vector operations involve multiplication with the del operator. Another word for multiplication is product, and there are two types of vector products.

Example 2.1 Gradient Calculations Find the gradient of the following temperature distribution at locations $(x,y,z) = (1,2,3)$ and $(4,-2,5)$:

$$T = 5x + 8y^2 + 3z \tag{E2.1.1}$$

Solution You must be careful in taking the partial derivatives in the gradient equation (2.2), and you must first find the expression for the gradient before evaluating it at any location. Thus the first step is to find the gradient expression:

$$\nabla T = \frac{\partial(5x + 8y^2 + 3z)}{\partial x}\mathbf{u}_x + \frac{\partial(5x + 8y^2 + 3z)}{\partial y}\mathbf{u}_y + \frac{\partial(5x + 8y^2 + 3z)}{\partial z}\mathbf{u}_z \tag{E2.1.2}$$