TWELFTH EDITION

RADIOLOGIC SCIENCE FOR TECHNOLOGISTS

PHYSICS, BIOLOGY, AND PROTECTION

Stewart Carlyle Bushong

ELSEVIER

Review of Basic Physics

ELECTROSTATICS

1. The addition or removal of electrons is called electrification.
2. Like charges repel; unlike charges attract.
3. Coulomb's law of electrostatic force:

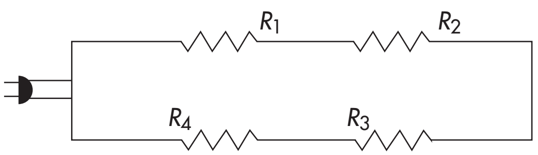
$$F = c\,\frac{Q_A Q_B}{d^2}$$

4. Only negative charges can move in solids.
5. Electrostatic charge is distributed on the outer surface of conductors.
6. The concentration of charge is greater when the radius of curvature is smaller.

ELECTRODYNAMICS

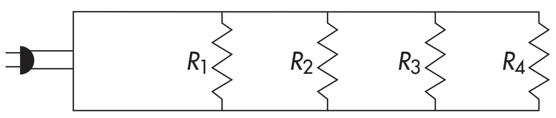
Ohm's law: V = IR

A series circuit:



1. $V_t = V_1 + V_2 + V_3 + V_4$
2. I is the same through all elements.
3. $R_t = R_1 + R_2 + R_3 + R_4$

A parallel circuit:



1. V is the same across each circuit element.
2. $I_t = I_1 + I_2 + I_3 + I_4$
3. $1/R_t = 1/R_1 + 1/R_2 + 1/R_3 + 1/R_4$

Electric power: P = IV = I 2 R [(A)(V) = W]
Work: Work = QV [(C)(V) = J]
Potential: V = W/Q [J/C = V]
Capacitance: C = Q/V [C/V = F]

MAGNETISM

1. Every magnet has a north pole and a south pole.
2. Like poles repel; unlike poles attract.
3. Gauss's law:

$$F = k\,\frac{M_1 M_2}{d^2}$$

ELECTROMAGNETISM

1. A magnetic field is always present around a conductor in which a current is flowing.
2. Changing magnetic fields can produce an electric field.
3. Transformer law:

$$\frac{V_P}{V_S} = \frac{N_P}{N_S}$$

CLASSICAL PHYSICS

Linear force: F = ma [(kg)(m/s^2) = N]
Momentum: p = mv [(kg)(m/s)]
Mechanical work (or energy):
Work (or E) = Fs [(N)(m) = J]
Kinetic energy: E = ½ mv^2 [(kg)(m^2/s^2) = J]
Mechanical power: P = Fs/t [(N)(m)/s = J/s = W]

Useful Units in Radiology

SI Prefixes

Factor	Prefix	Symbol
10^{18}	Exa	E
10^{15}	Peta	P
10^{12}	Tera	T
10^{9}	Giga	G
10^{6}	Mega	M
10^{3}	Kilo	k
10^{2}	Hecto	h
10^{1}	Deca	da
10^{-1}	Deci	d
10^{-2}	Centi	c
10^{-3}	Milli	m
10^{-6}	Micro	μ
10^{-9}	Nano	n
10^{-12}	Pico	p
10^{-15}	Femto	f
10^{-18}	Atto	a

SI Base Units

Quantity	Name	Symbol
Length	Meter	m
Mass	Kilogram	kg
Time	Second	s
Electric current	Ampere	A

SI Derived Units Expressed in Terms of Base Units

	SI UNIT	
Quantity	**Name**	**Symbol**
Area	Square meter	m^2
Volume	Cubic meter	m^3
Velocity	Meter per second	m/s
Acceleration	Meter per second squared	m/s^2
Mass density	Kilogram per cubic meter	kg/m^3
Current density	Ampere per square meter	A/m^2
Concentration (amount of substance)	Mole per cubic meter	$Mole/m^3$
Specific volume	Cubic meter per kilogram	m^3/kg

Special Quantities of Radiologic Science and Their Associated Special Units

	CUSTOMARY UNIT			SI UNIT	
Quantity	**Name**		**Symbol**	**Name**	**Symbol**
Exposure	roentgen		R	air kerma	Gy_a
Absorbed dose	rad		rad	gray	Gy_1
Effective dose	rem		rem	sievert	Sv
Radioactivity	curie		Ci	becquerel	Bq
Multiply	R	by	0.01	to obtain	Gy_a
Multiply	rad Gy	by	0.01	to obtain	Gy_t
Multiply	rem	by	0.01	to obtain	Sv
Multiply	Ci	by	3.73×10^{10}	to obtain	Bq
Multiply	R	by	2.583×10^{-4}	to obtain	C/kg

RADIOLOGIC SCIENCE FOR TECHNOLOGISTS

PHYSICS, BIOLOGY, AND PROTECTION

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TWELFTH EDITION

RADIOLOGIC SCIENCE FOR TECHNOLOGISTS

PHYSICS, BIOLOGY, AND PROTECTION

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BCM

Baylor College of Medicine

I wrote the first edition of this textbook in 1974, not expecting anyone to read it, much less buy it! I wrote it to get promoted. My academic chairman explained to me that in order to be promoted to full professor at Baylor College of Medicine, one had to write a textbook (Bushong SC. A book report. *Radiologic Technology,* 84[4], pp 405–409, March/April 2013).

The greatest reward I have received in writing this twelfth edition is the many new friends I now have because of this textbook. So, I dedicate this edition to you, my friends in radiology education. Many have contributed to this textbook and many have shared with me the speaking platform at educational meetings. Thank you very much for your friendship, and I apologize to those I have left out because I have made it to overtime and I can't remember!

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Teddy Carlyle Ellis preparing for the ARRT examination.

Dedication for Kraig Emmert

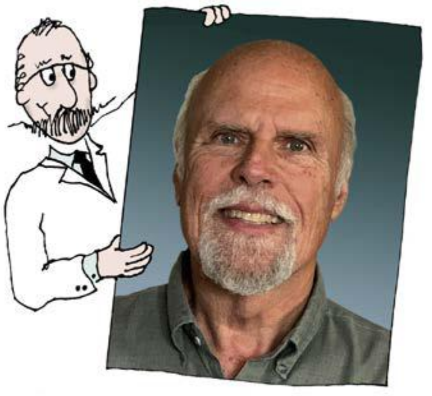
If you have read "A Book Report" (*Radiologic Technology,* 84[4], pp 405–409, March/April 2013), you understand why the first edition of this textbook was published in 1975—academic promotion! At that time at Baylor College of Medicine, one requirement for promotion to a tenured professorship was book authorship. That first edition was lousy, but I got my promotion.

Beginning with the second edition in 1980, recognition, sales, and especially the embrace of educators and students bumped up exceptionally. Why? Not the clarity of writing of physics or the level of physics or the appropriate selection of physics topics!

No, beginning with the second edition, my friend, colleague, and artist, Kraig Emmert, began to illustrate this textbook with a cartoon caricature of ME! And it wasn't just the caricature but the humor associated with each illustration.

Here we are, 40 years later and 10 years into Kraig's retirement, and I am so thankful for his work and more importantly for his friendship and his role as my teacher of giving. Kraig came to Baylor College of Medicine as an artist in 1973. We became instant friends when he helped me with illustrations for early scientific papers.

Kraig taught me the art and pleasure of giving. While working, he was very active in several community charities. In retirement, he has become a principal leader of the American Red Cross, southwest district. He gives his time and talent excessively and is an inspiration for many, including me.



Preface

PURPOSE AND CONTENT

The purpose of *Radiologic Science for Technologists: Physics, Biology, and Protection* is threefold: to convey a working knowledge of radiologic physics, to prepare radiography students for the certification examination by the ARRT, and to provide a base of knowledge from which practicing radiographers can make informed decisions about technical factors, diagnostic image quality, and radiation management for both patients and personnel.

This textbook provides a solid presentation of radiologic science, including the fundamentals of radiologic physics, diagnostic imaging, radiobiology, and radiation management. Special topics include mammography, fluoroscopy, interventional radiology, multislice helical computed tomography, tomosynthesis, and the various modes of digital imaging.

The fundamentals of radiologic science cannot be removed from mathematics, but this textbook does not assume a mathematics background. The few mathematical equations presented are always followed by sample problems with direct clinical application. As a further aid to learning, all mathematical formulas are highlighted with their own icon.

Likewise, the most important ideas under discussion are presented with their own penguin icon.

The twelfth edition improves this popular feature of informational bullets by including even more key concepts and definitions in each chapter. This textbook also presents learning objectives and chapter summaries that encourage students and make the text user friendly for all. Challenge Questions at the end of each chapter include definition exercises, short-answer questions, and a few calculations. Answers to all questions are provided on the Evolve site at http://evolve.elsevier.com.

HISTORICAL PERSPECTIVE

For decades after Roentgen's discovery of x-rays in 1895, diagnostic radiology remained a relatively stable field of study and practice. Truly great changes during that time can be counted on one hand: the Crookes tube, the radiographic grid, radiographic intensifying screens, and image intensification.

Since the publication of the first edition of this textbook in 1975, however, newer systems for diagnostic x-ray imaging have come into routine use: multislice helical computed tomography, tomosynthesis, digital radiography, and digital fluoroscopy. Truly spectacular advances in computer technology and image receptors have made these innovations possible.

NEW TO THIS EDITION

Digital radiography has replaced screen-film radiography, and this requires that radiologic technologists acquire a new and different fund of knowledge in addition to what has been required previously and in the same length of training time! The chapters of this edition have been reorganized, consolidated, and updated to reflect the current medical imaging environment.

Such an update involves descriptions of subjects that promise incredible acceleration of medical imaging—tomosynthesis, artificial intelligence (AI), quantum computing (qubits), and changes in radiation management. The expansion of the universe is accelerating, and so is the expansion of radiologic science.

Preparing the text for this twelfth edition has been a very educational experience for me. I know the purpose for composing this book is to help you, the student, to understand this very difficult subject of physics and its application to medical imaging. When I questioned the usefulness of a Summary at the end of each chapter, many reasons were given for not abandoning it. The most compelling reason that the Summary remains is to have you page to the end of each chapter first and read the Summary. That will give you a quick look and review of the deeper material you will encounter in the chapter.

That suggestion from educators led to another suggestion that resulted in a section I titled TERMS and placed at the beginning of each chapter. It is apparent that the English language confuses the understanding of physics, and the TERMS section was designed to reduce this confusion.

This confusion was discussed at the 2000 annual meeting of the Association of Collegiate Educators in Radiologic Technology (ACERT). The result was what I call the Terms Team (TT), a committee of perhaps ten educators who are attempting to standardize terms. Following the formation of the TT, I removed my TERMS effort from each chapter. Let's see the TT recommendations first.

ANCILLARIES

Workbook

This resource has been updated to reflect the changes in the text and the rapid advancements in the field of radiologic science, and it offers a complete selection of worksheets organized by textbook chapter.

Evolve Resources

Instructor ancillaries, including an ExamView test bank of over 900 questions, an image collection of the images in the text, and a PowerPoint lecture presentation are all available at http://evolve.elsevier.com.

For *Mosby's Radiography Online*, instructional materials to support teaching and learning of radiologic physics, radiographic imaging, radiobiology, and radiation protection have been developed by Elsevier and may be obtained by contacting the publisher directly.

A NOTE ON THE TEXT

Although the ARRT has not formally adopted the International System of Units (SI units), they are used in this twelfth edition. With this system comes the corresponding units of radiation and radioactivity. The roentgen and the rad are replaced by the gray (Gy_a and Gy_t, respectively) and the rem by the sievert (Sv). A summary of special quantities and units in radiologic science can be found on the inside covers of the text.

Radiation exposure is measured in the base SI unit of C/kg and then expressed in the special radiologic unit of mGy. Because mGy is also a unit of radiation dose, a measurement of radiation exposure is distinguished from tissue dose by applying a subscript *a* or *t* to mGy.

ACKNOWLEDGMENTS

For the preparation of the twelfth edition, I am indebted to the many readers of the previous editions who submitted suggestions, criticisms, corrections, and compliments.

I am particularly indebted to the many radiologic science educators whom I have identified on a Dedication page of this twelfth edition. Their suggestions for changes and clarifications were always right on target. Many of them supplied illustrations, and they are additionally acknowledged with the illustrations.

My friend and colleague Ben Archer is the author of the Penguin Tale, which for me has become a particularly effective teaching tool. That, in turn, has led to some thirty Penguintoons suggested by educators and students, which I now show regularly during lectures. I'll never forget the first. Three of Ruby Montgomery's students interrupted me at Judy William's Atlanta SRT Student and Educators' Conference in 2002. "Do polar bears eat penguins?" they asked. "Sure they do, they're carnivorous," I responded. "No, polar bears live at the North Pole, penguins at the South Pole!" Cue intense audience laughter.

The Penguintoons and many of the illustrations in this book are the work of another close friend and colleague, Kraig Emmert. Thanks, Kraig, for your exceptional time and effort.

As you, the student or educator, use this text and have questions or comments, I hope you will email me at sbushong@bcm.edu so that together we can strive to make this very difficult material easier to learn. I may not respond immediately, but I promise I will respond.

"Physics is fun" is the motto of my radiologic science courses. "Physics is good for you" is my bumper sticker. E-mail me if you want one.

Stewart Carlyle Bushong

Contents

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PART

I

RADIOLOGIC PHYSICS

CHAPTER

1

Essential Concepts of Radiologic Science

OBJECTIVES

At the completion of this chapter, the student should be able to do the following:

1. Describe the characteristics of matter and energy.
2. Identify the various forms of energy.
3. Define electromagnetic radiation and ionizing radiation.
4. State the relative intensity of ionizing radiation from various sources.
5. List the concepts of basic radiation protection.
6. Discuss the derivation of scientific systems of measurement.
7. List and define units of radiation and radioactivity.

OUTLINE

THIS CHAPTER explores the basic concepts of the science and technology of x-ray imaging. These include the study of matter, energy, the electromagnetic spectrum, and ionizing radiation. The production and use of ionizing radiation as a diagnostic tool serve as the basis for radiography. Radiologic technologists who deal specifically with x-ray imaging are radiographers. Radiographers have a great responsibility in performing x-ray examinations in accordance with established radiation protection standards for the safety of patients and medical personnel.

The instant an x-ray tube produces x-rays, all of the laws of physics are evident. The projectile electron from the cathode hits the target of the anode producing x-rays. Some x-rays interact with tissue, and other x-rays interact with the image receptor (IR), forming an image. The physics of radiography deals with the production and interaction of x-rays.

Radiography is a career choice with great opportunities in a number of diverse fields. Welcome to the field of medical imaging!

NATURE OF OUR SURROUNDINGS

In a physical analysis, all things can be classified as matter or energy. Matter is anything that occupies space and has mass. It is the material substance of which physical objects are composed. All matter is composed of fundamental building blocks called **atoms,** which are arranged in various complex ways. These atomic arrangements are considered at great length in Chapter 3.

A primary, distinguishing characteristic of matter is **mass,** the quantity of matter contained in any physical object. We generally use the term **weight** when describing the mass of an object, and for our purposes we may consider mass and weight to be the same. Remember, however, that in the strictest sense they are not the same. Mass is actually described by its energy equivalence, whereas weight is the force exerted on a body under the influence of gravity.

Mass is measured in kilograms (kg). For example, on Earth, a 200-lb (91-kg) man weighs more than a 120-lb (55-kg) woman. This occurs because of the mutual attraction, called **gravity,** between the Earth's mass and the mass of the man or woman. On the moon, the man and the woman would weigh only about one-sixth what they weigh on Earth because the mass of the moon is much less than that of the Earth. However, the mass of the man and the woman remains unchanged at 91 kg and 55 kg, respectively.

Mass is the quantity of matter as described by its energy equivalence.

MATTER AND ENERGY

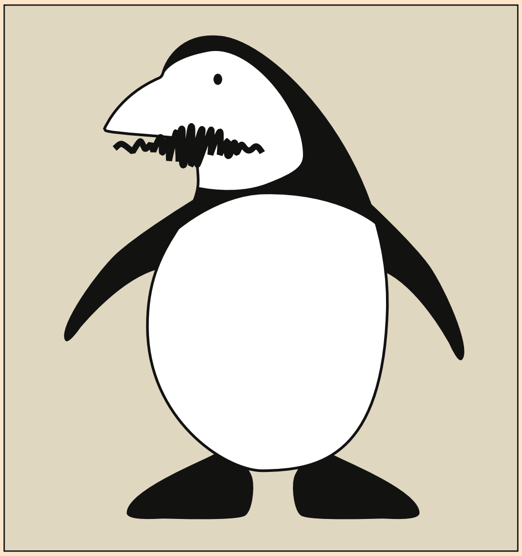
Matter is anything that occupies space. It is the material substance having mass of which physical objects are composed. The fundamental, complex building blocks of matter are **atoms** and **molecules.** The kilogram, the International System (SI) unit of mass, is unrelated to gravitational effects. The prefix **kilo** stands for 1000; a kilogram (kg) is equal to 1000 grams (g).

Although mass, the quantity of matter, remains unchanged regardless of its state, it can be transformed from one size, shape, and form to another. Consider a 1-kg block of ice, in which shape changes as the block of

A PENGUIN TALE BY BENJAMIN RIPLEY ARCHER, PhD

In the vast expanse of the Antarctic region, there was once a great, beautiful, isolated iceberg floating in the serene sea. Because of its location and accessibility, the great iceberg became a mecca for penguins from the entire area. As more and more penguins flocked to their new home and began to cover the slopes of the ice field, the iceberg began to sink farther and farther into the sea. Penguins kept climbing on, forcing others off the iceberg and back into the ocean. Soon the iceberg became nearly submerged owing to the sheer number of penguins that attempted to take up residence there.

Moral: The **PENGUIN** represents an important fact or bit of information that we must learn to understand a subject. The brain, similar to the iceberg, can retain only so much information before it becomes overloaded. When this happens, concepts begin to become dislodged, like penguins from the sinking iceberg. So, the key to learning is to reserve space for true "penguins" to fill the valuable and limited confines of our brains. Thus key points in this book are highlighted and referred to as **"PENGUINS."**



ice melts into a puddle of water. If the puddle is allowed to dry, the water apparently disappears entirely. However, we know that the ice is transformed from a solid state to a liquid state and that liquid water becomes water vapor suspended in air. If we could gather all the molecules that make up the ice, the water, and the water vapor and measure their masses, we would find that each form has the same mass.

Similar to matter, energy can exist in several forms. In the SI, energy is measured in joules (J). In radiology the unit electron volt (eV) is often used.

Potential energy is the ability to do work by virtue of position. A guillotine blade held aloft by a rope and pulley is an example of an object that possesses potential energy (Fig. 1.1). If the rope is cut, the blade will descend and do its ghastly task. Work is required to get the blade to its high position, and because of this position, the blade is said to possess potential energy. Other examples of objects that possess potential energy include a rollercoaster on top of the incline and the stretched spring of an open screen door.

> Energy is the ability to do work.

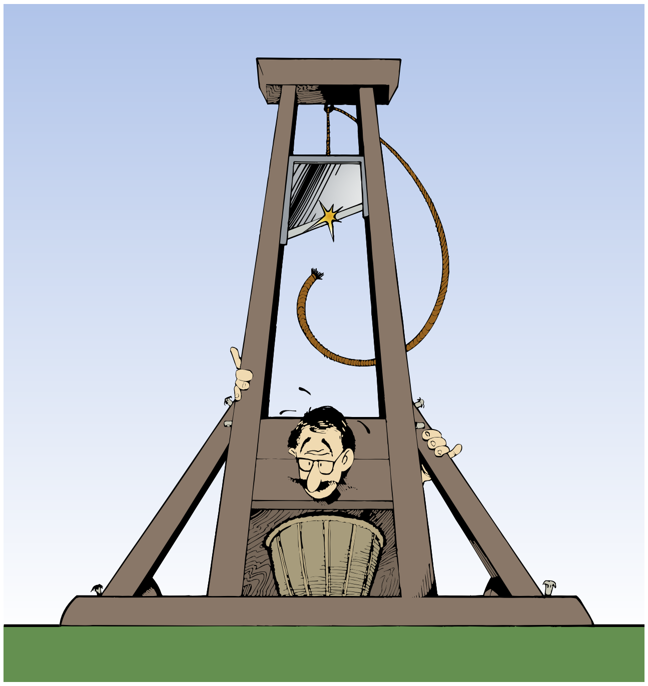


FIGURE 1.1 The blade of a guillotine offers a dramatic example of both potential and kinetic energy. When the blade is pulled to its maximum height and is locked into place, it has potential energy. When the blade is allowed to fall, the potential energy is released as kinetic energy.

Kinetic energy is the energy of motion. It is possessed by all matter in motion: a moving automobile, a turning windmill wheel, a falling guillotine blade. These systems can all do work because of their motion.

Chemical energy is the energy released by a chemical reaction. An important example of this type of energy is that which is provided to our bodies through chemical reactions involving the foods we eat. At the molecular level, this area of science is called **biochemistry.** The energy released when dynamite explodes is a more dramatic example of chemical energy.

Electrical energy represents the work that can be done when an electron moves through an electric potential difference (voltage). The most familiar form of electrical energy is normal household electricity, which involves the movement of electrons through a copper wire by an electric potential difference of 110 volts (V). All electric apparatus, such as motors, heaters, and blowers, function through the use of electrical energy.

Thermal energy (heat) is the energy of motion at the molecular level. It is the kinetic energy of molecules and is closely related to temperature. The faster the molecules of a substance are vibrating, the more thermal energy the substance has and the higher is its temperature.

Nuclear energy is the energy that is contained within the nucleus of an atom. We control the release and use of this type of energy in electric nuclear power plants. An example of the uncontrolled release of nuclear energy is the atomic bomb.

Electromagnetic energy is perhaps the least familiar form of energy. However, it is the most important for our purposes because it is the type of energy that is used in x-ray imaging. The energy traveling through space is a combination of electric and magnetic fields. In addition to x-rays and gamma rays, electromagnetic energy includes radio waves; microwaves; and ultraviolet, infrared, and visible light. Electromagnetic energy does not include sound or diagnostic ultrasound.

Just as matter can be transformed from one size, shape, and form to another, so can energy be transformed from one type to another. In radiology, for example, electrical energy in the x-ray imaging system is used to produce electromagnetic energy (the x-ray), which then is converted to an electrical signal in a digital IR.

Reconsider now the statement that all things can be classified as matter or energy. Look around you and think of absolutely anything, and you should be convinced of this statement. You should be able to classify anything as matter, energy, or both. Frequently, matter and energy exist side by side—a moving automobile has mass and kinetic energy; boiling water has mass and thermal energy; the Leaning Tower of Pisa has mass and potential energy.

Perhaps the strangest property associated with matter and energy is that they are interchangeable, a characteristic first described by Albert Einstein in his famous theory of relativity. Einstein's **mass-energy equivalence** equation is a cornerstone of that theory.

This mass-energy equivalence serves as the basis for the atomic bomb, nuclear power plants, and certain nuclear medicine imaging modalities.

MASS-ENERGY

$E = mc^2$

where E is energy, m is mass, and c is the velocity (speed) of electromagnetic radiation (light) in a vacuum.

Energy emitted and transferred through space is called **radiation.** When a piano string vibrates, it is said to radiate sound; the sound is a form of radiation. Ripples or waves radiate from the point where a pebble is dropped into a still pond. Visible light, a form of electromagnetic energy, is radiated by the sun and is **electromagnetic radiation.** Electromagnetic energy is usually referred to as electromagnetic radiation or, simply, **radiation.**

Matter that intercepts radiation and absorbs part or all of it is said to be exposed or **irradiated.** Spending a day at the beach exposes you to ultraviolet light. Ultraviolet light is the type of radiation that causes sunburn. During a radiographic examination, the patient is exposed to x-rays. The patient is said to be irradiated.

Radiation is the transfer of energy.

Ionizing radiation is a special type of radiation that includes x-rays. Ionizing radiation is any type of radiation that is capable of removing an orbital electron from the atom with which it interacts (Fig. 1.2). This type of interaction between radiation and matter is called **ionization.** Ionization occurs when an x-ray passes close to an orbital electron of an atom and transfers sufficient energy to the electron to remove it from the atom. The ionizing radiation may interact with and ionize additional atoms. The orbital electron and the atom from which it was separated are called an **ion pair.** The electron is a negative ion, and the remaining atom is a positive ion.

Ionization is the removal of an electron from an atom.

Thus any type of energy that is capable of ionizing matter is known as ionizing radiation. X-rays, gamma rays, and ultraviolet light are the only forms of electromagnetic radiation with sufficient energy to ionize. Some fast-moving particles (particles with high kinetic energy) are also capable of ionization. Examples of particle-type ionizing radiation are alpha and beta particles (see Chapter 3). Although alpha and beta particles are sometimes called **rays,** this designation is incorrect.

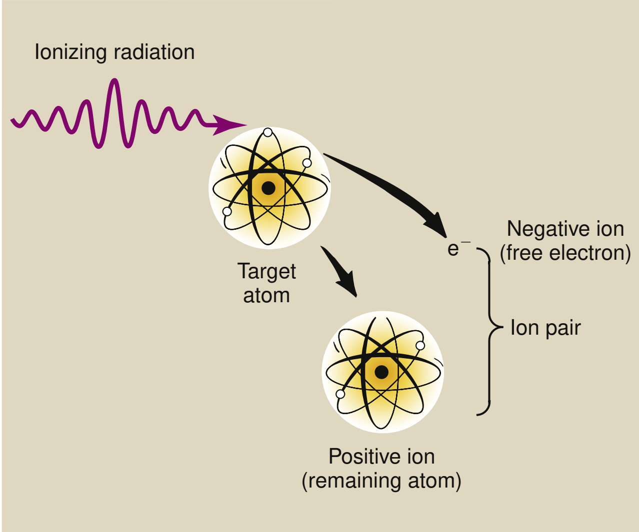


FIGURE 1.2 Ionization is the removal of an electron from an atom. The ejected electron and the resulting positively charged atom together are called an ion pair.

SOURCES OF IONIZING RADIATION

Many types of radiation are harmless, but ionizing radiation can injure humans. We are exposed to many sources of ionizing radiation (Fig. 1.3). These sources can be divided into two main categories: **natural environmental radiation** and **man-made radiation.**

Natural environmental radiation results in an annual dose of approximately 3 millisieverts (mSv). Human-made radiation results in 3.1 mSv annually. The mSv is the SI unit of effective dose. It is used to express radiation exposure of populations and radiation risk in those populations.

Natural environmental radiation consists of four components: **cosmic rays, terrestrial radiation, internally deposited radionuclides, and radon.** Cosmic rays are particulate and electromagnetic radiation emitted by the sun and stars. On Earth, the intensity of cosmic radiation increases with altitude and latitude. Terrestrial radiation results from deposits of uranium, thorium, and other radionuclides in the Earth. The intensity is highly dependent on the geology of the local area. Internally deposited radionuclides, mainly potassium-40 (^{40}K), are natural metabolites. They have always been with us and contribute an equal dose to each of us.

The largest source of natural environmental radiation is radon. Radon is a radioactive gas that is produced by the natural radioactive decay of uranium, which is present in trace quantities in the Earth. All Earth-based materials, such as concrete, bricks, and gypsum wallboard, contain radon. Radon emits alpha particles, which are not penetrating, and therefore contributes a radiation dose only to the lung.

Collectively, these sources of natural environmental radiation result in approximately 300 to 1000 microsievert (μSv)/h at waist level in the United States

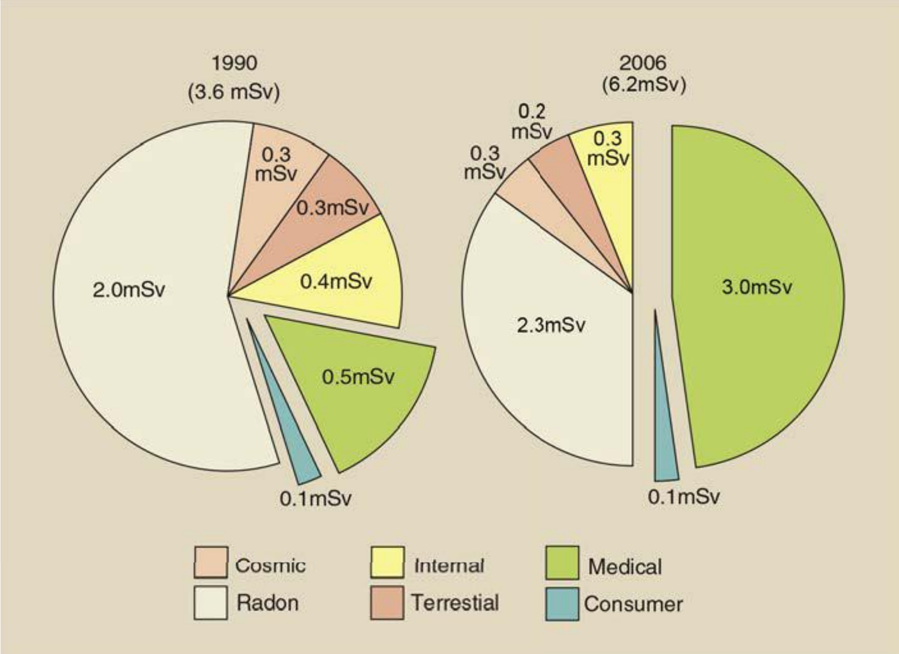


FIGURE 1.3 The contribution of various sources to the average US population radiation dose, 1990 and 2006. We will return to this very important pie chart in Chapter 39.

(Fig. 1.4). This equals an annual exposure of approximately 0.2 mSv/yr along the Gulf Coast and Florida to 1 mSv/yr or higher in the Rocky Mountains region.

Remember, however, that humans have existed for several hundred thousand years in the presence of this natural environmental radiation level. Human evolution undoubtedly has been influenced by natural environmental radiation. Some geneticists contend that evolution is influenced primarily by ionizing radiation. If this is so, then we must indeed be concerned with control of unnecessary radiation exposure because over the past century, with increasing medical applications of radiation, the average annual exposure of our population to radiation has increased significantly.

Diagnostic x-rays constitute the largest man-made source of ionizing radiation (3.0 mSv/yr). This estimate was made in 2006 by the National Council on Radiation Protection and Measurements (NCRP). Earlier estimates by the NCRP in 1990 put this source at nearly 0.5 mSv/yr. The increase during this 16-year period is principally attributable to the increasing use of computed tomography (CT) and high-level fluoroscopy.

The benefits derived from the application of x-rays in medicine are indisputable; however, such applications must be made with prudence and with care taken to reduce unnecessary exposure of patients and personnel. This responsibility falls primarily on radiologic technologists because they usually control the operation of x-ray imaging systems during radiologic examinations.

The currently accepted approximate annual dose resulting from medical applications of ionizing radiation is 3.0 mSv. In contrast to the natural environmental radiation dose, this level takes into account people who are not receiving a radiologic examination and those undergoing several within a year.

The medical radiation exposure for some in our population will be zero, but for others it may be quite high. This average level is comparable with natural environmental radiation levels, and therefore one could question why it is necessary to be concerned about radiation control and radiation safety in medical imaging.

Question: What percentage of our annual average radiation dose is attributable to medical imaging?

Answer: 3.0 mSv/6.2 mSv = 0.484 = 48%

Other sources of man-made radiation include nuclear power generation, research applications, industrial sources, and consumer items. Nuclear power stations and other industrial applications contribute very little to our radiation dose. Consumer products such as watch dials, exit signs, smoke detectors, camping lantern mantles, and airport surveillance systems contribute only 0.1 mSv to our annual radiation dose.

DISCOVERY OF X-RAYS

X-rays were not developed; they were discovered and quite by accident. During the 1870s and 1880s, many university physics laboratories were investigating the conduction of **cathode rays** through a large, partially evacuated glass tube known as a **Crookes tube.** Sir William Crookes was an Englishman from a rather humble background who was a self-taught genius.

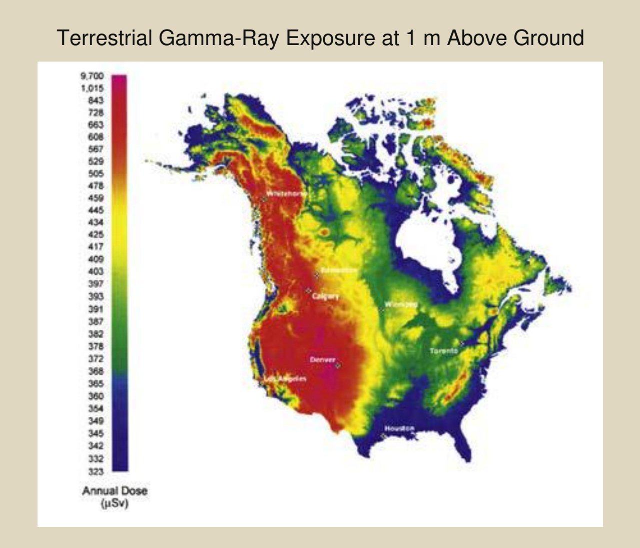


FIGURE 1.4 Radiation exposure at waist level throughout the United States. (Courtesy US Geological Survey.)

The tube that bears his name was the forerunner of modern fluorescent lamps and x-ray tubes. There were many different types of Crookes tubes; most of them were capable of producing x-rays. Wilhelm Roentgen was experimenting with a type of Crookes tube when he discovered x-rays (Fig. 1.5).

On November 8, 1895, Roentgen was working in his physics laboratory at Würzburg University in Germany. He had darkened his laboratory and completely enclosed his Crookes tube with black photographic paper so he could better visualize the effects of the cathode rays in the tube. A plate coated with **barium platinocyanide,** a fluorescent material, happened to be lying on a bench top several meters from the Crookes tube.

No visible light escaped from the Crookes tube because of the black paper that enclosed it, but Roentgen noted that the barium platinocyanide glowed. The intensity of the glow increased as the plate was brought closer to the tube; consequently, there was little doubt about the origin of the stimulus of the glow. This glow is called **fluorescence.**

Roentgen's immediate approach to investigating this "X-light," as he called it, was to interpose various materials—wood, aluminum, his hand!—between the Crookes tube and the fluorescing plate. The "X" was for unknown! He feverishly continued these investigations for several weeks.

Roentgen's initial investigations were extremely thorough, and he was able to report his experimental results to the scientific community before the end of 1895 (Table 1.1). For this work, in 1901, he received the first Nobel Prize in Physics.

Roentgen recognized the value of his discovery to medicine. He produced and published the first medical x-ray image in early 1896. It was an image of his wife's hand (Fig. 1.6). Fig. 1.7 is a photograph of what is

FIGURE 1.5 The type of Crookes tube Roentgen used when he discovered x-rays. Cathode rays (electrons) leaving the cathode are attracted by high voltage to the anode, where they produce x-rays and fluorescent light. (Courtesy Gary Leach, Memorial Hermann Hospital.)

TABLE 1.1 Roentgen's Original Properties of X-Rays

1. X-rays are highly penetrating, invisible rays that are a form of electromagnetic radiation.
2. X-rays are electrically neutral and therefore not affected by either electric or magnetic fields.
3. X-rays can be produced over a wide variety of energies and wavelengths.
4. X-rays release very small amounts of heat upon passing through matter.
5. X-rays travel in straight lines.
6. X-rays travel at the speed of light, 3×10^8 m/s in a vacuum.
7. X-rays can ionize matter.
8. X-rays cause fluorescence of certain crystals.
9. X-rays cannot be focused by a lens.
10. X-rays affect photographic film.
11. X-rays produce chemical and biological changes in matter through ionization and excitation.
12. X-rays produce secondary and scatter radiation.

reported to be the first x-ray examination in the United States, conducted in early February 1896, in the physics laboratory at Dartmouth College.

The discovery of x-rays is characterized by many amazing features, and this causes it to rank high among the events in human history. First, the discovery was accidental. Second, probably no fewer than a dozen contemporaries of Roentgen had previously observed x-radiation, but none of these other physicists had

FIGURE 1.6 The hand shown in this radiograph belongs to Mrs. Roentgen. This first indication of the possible medical applications of x-rays was made within a few days of the discovery. (Courtesy Deutsches Roentgen Museum.)

recognized its significance or investigated it. Third, Roentgen followed his discovery with such scientific vigor that within little more than 1 month, he had described x-radiation with nearly all of the properties we currently recognize.

DEVELOPMENT OF MEDICAL IMAGING

There are three general types of x-ray examinations: **radiography, fluoroscopy,** and **computed tomography (CT).** Radiography uses a solid-state **image receptor (IR)** and usually an x-ray tube mounted from the ceiling on a track that allows the tube to be moved in any direction. Such examinations provide the radiologist with fixed images.

Fluoroscopy is usually conducted with an x-ray tube located under the examination table supporting the patient. The radiologist is provided with moving images on a digital display device.

CT uses a rotating x-ray source and detector array. A volume of data is acquired so that fixed images can be reconstructed in any anatomic plane—coronal, sagittal, transverse, or oblique.

There are many variations of these three basic types of examinations, but in general, x-ray imaging equipment is similar.

To provide an x-ray beam that is satisfactory for imaging, you must supply the x-ray tube with a high voltage and an electric current.

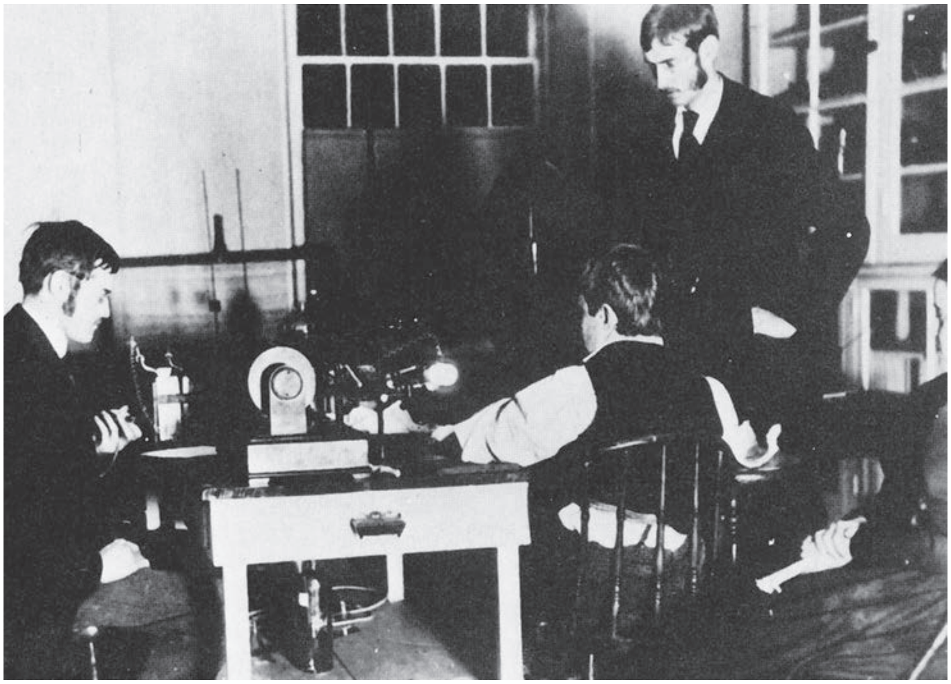


FIGURE 1.7 This photograph records the first medical x-ray examination in the United States. A young patient, Eddie McCarthy, broke his wrist while skating on the Connecticut River and submitted to having it photographed by the "X-light." With him are *(left to right)* Professor E.B. Frost, Dartmouth College, and his brother, Dr. G.D. Frost, Medical Director, Mary Hitchcock Hospital. The apparatus was assembled by Professor F.G. Austin in his physics laboratory at Reed Hall, Dartmouth College, on February 3, 1896. (Courtesy Mary Hitchcock Hospital.)

X-ray voltages are measured in kilovolt peak (**kVp**). One kilovolt (**kV**) is equal to 1000 V of electric potential. X-ray currents are measured in milliampere (**mA**), where the ampere (A) is a measure of electric current. The prefix **milli** stands for 1/1000 or 0.001.

Question: The usual x-ray source-to-image receptor distance (SID) during radiography is 1 m. How many millimeters is that?

Answer: 1 mm = 1/1000 m or 10^{-3}; therefore 1000 mm = 1 m.

Currently, voltage and current are supplied to an x-ray tube through rather complicated electric circuits, but in Roentgen's time, only simple static generators were available. These units could provide currents of only a few milliamperes and voltages up to 50 kVp. Currently, 1000 mA and 150 kVp are commonly used.

Early radiographic procedures often required exposure times of 30 minutes or longer. Long exposure time results in image blur. One development that helped reduce this exposure time was the use of a fluorescent **intensifying screen** in conjunction with the glass photographic plates.

Michael Pupin is said to have demonstrated the use of a radiographic intensifying screen in 1896, but only many years later did it receive adequate recognition and use. Radiographs during Roentgen's time were made by exposing a glass plate with a layer of photographic emulsion coated on one side.

Charles L. Leonard found that by exposing two glass x-ray plates with the emulsion surfaces together, exposure time was halved, and the image was considerably enhanced. This demonstration of double-emulsion radiography was conducted in 1904, but **double-emulsion film** did not become commercially available until 1918.

Much of the high-quality glass used in radiography came from Belgium and other European countries. This supply was interrupted during World War I; therefore radiologists began to make use of film rather than glass plates.

The demands of the army for increased radiologic services made a substitute for the glass plate necessary. The substitute was **cellulose nitrate,** and it quickly became apparent that the substitute was better than the original glass plate.

The **fluoroscope** was developed in 1898 by the American inventor Thomas A. Edison (Fig. 1.8). Edison's original fluorescent material was barium platinocyanide, a widely used laboratory material. He investigated the fluorescent properties of more than 1800 other materials, including **zinc cadmium sulfide** and **calcium tungstate**—two materials in use currently.

There is no telling what additional inventions Edison might have developed had he continued his x-ray research, but he abandoned it when his assistant and long-time friend, Clarence Dally, experienced a severe x-ray burn that eventually required amputation of both arms. Dally died in 1904 and is counted as the first x-ray fatality in the United States.

FIGURE 1.8 Thomas Edison is seen viewing the hand of his unfortunate assistant, Clarence Dally, through a fluoroscope of his own design. Dally's hand rests on the box that contains the x-ray tube.

Two devices designed to reduce the exposure of patients to x-rays and thereby minimize the possibility of x-ray burn were introduced before the turn of the 20th century by a Boston dentist, William Rollins. Rollins used x-rays to image teeth and found that restricting the x-ray beam with a sheet of lead with a hole in the center, a **diaphragm,** and inserting a leather or aluminum filter improved the diagnostic quality of radiographs.

This first application of **collimation** and **filtration** was followed very slowly by general adoption of these techniques. It was later recognized that these devices reduce the hazard associated with x-rays.

Two developments that occurred at approximately the same time transformed the use of x-rays from a novelty in the hands of a few physicists into a valuable, large-scale medical specialty. In 1907 H.C. Snook introduced a substitute high-voltage power supply, an interrupterless **transformer,** for the static machines and induction coils then in use.

Although the Snook transformer was far superior to these other devices, its capability greatly exceeded the capability of the Crookes tube. It was not until the introduction of the Coolidge tube that the Snook transformer was widely adopted.

The type of Crookes tube that Roentgen used in 1895 had existed for a number of years. Although some modifications were made by x-ray workers, it remained essentially unchanged into the second decade of the 20th century.

After considerable clinical testing, William D. Coolidge unveiled his hot-cathode x-ray tube to the medical community in 1913. It was immediately recognized as far superior to the Crookes tube. It was a vacuum tube that allowed x-ray intensity and energy to be selected separately and with great accuracy. This had not been possible with gas-filled tubes, which made standards for techniques difficult to obtain. X-ray tubes in use today are refinements of the **Coolidge tube.**

> Radiology emerged as a medical specialty because of the Snook transformer and the Coolidge x-ray tube.

The era of modern radiography is dated from the matching of the Coolidge tube with the Snook transformer; only then did acceptable kVp and mA levels become possible. Few developments since that time have had such a major influence on medical imaging.

In 1913 Gustav Bucky (German) invented the stationary grid ("Glitterblende"); 2 months later he applied for a second patent for a moving grid. In 1915 H. Potter (American), probably unaware of Bucky's patent because of World War I, also invented a moving grid. To his credit, Potter recognized Bucky's work, and the Potter-Bucky grid was introduced in 1921.

In 1946 the light amplifier tube was demonstrated at Bell Telephone Laboratories. This device was adapted for fluoroscopy by 1950 as an image intensifier tube. Currently, image-intensified fluoroscopy is being replaced by solid-state IRs.

Each recent decade has seen remarkable improvements in medical imaging. Diagnostic ultrasonography appeared in the 1960s, as did the gamma camera. Positron emission tomography and x-ray CT were developed in the 1970s. Magnetic resonance imaging (MRI) became an accepted modality in the 1980s, and currently digital radiography and digital fluoroscopy are rapidly replacing screen-film radiography and image-intensified fluoroscopy. Table 1.2 chronologically summarizes some of the more important developments.

REPORTS OF RADIATION INJURY

The first x-ray fatality in the United States occurred in 1904. Unfortunately, radiation injuries occurred rather frequently in the early years. These injuries usually took the form of skin damage (sometimes severe), loss of hair, and anemia. Physicians and, more commonly, patients were injured, primarily because the low energy of radiation then available resulted in the necessity for long exposure times to obtain acceptable images.

By about 1910, these acute injuries began to be controlled as the biologic effects of x-rays were scientifically investigated and reported. With the introduction of the Coolidge tube and the Snook transformer, the frequency of reports of injuries to superficial tissues decreased.

Years later, it was discovered that blood disorders such as aplastic anemia and leukemia were occurring in radiologists at a much higher rate than in others. Because of these observations, protective devices and apparel, such as lead gloves and aprons, were developed for use by radiologists. X-ray workers were routinely observed for any effects of their occupational exposure and were provided with personnel radiation monitoring devices. This attention to radiation safety in radiology has been effective.

> Because of effective radiation protection practices, radiology is now considered a safe occupation.

BASIC RADIATION PROTECTION

Today, the emphasis on radiation control in diagnostic radiology has shifted back to protection of patients. Current studies suggest that even the low doses of x-radiation used in routine diagnostic procedures may result in a small incidence of latent harmful effects. It is also well established that human fetuses are sensitive to x-radiation early in pregnancy.

It is hoped that this introduction has emphasized the importance of providing adequate protection for both radiologic technologists and patients. As you progress through your training in radiologic technology, you will quickly learn how to operate your x-ray imaging systems safely, with minimal radiation exposures, by following standard radiation protection procedures.

One caution is in order early in your training—after you have worked with x-ray imaging systems, you will become so familiar with your work environment that you may become complacent about radiation control. Do not allow yourself to develop this attitude because it can lead to unnecessary radiation exposure. Radiation protection must be an important consideration during each x-ray procedure. Table 1.3 reports the Ten Commandments of Radiation Protection.

> Always practice ALARA. Keep radiation exposures **as** **l**ow **as** **r**easonably **a**chievable.

Minimizing radiation exposure to radiologic technologists and to patients is easy if the x-ray imaging systems designed for this purpose are recognized and understood. A brief description of some of the primary radiation protection devices follows.

Protective Apparel

Lead-impregnated material is used to make aprons and gloves worn by radiologists and radiologic technologists during fluoroscopy and some radiographic procedures.

TABLE 1.2 Important Dates in the Development of Modern Radiology

Date	Event
1895	Roentgen discovers x-rays.
1896	First medical applications of x-rays in diagnosis and therapy are made.
1900	The American Roentgen Society, the first American radiology organization, is founded.
1901	Roentgen receives the first Nobel Prize in Physics.
1905	Einstein introduces his theory of relativity and the famous equation $E = mc^2$.
1907	The Snook interrupterless transformer is introduced.
1913	Bohr theorizes his model of the atom, featuring a nucleus and planetary electrons.
1913	The Coolidge hot-filament x-ray tube is developed.
1917	The cellulose nitrate film base is widely adopted.
1920	Several investigators demonstrate the use of soluble iodine compounds as contrast media.
1920	The American Society of Radiologic Technologists (ASRT) is founded.
1921	The Potter-Bucky grid is introduced.
1922	Compton describes the scattering of x-rays.
1923	Cellulose acetate “safety” x-ray film is introduced (Eastman Kodak).
1925	The First International Congress of Radiology is convened in London.
1928	The roentgen is defined as the unit of x-ray intensity.
1929	Forssmann demonstrates cardiac catheterization … on himself!
1929	The rotating anode x-ray tube is introduced.
1930	Tomographic devices are shown by several independent investigators.
1932	Blue tint is added to x-ray film (DuPont).
1932	The US Committee on X-Ray and Radium Protection (now the NCRP) issues the first dose limits.
1942	Morgan exhibits an electronic photo-timing device.
1942	The first automatic film processor (Pako) is introduced.
1948	Coltman develops the first fluoroscopic image intensifier.
1951	Multidirectional tomography (polytomography) is introduced.
1953	The rad is officially adopted as the unit of absorbed dose.
1956	Xeroradiography is demonstrated.
1956	First automatic roller transport film processing (Eastman Kodak) is introduced.
1960	Polyester base film is introduced (DuPont).
1963	Kuhl and Edwards demonstrate single-photon emission computed tomography (SPECT).
1965	Ninety-second rapid processor is introduced (Eastman Kodak).
1966	Diagnostic ultrasonography enters routine use.
1972	Single-emulsion film and one-screen mammography become available (DuPont).
1973	Hounsfield completes development of first computed tomography (CT) imaging system (EMI).
1973	Damadian and Lauterbur produce the first magnetic resonance image (MRI).
1974	Rare earth radiographic intensifying screens are introduced.
1977	Mistretta demonstrates digital subtraction fluoroscopy.
1979	The Nobel Prize in Physiology or Medicine is awarded to Allan Cormack and Godfrey Hounsfield for CT.
1980	The first commercial superconducting MRI system is introduced.
1981	Slot scan chest radiography is demonstrated by Barnes.
1981	The International System of Units (SI) is adopted by the International Commission on Radiation Units and Measurements (ICRU).
1982	Picture Archiving and Communication System (PACS) becomes available.
1983	First tabular grain film emulsion (Eastman Kodak) is developed.
1984	Laser-stimulable phosphors for computed radiography appear (Fuji).
1988	A superconducting quantum interference device (SQUID) for magnetoencephalography (MEG) is first used.
1989	The SI is adopted by the NCRP and most scientific and medical societies.
1990	The last xeromammography system is produced.
1990	Helical CT is introduced (Toshiba).
1991	Twin-slice CT is developed (Elscint).
1992	The Mammography Quality Standard Acts (MQSA) is passed.
1996	Digital radiography that uses thin-film transistors (TFTs) is developed.
1997	Charge-coupled device (CCD) digital radiography is introduced by Swissray.
1997	Amorphous selenium flat panel image receptor is demonstrated by Rowlands.
1998	Multislice CT is introduced (General Electric).
1998	Amorphous silicon-CsI image receptor is demonstrated for digital radiography.
2000	The first direct digital mammographic imaging system is made available (General Electric).
2002	Sixteen-slice helical CT is introduced.
2002	Positron emission tomography (PET) is placed into routine clinical service.
2003	The Nobel Prize in Physiology or Medicine is awarded to Paul Lauterbur and Sir Peter Mansfield for MRI.
2003	Digital radiographic tomosynthesis is demonstrated.
2004	The 64-slice helical CT is introduced.
2005	Dual-source CT is announced (Siemens).
2007	The 320-slice helical CT is introduced (Toshiba).
2009	NCRP Report No. 160, *Ionizing radiation exposure of the population of the United States: 2006*, is published.
2011	Digital mammographic tomosynthesis is clinically approved.
2012	Discovery of the Higgs boson at the CERN Large Hadron Collider, Switzerland.
2017	3D printers and segmentation algorithms expand CT and MRI applications.
2018	Artificial intelligence (AI) appears in special journals and meetings.

TABLE 1.3 The Ten Commandments of Radiation Protection

1. Understand and apply the cardinal principles of radiation control: time, distance, and shielding.
2. Do not allow familiarity to result in false security.
3. Never stand in the primary beam.
4. Always wear protective apparel when not behind a protective barrier.
5. Always wear an occupational radiation monitor and position it outside the protective apron at the collar.
6. Never hold a patient during radiographic examination. Use mechanical restraining devices when possible. Otherwise, have family or friends hold the patient.
7. The person who is holding the patient must always wear a protective apron and, if possible, protective gloves.
8. Use gonadal shields on all people of childbearing age or younger when such use will not interfere with the examination.
9. Examination of the pelvis and lower abdomen of pregnant patients should be avoided whenever possible, especially during the first trimester.
10. Always collimate to the smallest field size appropriate for the examination.

Gonadal Shielding

The same lead-impregnated material used in aprons and gloves is used to fabricate gonadal shields. Gonadal shields should be used with all persons of childbearing age or younger when the gonads are in or near the useful x-ray beam and when use of such shielding will not interfere with the diagnostic value of the examination.

Protective Barriers

The radiographic or CT control console is always located behind a protective barrier. Often, the barrier is lead lined and is equipped with a leaded-glass window. Under normal circumstances, personnel remain behind the barrier during x-ray examination. Fig. 1.9 is a rendering of a radiographic and fluoroscopic examination room. Many radiation safety features are illustrated.

Other procedures should be followed. Abdominal and pelvic x-ray examinations of expectant mothers should not be conducted during the first trimester unless absolutely necessary. Every effort should be made to ensure that an examination will not have to be repeated because of technical error. Repeat examinations subject the patient to twice the necessary radiation.

When shielding patients for x-ray examination, one should consider the medical management of the patient. Except for proper screening, x-ray examination of asymptomatic patients is not acceptable.

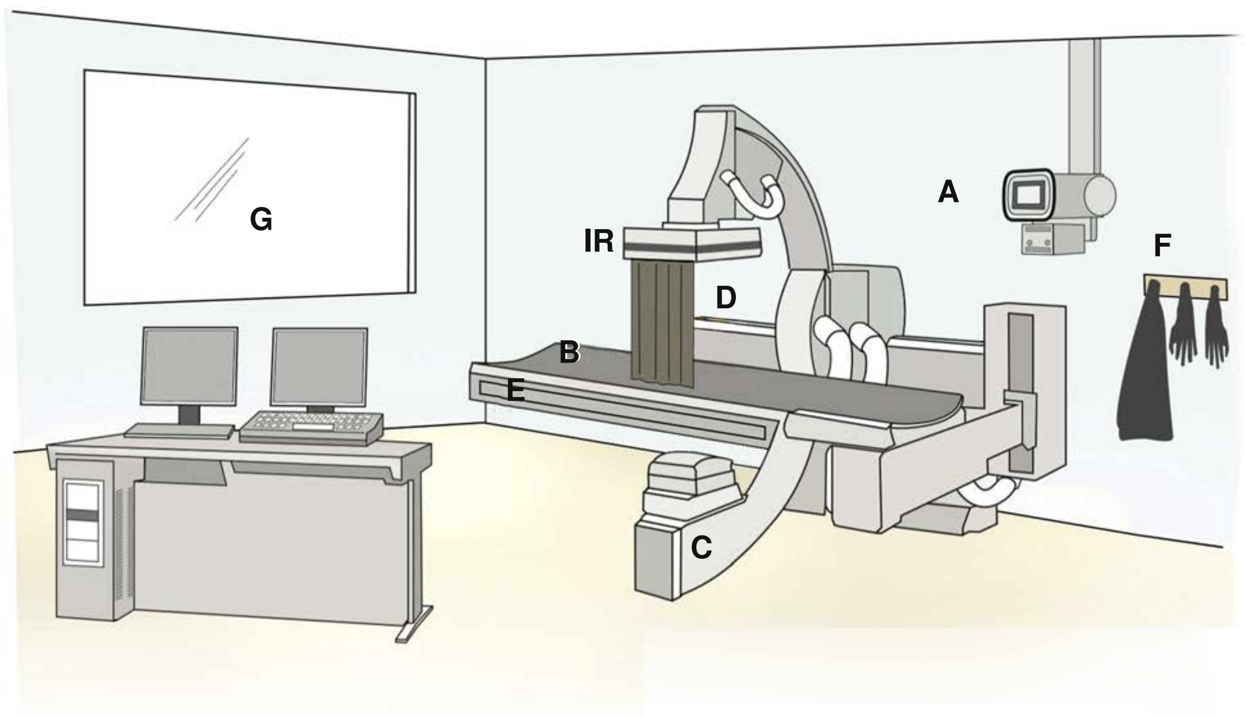


FIGURE 1.9 The general purpose radiographic and fluoroscopic imaging system includes an overhead radiographic tube (A) and a fluoroscopic examining table (B) with an x-ray tube under the table (C). Some of the more common radiation protection devices are the lead curtain (D), the Bucky slot cover (E), a lead apron and gloves (F), and the protective viewing window (G). The location of the image receptor (*IR*) and associated imaging equipment is shown.

Patients who require assistance during examination should never be held by x-ray personnel. Mechanical immobilization devices should be used. When necessary, a member of the patient's family, appropriately shielded, should provide the necessary assistance.

Filtration

Metal filters, usually aluminum or copper, are inserted into the x-ray tube housing so that low-energy x-rays are absorbed before they reach the patient. These x-rays have little diagnostic value.

Collimation

Collimation restricts the useful x-ray beam to that part of the body to be imaged and thereby spares adjacent tissue from unnecessary radiation exposure. Collimators take many different forms. Adjustable light-locating collimators are the most frequently used collimating devices. Collimation also reduces scatter radiation and thus improves image contrast.

TERMINOLOGY FOR RADIOLOGIC SCIENCE

Every profession has its own language. Radiologic science is no exception. Several words and phrases characteristic of radiologic science already have been identified; many more will be defined and used throughout this book. For now, an introduction to this terminology should be sufficient.

Numeric Prefixes

Often in radiologic science, we must describe very large or very small multiples of standard units. Two units, the milliampere (mA) and kilovolt peak (kVp), already have been discussed. By writing 70 kVp instead of 70,000 volt peak, we can understandably express the same quantity with fewer characters. For such economy of expression, scientists have devised a system of prefixes and symbols (Table 1.4).

TABLE 1.4 Standard Scientific Prefixes

Multiple	Prefix	Symbol
10^{18}	exa-	E
10^{15}	peta-	P
10^{12}	**tera-**	**T**
10^{9}	**giga-**	**G**
10^{6}	**mega-**	**M**
10^{3}	**kilo-**	**k**
10^{2}	hecto-	h
10	deka-	da
10^{-1}	deci-	d
10^{-2}	**centi**	**c**
10^{-3}	**milli-**	**m**
10^{-6}	**micro-**	**µ**
10^{-9}	**nano-**	**n**
10^{-12}	pico-	p
10^{-15}	femto-	f
10^{-18}	atto-	a

Boldfaced prefixes and symbols are those most used in radiologic science.

Question: How many kilovolts equal 37,000 V?

Answer:
$$37{,}000\ \text{V} = 37 \times 10^{3}\ \text{V} = 37\ \text{kV}$$

Question: The diameter of a blood cell is approximately 10 micrometers (µm). How many meters is that?

Answer:
$$10\ \mu\text{m} = 10 \times 10^{-6}\ \text{m} = 10^{-5}\ \text{m} = 0.00001\ \text{m}$$

Radiologic Units

The four units used to measure radiation should become a familiar part of your vocabulary. Fig. 1.10 relates them to a hypothetical situation in which they would be used. Table 1.5 shows the relationship of the earlier radiologic units to their SI equivalents.

In 1981 the International Commission on Radiation Units and Measurements issued standard units based on SI that have since been adopted by all countries except the United States. The NCRP and all US scientific and medical societies adopted the SI units by the early 1990s. It was not until 2017 that the American Registry of Radiologic Technologists (ARRT) adopted SI in their examination process.

Air Kerma (Kinetic Energy Released in Matter) (Gy_a). Air kerma is the kinetic energy transferred from photons to electrons during ionization and excitation. Air kerma is measured in joules per kilogram (J/kg), where 1 J/kg is 1 gray (Gy_a).

In keeping with the adoption of the Wagner/Archer method described in the preface, the SI unit of air kerma (mGy_a) is used to express radiation exposure.

> Air kerma (Gy_a) is the unit of radiation exposure.

Absorbed Dose (Gy_t). Biologic effects usually are related to the radiation absorbed dose (rad). Absorbed dose is the radiation energy absorbed per unit mass and has units of J/kg or Gy_t. The units Gy_a and Gy_t refer to radiation dose in air and tissue, respectively. For a given air kerma (radiation exposure), the absorbed dose depends on the type of tissue being irradiated. More about this is found in Chapters 9 and 37.

The gray (Gy_t) is the unit of **r**adiation **a**bsorbed **d**ose (rad).

The sievert (Sv) is the unit of occupational radiation exposure and effective dose.

Effective Dose: Sievert (Sv). Occupational radiation monitoring devices are analyzed in terms of sievert, which is used to express the quantity of radiation received by radiation workers and populations. The sievert also expresses a patient dose that accounts for partial-body irradiation.

Some types of radiation produce more damage than x-rays. The sievert accounts for these differences in biologic effectiveness. This is particularly important for persons working near nuclear reactors or particle accelerators. More about effective dose is discussed in Chapter 35.

Fig. 1.11 summarizes the conversion from the traditional units of occupational radiation exposure to SI units.

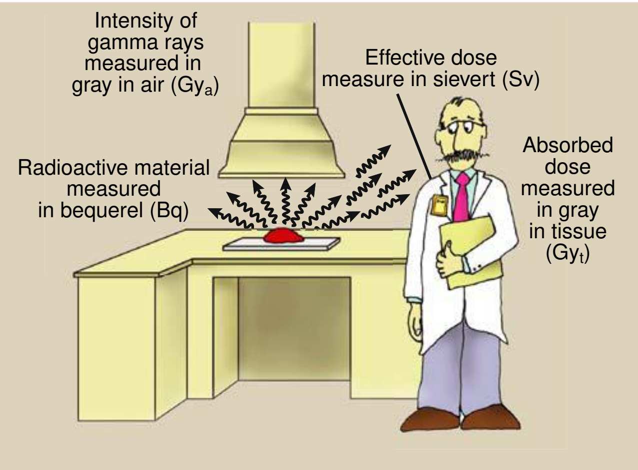


FIGURE 1.10 Radiation is emitted by radioactive material. The quantity of radioactive material is measured in becquerel. Radiation quantity is measured in gray or sievert, depending on the precise use.

Radioactivity: Becquerel (Bq). The becquerel is the unit of quantity of radioactive material, not the radiation emitted by that material. One becquerel is that quantity of radioactivity in which a nucleus disintegrates every second (1 d/s = 1 Bq). Megabecquerels (MBq) are common quantities of radioactive material. The traditional unit of radioactivity was the curie (Ci), where 1 Ci = 3.7 × 10^{10} Bq.

Radioactivity and the becquerel have nothing to do with x-rays.

The becquerel (Bq) is the unit of radioactivity.

Question: 0.05 μCi iodine-125 is used for radioimmunoassay. What is this radioactivity in becquerels?

Answer:
$$
\begin{aligned}
0.05\ \mu\text{Ci} &= 0.05\times10^{-6}\ \text{Ci}\\
&= (0.05\times10^{-6}\ \text{Ci})(3.7\times10^{10}\ \text{Bq/Ci})\\
&= 0.185\times10^{4}\ \text{Bq} = 1850\ \text{Bq}
\end{aligned}
$$

THE MEDICAL IMAGING TEAM

To become part of this exciting profession, a student must complete the prescribed academic courses, obtain clinical experience, and pass the national certification examination given by the ARRT. Both academic expertise and clinical skills are required of radiographers (Table 1.6).

Radiologic science programs accredited by the Joint Review Committee on Education in Radiologic

TABLE 1.5 Special Quantities of Radiologic Science and Their Associated Special Units

	CUSTOMARY UNIT			INTERNATIONAL SYSTEM OF UNITS (SI)	
Quantity	**Name**		**Symbol**	**Name**	**Symbol**
Exposure	Roentgen		R	air kerma	Gy_a
Absorbed dose	rad		rad	Gray	Gy_t
Effective dose	rem		rem	Sievert	Sv
Radioactivity	Curie		Ci	Becquerel	Bq
Multiply	R	by	0.01	to obtain	Gy_a
Multiply	rad	by	0.01	to obtain	Gy_t
Multiply	rem	by	0.01	to obtain	Sv
Multiply	Ci	by	3.7 × 10^{10}	to obtain	Bq

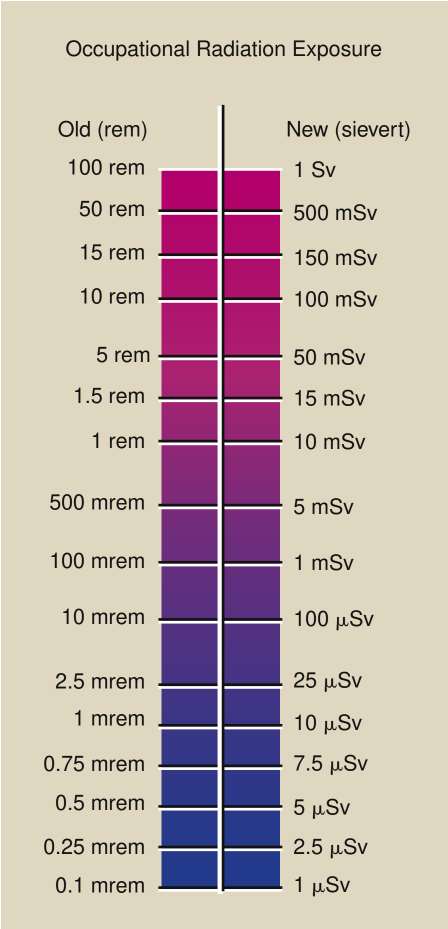


FIGURE 1.11 Scales for effective dose.

Technology (JRCERT) must follow a JRCERT-adopted curriculum. One such curriculum is the latest American Society of Radiologic Technologists (ASRT) Radiography Curriculum (www.asrt.org/docs/curriculum), which outlines a common body of knowledge is essential for entry-level radiographers.

The national certification examination for radiographers is administered by the ARRT. The primary purpose of ARRT examinations is to assess the knowledge and cognitive skills entry-level radiographers need to perform their jobs. The ARRT *Content Specifications for Radiography Examination* (www.asrt.org/docs/content-specification) outlines the topics covered on the exam. In addition, the ARRT Task Inventory (www.asrt.org/docs/task-inventory) lists the job responsibilities typically required of entry-level radiographers.

Every medical profession has a scope of practice which delineates parameters and identifies boundaries for their respected practice, and is formatted as lists of tasks appropriate as part of the work of the individual who is educated and clinically competent for that profession. The scope of practice for radiographers is outlined by the ASRT within the Radiography Practice Standards (www.asrt.org/docs/practice-standards). Additionally, federal and state laws and accreditation standards are necessary for participation in medical imaging as a radiologic technologist.

TABLE 1.6 Task Inventory for Radiography as Required for Examination by the American Registry of Radiologic Technologists

PATIENT CARE

1. Confirm the patient's identity.
2. Evaluate the patient's ability to understand and comply with requirements for the requested examination.
3. Explain and confirm the patient's preparation (e.g., dietary restrictions, preparatory medications) before performing radiographic and fluoroscopic examinations.
4. Examine radiographic requisition to verify accuracy and completeness of information (e.g., patient history, clinical diagnosis).
5. Sequence imaging procedures to avoid effects of residual contrast material on future examinations.
6. Maintain responsibility for medical equipment attached to patients (e.g., intravenous lines, oxygen) during radiographic procedures.
7. Provide for patient safety, comfort, and modesty.
8. Communicate scheduling delays to waiting patients.
9. Verify or obtain patient consent as necessary (e.g., with contrast studies).
10. Explain procedure instructions to the patient or the patient's family.
11. Practice standard precautions.
12. Follow appropriate procedures when in contact with a patient in isolation.
13. Select immobilization devices, when indicated, to prevent patient movement.
14. Use proper body mechanics or mechanical transfer devices when assisting patients.
15. Before administration of a contrast agent, gather information to determine the appropriate dosage and to discern whether patient is at increased risk for an adverse reaction.
16. Confirm type of contrast media to be used and prepare for administration.
17. Use sterile or aseptic technique when indicated.
18. Perform venipuncture.
19. Administer intravenous contrast media.
20. Observe patient after administration of contrast media to detect adverse reactions.
21. Obtain vital signs.
22. Recognize need for prompt medical attention and administer emergency care.
23. Explain postprocedural instructions to the patient or the patient's family.
24. Maintain confidentiality of the patient's information.
25. Document required information (e.g., radiographic requisitions, radiographs) on the patient's medical record.

TABLE 1.6 Task Inventory for Radiography as Required for Examination by the American Registry of Radiologic Technologists—cont'd

RADIATION PROTECTION

26. Clean, disinfect, or sterilize facilities and equipment and dispose of contaminated items in preparation for the next examination.
27. Evaluate the need for and use of protective shielding.
28. Take appropriate precautions to minimize radiation exposure to the patient.
29. Question female patient of childbearing age about possible pregnancy and take appropriate action (e.g., document response, contact physician).
30. Restrict the beam to limit the exposure area, improve image quality, and reduce radiation dose.
31. Set kVp, mA, and time or automatic exposure system to achieve optimum image quality, safe operating conditions, and minimum radiation dose.
32. Prevent all unnecessary persons from remaining in the area during x-ray exposure.
33. Take appropriate precaution to minimize occupational radiation exposure.
34. Wear a personnel radiation monitoring device while on duty.
35. Evaluate individual occupational exposure reports to determine whether values for the reporting period are within established limits.

EQUIPMENT OPERATION

36. Prepare and operate the radiographic unit and accessories.
37. Prepare and operate the fluoroscopy unit and accessories.
38. Prepare and operate specialized units.
39. Prepare and operate digital imaging devices.

IMAGE PRODUCTION

40. Remove from the patient or table all radiopaque materials that could interfere with the radiographic image.
41. Select appropriate equipment and accessories (e.g., grid, compensating filters, shielding) for the examination requested.
42. Use radiopaque markers to indicate anatomic side, position, or other relevant information (e.g., time, upright, decubitus, postvoid).
43. Explain breathing instructions before beginning the exposure.
44. Position the patient to demonstrate the desired anatomy with body landmarks.
45. Using calipers and technique charts, determine appropriate exposure factors.
46. Modify exposure factors for circumstances such as involuntary motion, casts and splints, pathologic conditions, and the patient's inability to cooperate.
47. Process exposed images.
48. Prepare the digital or computed image receptor for exposure.
49. Verify the accuracy of patient identification on radiography.
50. Evaluate radiographs for diagnostic quality.
51. Determine corrective measures that should be used if radiographs are not of diagnostic quality and take appropriate action.
52. Store and handle the film or cassette in a manner that will reduce the possibility of artifact production.

EQUIPMENT MAINTENANCE

53. Recognize and report malfunctions in the radiographic or fluoroscopic unit and accessories.
54. Perform basic evaluations of radiographic equipment and accessories.
55. Recognize and report malfunctions in processing equipment.
56. Perform basic evaluations of processing equipment and accessories.

RADIOGRAPHIC PROCEDURES

57. Position the patient, x-ray tube, and image receptor to produce diagnostic images of the following:
    a. Thorax
    b. Abdomen and gastrointestinal studies
    c. Urologic studies
    d. Spine and pelvis
    e. Cranium
    f. Extremities
    g. Other: arthrography, myelography, venography, and so on

SUMMARY

Radiology offers a career in many areas of medical imaging, and it requires knowledge of medicine, biology, and physics (radiologic science). This first chapter weaves the history and development of radiography with an introduction to medical physics.

Medical physics includes the study of matter, energy, and the electromagnetic spectrum of which x-rays are a part. The production of x-radiation and its safe, diagnostic use serve as the basis of medical imaging. As well as emphasizing the importance of radiation safety, this chapter presents a detailed list of clinical and patient care skills required of radiographers.

This chapter also introduces the various standards of measurement and applies them to concepts associated with several areas within radiologic science. The technical aspects of radiologic science require the identification and proper use of the units of radiation measurements.

CHALLENGE QUESTIONS

1. Define or otherwise identify the following:
   a. Energy
   b. Derived quantity
   c. Ionizing radiation
   d. Air kerma
   e. The average level of natural environmental radiation
   f. The Coolidge tube
   g. Fluoroscopy
   h. Acceleration
   i. The term applied to the chemistry of the body
   j. Barium platinocyanide
2. Match the following dates with the appropriate event:

a. 1901	1. Roentgen discovers x-rays.
b. 1907	2. Roentgen wins the first Nobel Prize in Physics.
c. 1913	3. The Snook transformer is developed.
d. 1895	4. The Coolidge hot-cathode x-ray tube is introduced.

3. Describe how weight is different from mass.
4. Name four examples of electromagnetic radiation.
5. How is x-ray interaction different from that seen in other types of electromagnetic radiation?
6. What is the purpose of x-ray beam filtration?
7. Describe the process that results in the formation of a negative ion and a positive ion.
8. What percentage of average radiation exposure to a human is attributable to medical imaging?
9. What is the velocity of the mobile x-ray imaging system if the hospital elevator travels 20 m to the next floor in 30 s?
10. A radiographer has a mass of 58 kg. What is her weight on Earth? On the moon?
11. The acronym ALARA stands for what?
12. Name devices designed to minimize radiation exposure to the patient and the operator.
13. Liquid hydrogen with a boiling temperature of 77 K is used to cool some superconducting magnets. What is this temperature in degrees Celsius? In degrees Fahrenheit?
14. What are the three natural sources of whole-body radiation exposure?
15. What naturally occurring radiation source is responsible for radiation dose to lung tissue?
16. How would you define the term "radiation"?
17. What are the four special quantities of radiation measurement?
18. Place the following in chronologic order of appearance:
    a. Digital fluoroscopy
    b. American Society of Radiologic Technologists (ASRT)
    c. Computed tomography (CT)
    d. Radiographic grids
    e. Automatic film processing
19. List five clinical skills required by the ARRT.
20. What are the three units common to the SI and MKS systems?

The answers to the Challenge Questions can be found by logging on to our website at http://evolve.elsevier.com.

CHAPTER

2

Basic Physics Primer

OBJECTIVES

At the completion of this chapter, the student should be able to do the following:

1. Perform mathematical problems using fractions, decimals, and exponents.
2. Determine significant digits in the answer to a mathematic problem.
3. Solve for the unknown (x) using the rules of algebra.
4. Identify scientific exponential notation and the associated prefixes.
5. Properly construct and interpret a graph.
6. Define base quantities, derived quantities, and special quantities used in radiologic science and their International System of Units (SI) of measure.
7. State Newton's three fundamental laws of motion.
8. Define the properties of mechanics.

OUTLINE

HAVING considered the historic events of the application of ionizing radiation in the form of x-rays this chapter examines the important characteristics of some basic physics concepts that impact your understanding of x-ray physics. In 1976, the US Congress passed the Metrification Act of America which gave us 20 years to abandon the traditional English units for the International System of Units (SI). We're still not there!

The instant an x-ray tube produces x-rays, all of the laws of physics are evident. The projectile electron from the cathode hits the target of the anode producing x-rays. Some x-rays interact with tissue, and other x-rays interact with the image receptor, forming an image. The physics of radiography deals with the production and interaction of x-rays.

Every field of science involves taking measurements, understanding them, and communicating them to others. This chapter presents a brief review of the mathematics essential to radiologic science and to the standard units of measurements all radiographers should use to ensure accuracy.

MATHEMATICS FOR RADIOLOGIC SCIENCE

Physics owes a great deal of its certainty to mathematics, and accordingly, most of the concepts of physics can be expressed mathematically. It is therefore important in the study of radiologic science to have a solid foundation in the basic concept of mathematics. The following sections review fundamental mathematics. You should become proficient at working each type of problem presented in this review.

Fractions

A fraction is a numeric value expressed by dividing one number by another. Such division results in the **quotient** of the two numbers. A fraction has a numerator and a denominator.

> Fraction = x/y = numerator/denominator = a value called the quotient

If the quotient of the numerator divided by the denominator is less than one, the value is a proper fraction. Improper fractions have values greater than one.

Question: Give examples of a proper fraction.
Answer: 1/2, 3/5, 5/7, 9/10
Question: Give examples of an improper fraction.
Answer: 3/2, 6/5, 10/7, 13/10

> **ADDITION AND SUBTRACTION**
> First, find a common denominator, then add or subtract.
> $x/y + a/b = xb/yb + ay/yb = (xb + ay)/yb$

Question: What is the value of $2/3 + 4/5$?
Answer: $2/3 + 4/5 = 10/15 + 12/15 = 22/15$, which is an improper fraction.
Question: What is the value of $4/5 - 2/3$?
Answer: $4/5 - 2/3 = 12/15 - 10/15 = 2/15$, which is a proper fraction.

> **MULTIPLICATION**
> To multiply fractions, simply multiply numerators and denominators.
> $x/y \times a/b = xa/yb$

Question: What is the value of $2/5 \times 7/4$?
Answer: $2/5 \times 7/4 = 14/20 = 7/10$, which is a proper fraction.
Question: What is the value of $9/8 \times 12/7$?
Answer: $9/8 \times 12/7 = 108/56 = 27/14$, which is an improper fraction, or 1 13/14, which is a proper fraction.

> **DIVISION**
> To divide fractions, invert the second fraction and multiply.
> $x/y \div a/b = x/y \times b/a = xb/ya$

Question: What is the value of $5/2 \div 7/4$?
Answer: $5/2 \div 7/4 = 5/2 \times 4/7 = 20/14 = 10/7$, which is an improper fraction, or 1 3/7, which is a proper fraction.
Question: What is the value of $3/10 \div 7/2$?
Answer: $3/10 \div 7/2 = 3/10 \times 2/7 = 6/70 = 3/35$, which is a proper fraction.

A special application of fractions in medical imaging is the ratio. Ratios express the mathematical relationship between similar quantities, such as feet to the mile or pounds to the kilogram.

Question: What is the ratio of feet to a mile?
Answer: There are 5280 feet in a mile; therefore the ratio is 5280 ft/mi.
Question: What is the ratio of the pound to the kilogram?
Answer: There are 2.2 pounds in a kilogram; therefore the ratio is 2.2 lb/kg

These ratios can also be used when converting units from one system to another. Dimensional analysis is a problem-solving technique that uses the fact that any quantity can be multiplied by one without changing its value.

Question: How many feet are in 81 miles?
Answer: 81 mi × 5280 ft/1 mi = 427,680 ft
Question: How many kilograms are in 185 pounds?
Answer: 185 lbs × 1 kg/2.2 lb = 84 kg

Decimals

Fractions in which the denominator is a power of 10 may easily be converted to decimals.

CONVERTING FRACTIONS TO DECIMALS

3/10 = 0.3
3/1000 = 0.003
161/10,000 = 0.0161
1527/10,000 = 0.1527

If the denominator is not a power of 10, the decimal equivalent can be found by division or with a calculator.

5/12 = (division process) = $12\overline{)5.000}$ = $0.41\overline{6}$

```
      0.416̄
12)5.000
   48
    20
    12
     80
     72
      8
```

The bar above the 6 indicates that this digit is repeating. When one divides 5 by 12 using a calculator, the answer is 0.416666.....

Rarely do we convert fractions to decimals without a calculator, computer, or smartphone. Depending on the calculator, it is simply a matter of keying numbers in the proper sequence.

Question: What is the decimal equivalent of the proper fraction 3/7?
Answer: 3/7 = 0.429
Question: What is the decimal equivalent of the improper fraction 123/69?
Answer: 123/69 = 1.78

Significant Figures

Students often wonder how many decimal places to report in an answer. For example, suppose you were asked to find the area of a circle.

Question: What is the area of a circle with a radius of 1.25 cm?
Answer:

$$A = \pi r^2$$
$$= (3.14)(1.25\ \text{cm})^2$$
$$= (3.14)(1.5625\ \text{cm})^2$$
$$= 4.90625\ \text{cm}^2$$

This answer is unsuitable because it implies much greater precision in the measurement of the area than we actually have. This result must be rounded off according to specific rules.

In addition and subtraction, round to the same number of decimal places as the entry with the least number of digits to the right of the decimal point.

Question: Add 5.0631, 117.2, and 21.42, and round off the answer.
Answer:

```
   5.0631
 117.2
+21.42
 143.6831
```

Because 117.2 has one digit to the right of the decimal point, the answer is 143.7.

Question: Solve the following and round off the answer. 42.83 – 7.6147
Answer:

```
 42.83
–7.6147
 35.2153
```

Because 42.83 has two digits, 83, to the right of the decimal point, the answer is 35.22.

> In multiplication and division, round to the same number of digits as the entry with the least number of significant digits.

Question: What is the product of 17.24 and 0.382?

Answer:

$$\begin{array}{r} 17.24 \\ \times\ 0.382 \\ \hline 6.58568 \end{array}$$

Because 0.382 has three significant digits (the zero is not significant) and 17.42 has four, the answer must have three digits. The answer is 6.59.

Question: How would you report the area of the circle discussed previously?

Answer: 4.91 cm^2

Question: What is the quotient of 3.1416 by 1.05?

Answer: $3.1416/1.05 = 2.992$

Because 1.05 has three significant digits (in this case, the zero is significant because it is followed by a number greater than zero) and 3.1416 five significant digits, the answer must have three digits. The answer is 2.99.

Algebra

Rules of algebra provide definite ways to manipulate fractions and equations to solve for unknown quantities. Usually, the unknowns are designated by an alphabetic symbol such as x, y, or z. Three principal rules of algebra are used in the solution of problems in medical imaging.

> When an unknown, x, is multiplied by a number, divide both sides of the equation by that number.
> $ax = c,\ ax/a = c/a,\ x = c/a$

Question: Solve the equation $5x = 10$ for x.

Answer:

$$5x = 10$$
$$5x/5 = 10/5$$
$$x = 2$$

> When numbers are added to an unknown, x, subtract that number from both sides of the equation.
> $xa = b,\ xa - a = b - a,\ x = b - a$

Question: Solve the equation $x + 7 = 10$.

Answer:

$$x + 7 - 7 = 10 - 7$$
$$x = 3$$

> When an equation is presented in the form of a proportion, cross-multiply and then solve for the unknown, x.
> $x/a = b/c,\ x/a \times b/c,\ cx = ab,\ x = ab/c$

The crossed arrows (×) show the direction of cross-multiplication.

Question: Solve the equation $x/5 = 3/8$.

Answer:

$$x/5 = 3/8$$
$$8x = 3 \times 5$$
$$8x = 15$$
$$8x/8 = 15/8$$
$$x = 17/8$$

Often, all three rules may be necessary to solve a particular problem.

Question: Solve $6x + 3 = 15$ for the value of x.

Answer:

$$6x + 3 = 15$$
$$6x + 3 - 3 = 15 - 3$$
$$6x = 12$$
$$6x/6 = 12/6$$
$$x = 2$$

Question: Solve $4/x = (3/4)^2$ for the value of x.

Answer:

$$4/x = (3/4)^2$$
$$4/x = 9/16$$
$$64 = 9x$$
$$9x = 64$$
$$9x/9 = 64/9$$
$$x = 7.1$$

Question: Solve $ABx + C = D$ for x.

Answer:

$$ABx + C = D$$
$$ABx + C - C = D - C$$
$$ABx = D - C$$
$$ABx/AB = (D - C)/AB\ \ x = (D - C)/AB$$

Note that the first and third of the previous examples are nearly identical in form. Symbols are often used in physics equations instead of numbers.

A special application of fractions and rules of algebra to medical imaging is the proportion. A proportion expresses the equality of two ratios. The ratio of a radiographic grid is directly proportional to the quotient of the height of the grid strips to the interspace between grid strips.

Question: If the grid height is 800 μm and the interspace 80 μm, what is the grid ratio?

Answer: 800 μm/80 μm = 10/1
The grid ratio = 10/1

Usually this is written 10:1 and is expressed as a "ten to one ratio grid."

The statement "gas mileage is inversely proportional to automobile weight" can be used as a numeric proportion to solve for an unknown quantity.

Question: A 1650-pound compact car gets 34 mpg. What is the expected mileage for a 3600-pound luxury car?

Answer: Set up the inverse proportion as follows: x/1650 lb = 34 mpg/3600 lb and use the rules for algebra to solve for x.
x = (34 mpg)(1650 lb)/3600 lb
x = 15.6 mpg

FIGURE 2.1 The probable origin of the decimal number system.

Radiation intensity is directly proportional to the mAs of a radiographic imaging system.

Question: At 50 mAs, the entrance skin exposure (ESE) is 2.4 mGy_a. What will be the ESE if the technique is increased to 60 mAs?

Answer: $x/60\ mAs = 2.4\ mGy_a/50\ mAs$
$x = (2.4\ mGy_a)(60\ mAs)/50\ mAs$
$x = 2.88\ mGy_a$

An understanding of algebraic relationships is important to many concepts in radiography. For directly proportional relationships, when one variable changes, the other variable changes in the same direction by the same factor. Given k is constant, A = kB, then if A doubles, B doubles. For directly related relationships, a change in one variable results in a change in the other variable in the same direction, but not by the same factor. When A increases, B increases but not by the same factor.

For inversely proportional relationships, when one variable changes, the other variable changes in the opposite direction by the reciprocal factor. Given k is constant, A = k/B, then if A doubles, B is halved. For inversely related relationships, a change in one variable results in a in a change in the other variable in the opposite direction, but not by the reciprocal factor. When A increases, B decreases but not by the reciprocal factor.

Number Systems

We use a system of numbers that is based on multiples of 10, called the **decimal system**. The origin of this decimal system is unknown, but theories have been proposed (Fig. 2.1). Numbers in this system can be represented in various ways, four of which are shown in Table 2.1.

TABLE 2.1 Various Ways to Represent Numbers in the Decimal System

Fractional Form	Decimal Form	Exponential Form	Logarithmic Form
10,000	10,000	10^4	4.000
1000	1000	10^3	3.000
100	100	10^2	2.000
10	10	10^1	1.000
1	1	10^0	0.000
1/10	0.1	10^{-1}	–1.000
1/100	0.01	10^{-2}	–2.000
1/1000	0.001	10^{-3}	–3.000
1/10,000	0.0001	10^{-4}	–4.000

The superscript on “10” in the exponential form of Table 2.1 is called the **exponent**. The exponential form, also referred to as scientific notation, is particularly useful in medical imaging.

Note that very large and very small numbers are difficult to write in decimal and fractional forms. In medical imaging, many numbers are very large or very small. Exponential form allows these numbers to be written and manipulated with relative ease.

To express a number in exponential form, first write the number in decimal form. If there are digits to the left of the decimal point, the exponent will be positive.

To determine the value of this positive exponent, position the decimal point after the first digit and count the number of digits the decimal point was moved. For example, the national debt of the United States was approximately $23 trillion on November 25, 2019.

To express this in scientific notation, we must position the decimal point after the first digit, 2, and count the number of digits that the decimal point was moved. The result of this exercise shows that the exponent will be +13.

United States national debt = \$22,602,942,644,871.49 = \$2.26 × 10^{13}

If there are no nonzero digits to the left of the decimal point, the exponent is found by positioning the decimal point to the right of the first nonzero digit and counting the number of digits the decimal point was moved.

A string on Robert Earl Keen’s guitar has a diameter of 0.00075 m. What is its diameter in exponential notation? First, position the decimal point between the 7 and the 5. Next, count the number of digits the decimal point has moved and express this quantity as a negative exponent.

0.00075 m = 7.5 × 10^{-4} m

Another example from physics is a number called **Planck's constant**, symbolized by **h**. Planck's constant is related to the energy of an x-ray. Its decimal form is as follows:

$$h = 0.000000000000000000000000000000000663 \text{ J s}$$

Obviously this form is too cumbersome to write each time. Thus Planck's constant is always written in exponential form:

$$h = 6.63 \times 10^{-34} \text{ J s}$$

Question: Express 4050 in exponential form.
Answer: $4050 = 4.05 \times 10^3$
Question: Express in exponential form: 1/2000.
Answer: First, convert to decimal form.
$1/2000 = 0.0005$
$0.0005 = 5 \times 10^{-4}$
Question: X-rays have a velocity of 300,000,000 m/s. Express this in exponential form.
Answer: $300{,}000{,}000 \text{ m/s} = 3 \times 10^8 \text{ m/s}$
Question: Dedicated chest x-ray imaging systems used to be installed with a 10-ft source-to-image receptor distance (SID). Express this in centimeters in exponential form.
Answer: $10 \text{ ft} \times 12 \text{ in/ft} \times 2.54 \text{ cm/in} = 304.8 \text{ cm}$
$304.8 \text{ cm} = 3.048 \text{ m} \times 10^2 \text{ cm}$

Actually, today's dedicated chest imaging systems are installed at a 3-m SID.

Rules for Exponents

Another advantage of handling numbers in exponential form is evident in operations other than addition and subtraction. The general rules for these types of numeric operations are shown in Table 2.2.

The following examples should sufficiently emphasize the principles involved. For multiplication, add the exponents.

Question: Simplify $10^6 \times 10^8$
Answer: $10^6 \times 10^8 = 10^{(6+8)} = 10^{14}$
Question: Simplify $2^8 \times 2^{12}$
Answer: $2^8 \times 2^{12} = 2^{(8+12)} = 2^{20}$

TABLE 2.2 Rules for Handling Numbers in Exponential Form

Operation	Rule	Example
Multiplication	$10^x \times 10^y = 10^{(x+y)}$	$10^2 \times 10^3 = 10^{(2+3)} = 10^5$
Division	$10^x / 10^y = 10^{(x-y)}$	$10^6 - 10^4 = 10^{(6-4)} = 10^2$
Raising to a Power	$(10^x)^y$	$(10^5)^3 = 10^{(5\times3)} = 10^{15}$
Inverse	$10^{-x} = 1/10^x$	$10^{-3} = 1/10^3 = 1/1000$
Unity	$10^0 = 1$	$3.7 \times 10^0 = 3.7$

For division, subtract the exponents.

Question: $10^{10}/10^2$
Answer: $10^{10}/10^2 = 10^{(10-2)} = 10^8$
Question: Simplify $2^3/3^5$
Answer: $2^3/3^5 = 2^{(3-5)} = 2^{-2} = 1/2^2 = 1/4$

To raise to a power, multiply the exponents.

Question: Simplify $(3 \times 10^{10})^2$
Answer: $(3 \times 10^{10})^2 = 3^2 \times (10^{10})^2$
$= 9 \times 10^{20}$
Question: Simplify $(2.718 \times 10^{-4})^3$
Answer: $(2.718 \times 10^{-4})^3 = 20.08 \times 10^{12}$
$= 2.008 \times 10^{-11}$

Note that the rules for exponents apply only when the numbers raised to a power are raised to the same power.

Question: Given $a = 6.62 \times 10^{-27}$, and $b = 3.766 \times 10^{12}$, what is $a \times b$?
Answer: $a \times b = (6.62 \times 10^{-27}) \times (3.766 \times 10^{12})$
$a \times b = (6.62 \times 3.766) \times 10^{-27} \times 10^{12}$
$= 24.931 \times 10^{(-27+12)}$
$= 24.93 \times 10^{-15}$
$= 2.49 \times 10^{-14}$

Graphing

Knowledge of graphing is essential to the study of radiologic science. It is important not only to be able to read information from graphs but to graph data obtained from measurements or observations.

Most graphs are based on two axes: a horizontal or x-axis and a vertical or y-axis. The point where the two axes meet is called the origin, labeled 0 in Fig. 2.2. Coordinates are points on a graph. Coordinates have

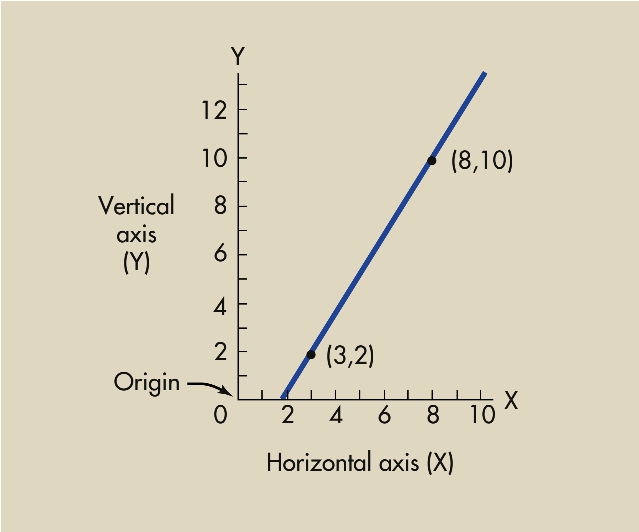


FIGURE 2.2 The principal features of any graph are x- and y-axes that intersect at the origin. Points of data are entered as ordered pairs.

the form of ordered pairs (x,y), where the first number of the pair represents a distance along the x-axis and the second number represents a distance up the y-axis.

The ordered pair (3,2) represents a point 3 units along the x-axis and 2 units up the y-axis. This point is plotted in Fig. 2.2. How does it differ from the point (2,3)? If the value of one additional ordered pair is known, say (8,10), a straight-line graph can be constructed.

In radiologic science, the axes of graphs are not usually labeled x and y. Usually, the relationship between two specific quantities is desired. Suppose, for example, that after a week of camping in the hill country west of Austin, Texas, you arrived home with enough caged opossums to conduct a radiation lethality experiment.

The results of your experimental opossum irradiation are given in Table 2.3. You now plot the percent radiation lethality as a function of radiation dose and that results in Fig. 2.3. You want to estimate the opossum $LD_{50/60}$, which is that dose of radiation which will kill half of the opossums, 50%, within 60 days.

TABLE 2.3 Observations of Opossum Response to Radiation Used to Estimate $LD_{50/60}$

Radiation Dose (Gy_t)	Number Irradiated	Number Dead	Percent Lethality
1.3	12	0	0
3.2	8	1	9
3.8	9	2	21
4.7	10	4	42
5.6	11	6	58
6.5	6	5	86
8.7	10	9	93
10.5	7	7	100

Question: Plot the data from Table 2.3 and estimate the opossum $LD_{50/60}$.

Answer: View Fig. 2.3, which shows the plot of the data from Table 2.3. Draw a horizontal line at the 50% lethality level and, when it intersects the smooth curve, drop down to the dose axis. The $LD_{50/60}$ for the opossums in this experiment is 5.1 Gy_t.

Usually, the data to be plotted are in exponential form and therefore extend over a very large range of values. In such situations, a linear scale is not adequate, and a logarithmic scale as shown in Fig. 2.4 must be used.

Radiologic data frequently require a graph that uses a semilogarithmic scale as shown in Fig. 2.5. The y-axis on a semilogarithmic scale is logarithmic and is used to accommodate a wide range of values. The x-axis is a linear scale.

Question: The following data were obtained to determine how much lead would be required to reduce x-ray intensity from 3.3 mGy_a to 0.1 mGy_a.

Answer: From the semilogarithmic plot of Fig. 2.5, it is easy to estimate the answer of 8.2 mm Pb. The linear plot is not so easy to interpret.

STANDARD UNITS OF MEASUREMENT

Physics is the study of interactions of matter and energy in all their diverse forms. Similar to all scientists, physicists strive for exactness or certainty in describing these interactions. They try to remove the uncertainties by eliminating subjective descriptions of events. Assuming that all measurements are made correctly, all observers who use the methods of physics will obtain exactly the same results.

In addition to seeking certainty, physicists strive for simplicity; therefore only three measurable quantities

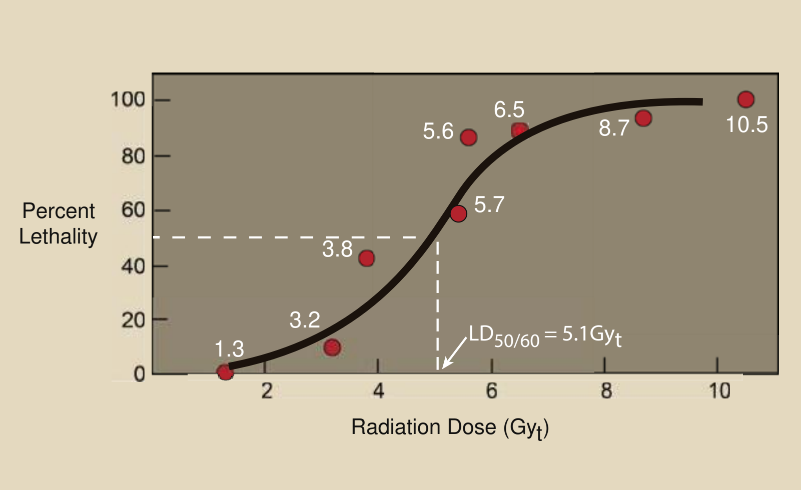


FIGURE 2.3 The data from Table 2.3 are plotted as percent opossum lethality as a function of radiation dose.

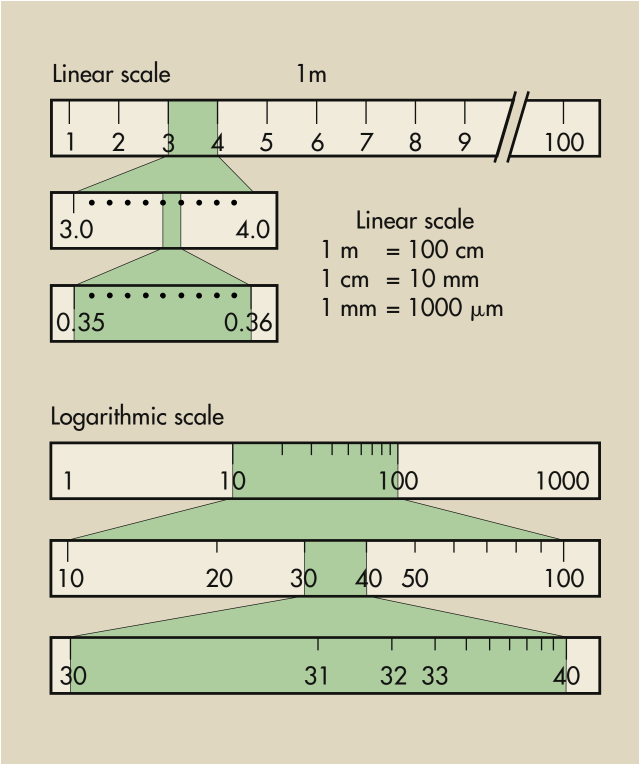


FIGURE 2.4 Equal lengths of linear scale have equal value. The logarithmic scale allows a large range of values to be plotted.

are considered basic. These **base quantities** are length, mass, and time, and they are the building blocks of all other quantities. Fig. 2.6 indicates the role these base quantities play in supporting some of the other quantities used in radiologic science.

The secondary quantities are called **derived quantities** because they are derived from a combination of one or more of the three base quantities. For example, volume is length cubed (l^3), mass density is mass divided by volume (m/l^3), and velocity is length divided by time (l/t).

Additional quantities are designed to support measurement in specialized areas of science and technology. These additional quantities are called **special quantities**. In radiologic science, special quantities are those of exposure, dose, effective dose, and radioactivity.

Whether a physicist is studying something large, such as the universe, or something small, such as an atom, meaningful measurements must be reproducible. Therefore, after the fundamental quantities have been established, it is essential that they be related to a well-defined and invariable standard. Standards are normally defined by international organizations and usually are redefined when the progress of science requires greater precision.

Length

For many years, the standard unit of length was accepted to be the distance between two lines engraved on a platinum-iridium bar kept at the International Bureau of Weights and Measures in Paris, France. This distance was defined to be exactly 1 m. The English-speaking countries also base their standards of length on the meter.

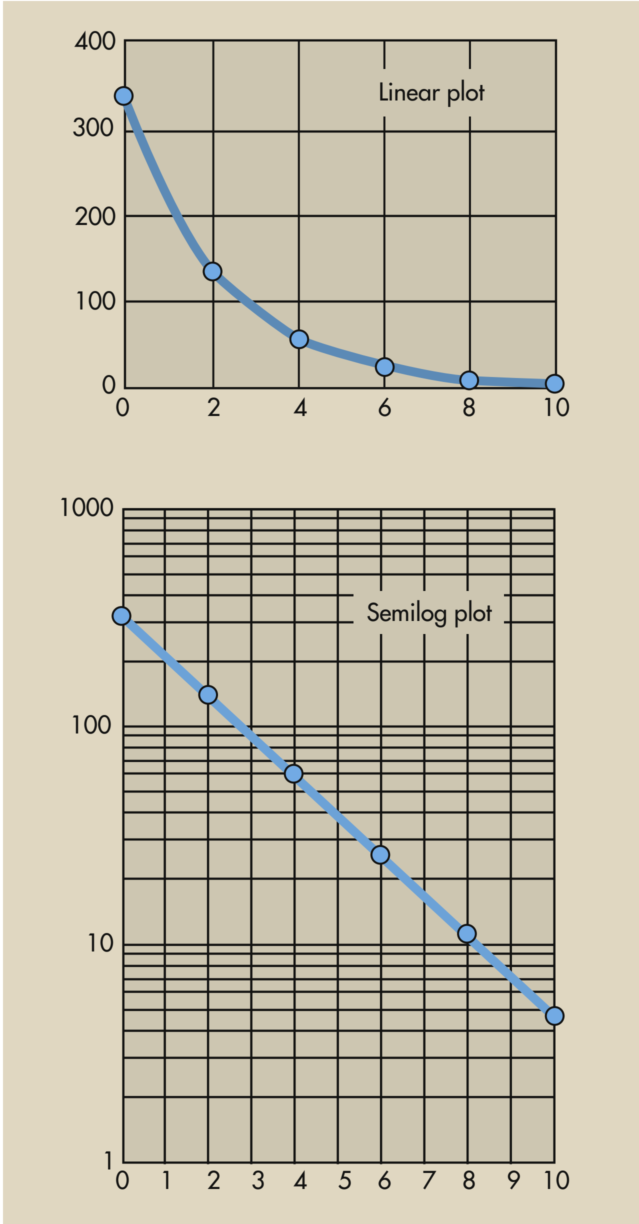


FIGURE 2.5 Semilogarithmic graph paper is often used to plot radiologic data.

In 1960, the need for a more accurate standard of length led to redefinition of the meter in terms of the wavelength of orange light emitted from an isotope of krypton (krypton-86). One meter is now defined as the distance traveled by light in 1/299,792,468 second.

Mass

The kilogram was originally defined to be the mass of 1000 cm^3 of water at 4° Celsius (°C). In the same

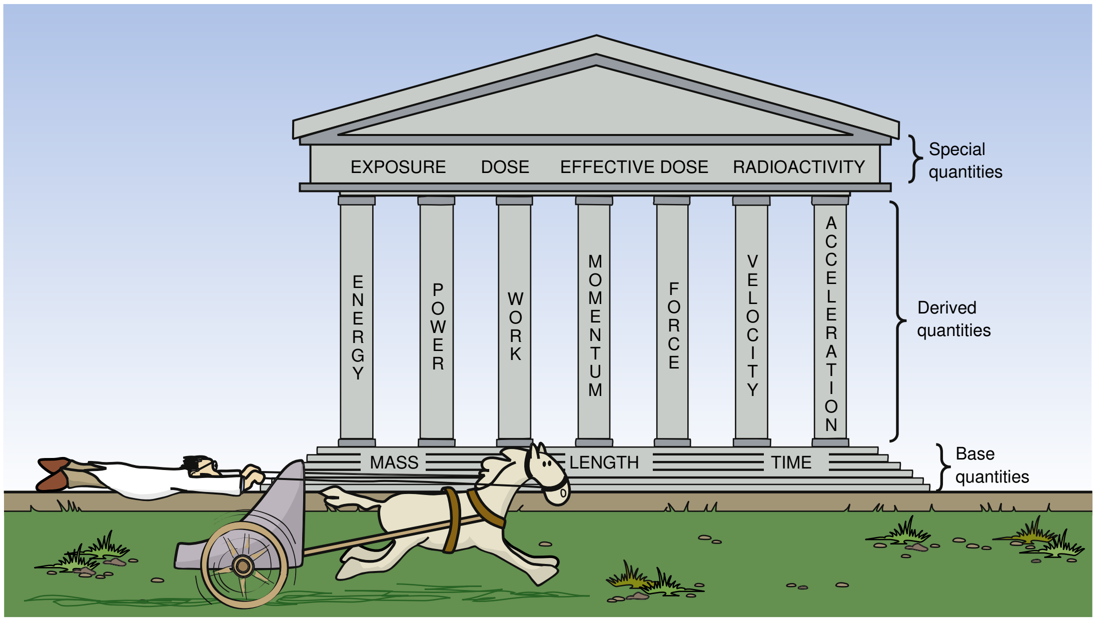


FIGURE 2.6 Base quantities support derived quantities, which in turn support the special quantities of radiologic science.

vault in Paris where the standard meter was kept, a platinum-iridium cylinder represents the standard unit of mass—the **kilogram (kg),** which has the same mass as 1000 cm^3 of water. The kilogram is a unit of mass, and the **newton** and the **pound,** a British unit, are units of weight.

Time

The standard unit of time is the **second** (s). Originally, the second was defined in terms of the rotation of the Earth on its axis—the mean solar day. In 1956, it was redefined as a certain fraction of the tropical year 1900. In 1964, the need for a better standard of time led to another redefinition.

Now, time is measured by an atomic clock and is based on the vibration of cesium atoms. The atomic clock is capable of keeping time correctly to approximately 1 second in 5000 years.

> The second (s) is based on the vibration of atoms of cesium.

Units

Every measurement has two parts: a **magnitude** and a **unit.** For example, the SID is 100 cm. The magnitude, 100, is not meaningful unless a unit is also designated. Here, the unit of measurement is the centimeter.

Table 2.4 shows four **systems of units** that represent base quantities. The SI (Le Système International d'Unités), an extension of the MKS (meters, kilograms, and seconds) system, represents the current state of units. SI includes the three base units of the MKS system plus an additional four. Derived units and special units of SI represent derived quantities and special quantities of radiologic science (Table 2.5).

> The same system of units must always be used when one is working on problems or reporting answers.

The following would be unacceptable because of inconsistent units: mass density = 8.1 g/ft^3 and pressure = 700 lb/cm^2.

Mass density should be reported with units of kilograms per cubic meter (kg/m^3). Pressure should be given in newtons per square meter (N/m^2).

Question: The dimensions of a box are 30 cm × 86 cm × 4.2 m. Find the volume.

Answer: Formula for the volume of an object:
V = length × width × height or V = lwh
However, because the dimensions are given in different systems of units, we must choose only one system. Therefore V = (0.3 m) (0.86 m) (4.2 m) = 1.1 m^3

Note that the units are multiplied also: m × m × m = m^3.

Table 2.4 System of Units

	International System (SI)[a]	System of Meters, Kilograms, and Seconds	System of Centimeters, Grams, and Seconds	British
Length	Meter (m)	Meter (m)	Centimeter (cm)	Foot (ft)
Mass	Kilogram (kg)	Kilogram (kg)	Gram (g)	Pound (lb)[b]
Time	Second (s)	Second (s)	Second (s)	Second (s)

[a] The SI includes four additional base units.
[b] The pound is actually a unit of force that is related to mass.

Table 2.5 Special Quantities of Radiologic Science and Their Units

Radiographic Quantities	Special Units	International System (SI) Units
Exposure	C/kg	Air kerma (Gy_a)
Dose	J/kg	$Gray_t$ (Gy_t)
Effective Dose	J/kg	Sievert (Sv)
Radioactivity	s^{-1}	Becquerel (Bq)

Question: Find the mass density of a solid box 10 cm on each side with a mass of 0.4 kg.

Answer: D = mass/volume (change 10 cm to 0.1 m)

$$= 0.4\ \text{kg}/(0.1\ \text{m} \times 0.1\ \text{m} \times 0.1\ \text{m})$$
$$= 0.4\ \text{kg}/0.001\ \text{m}^3$$
$$= 400\ \text{kg/m}^3$$

Question: A 9-inch-thick patient has a coin placed on the skin. The source-to-image receptor distance (SID) is 100 cm. What will be the magnification of the coin?

Answer: The formula for magnification is:

$$M = \frac{SID}{SOD} = \frac{\text{source-to-image receptor distance}}{\text{source-to-object distance}}$$

$$M = \frac{SID}{SOD} = \frac{100\ \text{cm}}{100\ \text{cm} - 9\ \text{in}}$$

The 9 inches must be converted to centimeters so that units are consistent.

$$M = \frac{SID}{SOD} = \frac{100\ \text{cm}}{100\ \text{cm} - (9\ \text{in} \times 2.54\ \text{cm/in})}$$
$$= \frac{100\ \text{cm}}{100\ \text{cm} - (23\ \text{cm})}$$
$$= \frac{100\ \text{cm}}{77\ \text{cm}}$$
$$= 1.3\ \text{cm}$$
$$M = 1.3$$

The image of the coin will be 1.3 times the size of the coin.

MECHANICS

Mechanics is a segment of physics that deals with objects at rest and objects in motion. Objects at rest are static. Objects in motion are dynamic.

Velocity

The motion of an object can be described with the use of two terms: **velocity** and **acceleration.** Velocity, sometimes called speed, is a measure of how fast something is moving or, more precisely, the rate of change of its position with time.

The velocity of a car is measured in kilometers per hour (miles per hour). Units of velocity in SI are meters per second (m/s). The equation for velocity (v) is as follows:

VELOCITY

$$v = \frac{d}{t}$$

where *d* represents the distance traveled in time, *t*.

Question: What is the velocity of a ball that travels 60 m in 4 s?

Answer:

$$v = \frac{d}{t}$$
$$v = 60\ \text{m}/4\ \text{s},$$
$$v = 15\ \text{m/s}$$

Question: Light is capable of traveling 669 million miles in 1 hour. What is its velocity in SI units?

Answer:

$$v = \frac{d}{t}$$
$$= \frac{6.69 \times 10^8\ \text{mi}}{\text{h}} \times \frac{1609\ \text{m/mi}}{3600\ \text{s/h}}$$
$$= 2.99 \times 10^8\ \text{m/s}$$

Often, the velocity of an object changes as its position changes. For example, a dragster at the Charlotte Motor Speedway starts from rest and finishes with a velocity of 80 m/s. The **initial velocity,** designated by v_o, is 0 (Fig. 2.7). The **final velocity,** represented by v_f, is

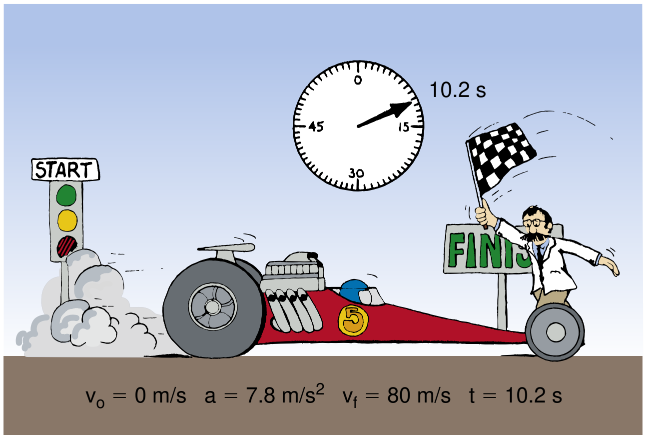


FIGURE 2.7 Drag racing provides a familiar example of the relationships among initial velocity, final velocity, acceleration, and time.

80 m/s. The **average velocity** can be calculated from the following expression:

> **AVERAGE VELOCITY**
>
> $$\bar{v} = \frac{v_o + v_f}{2}$$
>
> where the bar over the v represents average velocity.

Question: What is the average velocity of the dragster?

Answer:

$$\bar{v} = \frac{0\,\frac{m}{s} + \frac{80\ m}{s}}{2}$$

$$= 40\ m/s$$

> The velocity of light is constant and is symbolized by c: c = 3 × 10^8 m/s.

Acceleration

The rate of change of velocity with time is **acceleration.** It is how "quickly or slowly" the velocity is changing. Because acceleration is velocity divided by time, the unit is meters per second squared (m/s^2).

If velocity is constant, acceleration is zero. On the other hand, a constant acceleration of 2 m/s^2 means that the velocity of an object increased by 2 m/s each second. The defining equation for acceleration is given by the following:

> **ACCELERATION**
>
> $$a = \frac{v_f - v_o}{t}$$

Question: What is the acceleration of the dragster?

Answer:

$$a = \frac{80\ m/s - 0\ m/s}{10.2\ s}$$

$$= 7.8\ m/s^2$$

Newton's Laws of Motion

In 1686, the English scientist Isaac Newton presented three principles that even today are recognized as **fundamental laws of motion.**

> Newton's first law: Inertia—A body will remain at rest or will continue to move with constant velocity in a straight line unless acted on by an external force.

Newton's first law states that if no force acts on an object, there will be no acceleration. The property of matter that acts to resist a change in its state of motion is called **inertia.** Newton's first law is thus often referred to as the law of inertia (Fig. 2.8). A mobile x-ray imaging system obviously will not move until forced by a push. Once in motion, however, it will continue to move forever, even when the

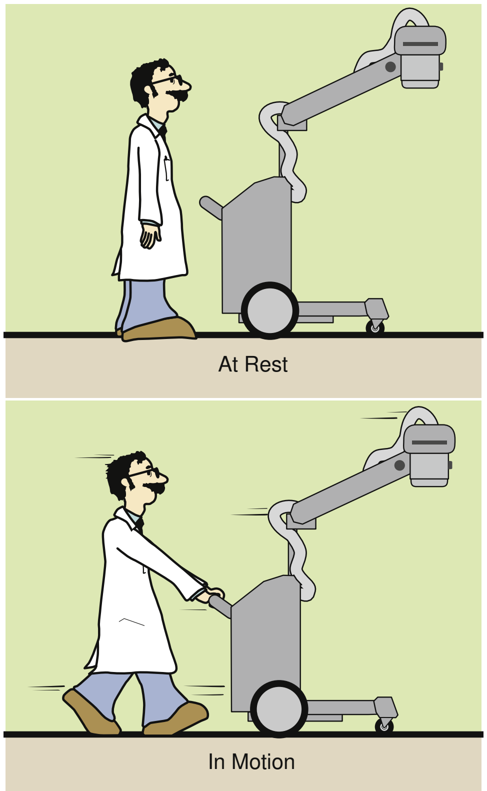


FIGURE 2.8 Newton's first law states that a body at rest will remain at rest and a body in motion will continue in motion until acted on by an outside force.

pushing force is removed, unless an opposing force is present—friction.

> Newton's second law: Force—The force (F) that acts on an object is equal to the mass (m) of the object multiplied by the acceleration (a) produced.

Newton's second law is a definition of the concept of **force.** Force can be thought of as a push or pull on an object. If a body of mass **m** has an acceleration **a**, then the force on it is given by the mass times the acceleration. Newton's second law is illustrated in Fig. 2.9. Mathematically, this law can be expressed as follows:

> **FORCE**
> F = ma
> The SI unit of force is the newton (N).

Question: Find the force on a 55-kg mass accelerated at 14 m/s^2.
Answer: F = ma
(55 kg)(14 m/s^2) = 770 N
Question: For a 3600-lb (1636-kg) Ford Mustang to accelerate at 15 m/s^2, what force is required?
Answer: F = ma
(1636 kg)(15 m/s^2) = 24,540 N

Newton's third law of motion states that **for every action, there is an equal and opposite reaction.** Action was Newton's word for force. According to this law, if you push on a heavy block, the block will push back on you with the same force that you apply. On the other hand, if you were the physics professor illustrated in Fig. 2.10, whose crazed students had tricked him into the clamp room, no matter how hard you pushed, the walls would continue to close.

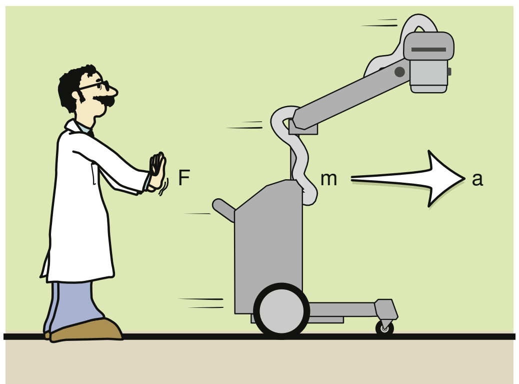


FIGURE 2.9 Newton's second law states that the force applied to move an object is equal to the mass of the object multiplied by the acceleration.

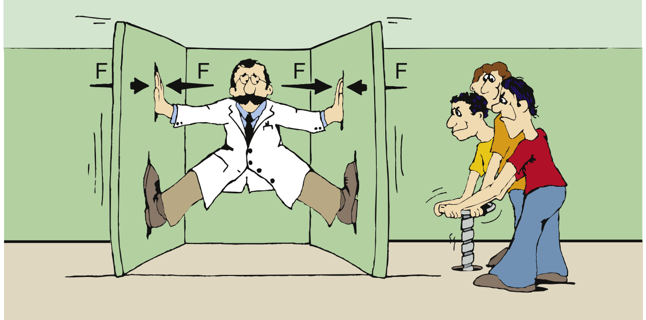


FIGURE 2.10 Crazed student technologists performing a routine physics experiment to prove Newton's third law.

> Newton's third law: Action/reaction—For every action, there is an equal and opposite reaction.

Weight

Weight (Wt) is a force on a body caused by the pull of gravity on it. Experiments have shown that objects that fall to Earth accelerate at a constant rate. This rate, termed the **acceleration due to gravity** and represented by the symbol g, is 9.8 m/s^2 on Earth and 1.6 m/s^2 on the moon.

Weightlessness observed in outer space is attributable to the absence of gravity. Thus the value of gravity in outer space is zero. The weight of an object is equal to the product of its mass and the acceleration of gravity.

Question: A student radiographer has a mass of 75 kg. What is her weight on Earth? On the moon?
Answer: Earth: g = 9.8 m/s^2
Wt = mg
= 75 kg (9.8 m/s^2)
= 735 N
Moon: g = 1.6 m/s^2
Wt = mg
= 75 kg (1.6 m/s^2)
= 120 N

> **WEIGHT**
> Wt = mg
> Weight is the product of mass and the acceleration of gravity on Earth: 1 lb = 4.5 N.
> The unit of weight is the same as that for force, the newton (N).

This example displays an important concept. The weight of an object can vary according to the value of gravity acting on it. However, note that the mass of an object does not change, regardless of its location. The student's 75-kg mass remains the same on Earth, on the moon, or in space.

Momentum

The product of the mass of an object and its velocity is called **momentum,** represented by **p**. The greater the velocity of an object, the more momentum the object possesses. For example, a truck accelerating down a hill gains momentum as its velocity increases.

> **MOMENTUM**
> p = mv
> Momentum is the product of mass and velocity.

The total momentum before any interaction is equal to the total momentum after the interaction. Imagine a billiard ball colliding with two other balls at rest (Fig. 2.11). The total momentum before the collision is the mass times the velocity of the cue ball. After the collision, this momentum is shared by the three balls. Thus the original momentum of the cue ball is conserved after the interaction.

Work

Work, as used in physics, has specific meaning. The work done on an object is the force applied to that object times the distance over which it is applied. In mathematical terms, the unit of work is the joule (J). When you lift an image receptor, you are doing work. However, when the image receptor is merely held motionless, no work (in the physics sense) is being performed, even though considerable effort is being expended.

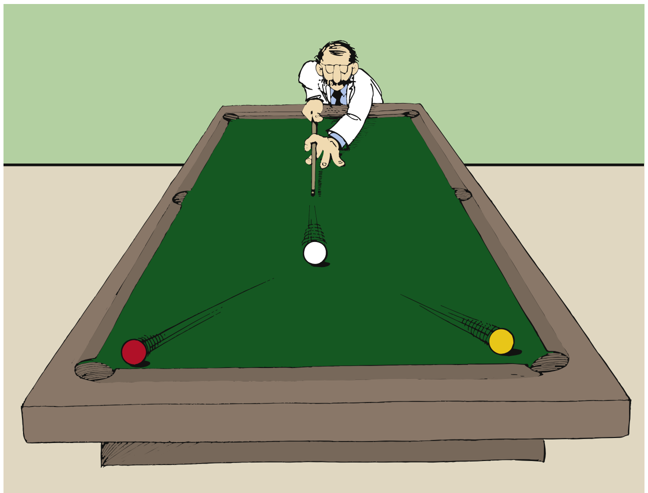


FIGURE 2.11 The conservation of momentum occurs with every billiard shot.

> **WORK**
> W = Fd
> Work is the product of force and distance.

Question: Find the work done in lifting an infant patient weighing 90 N (20 lb) to a height of 1.5 m.

Answer:
$$\text{Work} = Fd = (90\ \text{N})(1.5\ \text{m}) = 135\ \text{J}$$

Power

Power is the rate of doing work. The same amount of work is required to lift an image receptor to a given height, whether it takes 1 second or 1 minute to do so. Power gives us a way to include the time required to perform the work.

> **POWER**
> P = Work/t = Fd/t
> Power is the quotient of work by time.

The SI unit of power is the joule/second (J/s), which is a **watt (W).** The British unit of power is the **horsepower (hp).**

$$1\ \text{hp} = 746\ \text{W}$$
$$1000\ \text{W} = 1\ \text{kilowatt (kW)}$$

Question: A radiographer lifts a 0.8-kg image receptor from the floor to the top of a 1.5-m table with an acceleration of 3 m/s^2. What is the power exerted if it takes 1.0 s?

Answer: This is a multistep problem. We know that P = work/t; however, the value of work is not given in the problem. Recall that work = Fd and F = ma. First, find F.

$$F = ma = (0.8\ \text{kg})(3\ \text{m/s}^2) = 2.4\ \text{N}$$

Next, find work:

$$\text{Work} = Fd = (2.4\ \text{N})(1.5\ \text{m}) = 3.6\ \text{J}$$

Now, P can be determined:

$$P = \text{Work}/t = 3.6\ \text{J}/1.0\ \text{s} = 3.6\ \text{W}$$

Energy

There are many forms of energy, as previously discussed. The law of conservation of energy states that **energy may be transformed from one form to another, but it cannot be created or destroyed.** The total amount of energy is constant. For example, electrical energy is converted into light energy and heat energy in an electric light bulb. The unit of energy and of work is the same, the joule.

> Energy is the ability to do work.

Two forms of mechanical energy often are used in radiologic science: kinetic energy and potential energy. **Kinetic energy** is the energy associated with the motion of an object as expressed by the following:

> **KINETIC ENERGY**
>
> $KE = \frac{1}{2}mv^2$
>
> Kinetic energy depends on the mass of the object and on the square of its velocity.

Question: Consider two rodeo chuck wagons, A and B, with the same mass. If B has twice the velocity of A, verify that the kinetic energy of chuck wagon B is four times that of chuck wagon A.

Answer: Chuck wagon A: $KE_A = \frac{1}{2}mv_A{}^2$

Chuck wagon B: $KE_B = \frac{1}{2}mv_B{}^2$

However, $m_A = m_B$, $v_B = 2v_A$

Therefore, $KE_B = \frac{1}{2}m_A(2v_A)^2$

$= \frac{1}{2}m_A(4v_A{}^2)$

$KE_B = 2mv_A{}^2$

$= 4\left(\frac{1}{2}MV_A{}^2\right)$

$= 4\ KE_A$

Potential energy is the stored energy of position or configuration. A textbook on a desk has potential energy because of its height above the floor … and the potential for a better job if it is read. It has the ability to do work by falling to the ground. Gravitational potential energy is given by the following:

> **POTENTIAL ENERGY**
>
> $PE = mgh$
>
> where *h* is the distance above the Earth's surface.

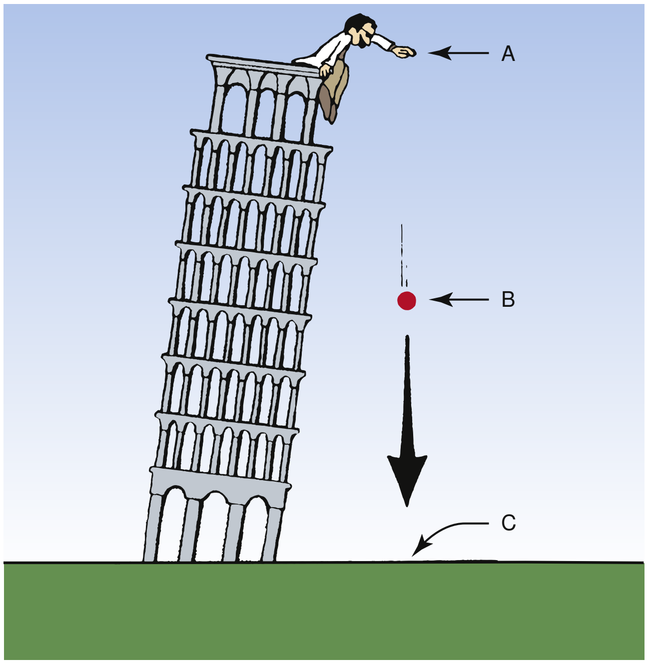


FIGURE 2.12 Potential energy results from the position of an object. Kinetic energy is the energy of motion. (A) Maximum potential energy, no kinetic energy. (B) Potential energy and kinetic energy. (C) Maximum kinetic energy, no potential energy.

A skier at the top of a jump, a coiled spring, and a stretched rubber band are examples of other systems that have potential energy because of their position or configuration.

If a scientist held a ball in the air atop the Leaning Tower of Pisa (Fig. 2.12), the ball would have only potential energy, no kinetic energy. When it is released and begins to fall, the potential energy decreases as the height decreases. At the same time, the kinetic energy is increasing as the ball accelerates. Just before impact, the kinetic energy of the ball becomes maximum as its velocity reaches maximum. Because it now has no height, the potential energy becomes zero. All the initial potential energy of the ball has been converted into kinetic energy during the fall.

Question: A radiographer holds a 6-kg x-ray tube 1.5 m above the ground. What is its potential energy?

Answer: Potential energy = mgh

$= 6\ kg \times 9.8\ m/s^2 \times 1.5\ m$

$= 88\ kg\ m^2/s^2$

$= 88\ J$

Table 2.6 presents a summary of the quantities and units in mechanics.

Heat

Heat is a form of energy that is very important to radiologic technologists. Excessive heat, a deadly enemy of an x-ray tube, can cause permanent damage. For this reason, the technologist should be aware of the properties of heat.

TABLE 2.6 Summary of Quantities, Equations, and Units Used in Mechanics

Quantity	Symbol	Defining Equation	International System (SI)
Velocity	V	v = d/t	m/s
Average velocity	$\bar{v}$	$\bar{v} = \frac{v_o + v_f}{2}$	m/s
Acceleration	a	$a = \frac{v_f + v_o}{t}$	m/s^2
Force	F	F = ma	N
Weight	Wt	Wt = mg	N
Momentum	p	p = mv	kg-m/s
Work	W	W = Fd	J
Power	P	P = W/t	W
Kinetic energy	KE	KE = ½ mv^2	J
Potential energy	PE	PE = mgh	J

Heat is the kinetic energy of the random motion of molecules.

The more rapid and disordered the motion of molecules, the more heat an object contains. The unit of heat, the **calorie,** is defined as the heat necessary to raise the temperature of 1 g of water by 1°C. The same amount of heat will have different effects on different materials. For example, the heat required to change the temperature of 1 g of silver by 1°C is approximately 0.05 calorie, or only that required for a similar temperature change in water.

Heat is transferred from one location to another by conduction, convection and radiation.

Conduction is the transfer of heat through a material or by touching. Molecular motion from a high-temperature object that touches a lower-temperature object equalizes the temperature of both.

Conduction is easily observed when a hot object and a cold object are placed in contact. After a short time, heat conducted to the cooler object results in equal temperatures of the two objects. Heat is conducted from an x-ray tube anode through the rotor to the insulating oil.

Convection is the mechanical transfer of "hot" molecules in a gas or liquid from one place to another. A steam radiator or forced-air furnace warms a room by convection. The air around the radiator is heated, causing it to rise, while cooler air circulates in and takes its place.

Thermal radiation is the transfer of heat by the emission of **infrared radiation.** The reddish glow emitted by hot objects is evidence of heat transfer by radiation. An x-ray tube cools primarily by radiation.

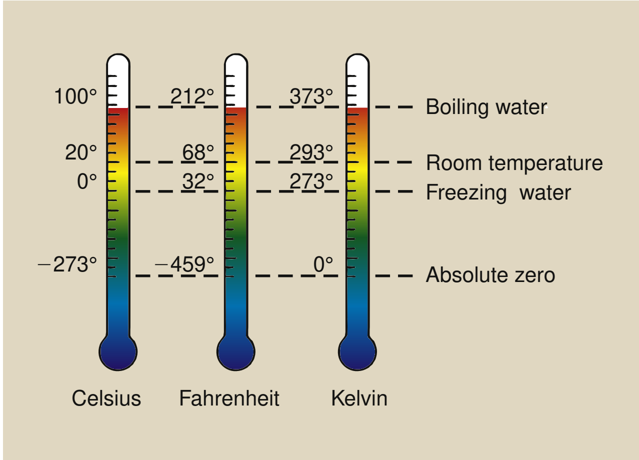


FIGURE 2.13 Three scales are used to represent temperature. Celsius is the adopted scale for weather reporting everywhere except the United States. Kelvin is the scientific scale.

A forced-air furnace blows heated air into the room, providing forced circulation to complement the natural convection. Heat is convected from the housing of an x-ray tube to air.

Temperature normally is measured with a thermometer. A thermometer is usually calibrated at two reference points—the freezing and boiling points of water. The three scales that have been developed to measure temperature are Celsius (°C), Fahrenheit (°F), and Kelvin (K) (Fig. 2.13).

These scales are interrelated as follows:

TEMPERATURE SCALES

$$T_C = \frac{5}{9}(T_F - 32)$$

$$T_F = \frac{9}{2}T_C + 32$$

$$T_K = T_C + 273$$

(T_F = 9/5 ….)

The subscripts *C, F,* and *K* refer to Celsius, Fahrenheit, and Kelvin, respectively.

Question: Convert 77°F to degrees Celsius.

Answer:

$$T_c = \frac{5}{9}(T_f - 32)$$

$$= \frac{5}{9}(77 - 32)$$

$$= \frac{5}{9}(45) = 25°C$$

One can use the following for easy, approximate conversion:

APPROXIMATE TEMPERATURE CONVERSION

From °F to °C, subtract 30 and divide by 2.

From °C to °F, double and then add 30.

Magnetic resonance imaging with a superconducting magnet requires extremely cold liquids called **cryogens.** Liquid nitrogen, which boils at 77K, and liquid helium, which boils at 4K, are the two cryogens that are used.

Question: Liquid helium is used to cool superconducting wire in magnetic resonance imaging (MRI) systems. What is its temperature in degrees Fahrenheit?

Answer:

$$T_k = T_c + 273$$
$$T_c = T_k - 273$$
$$T_c = 4 - 273$$
$$T_c = -269°C$$
$$T_f = 9/5\ T_c + 32$$
$$T_f = -484 + 32$$
$$T_f = -452°F$$

The relationship between temperature and energy is often represented by an energy thermometer (Fig. 2.14). We consider x-rays to be energetic, although on the cosmic scale, they are rather ordinary.

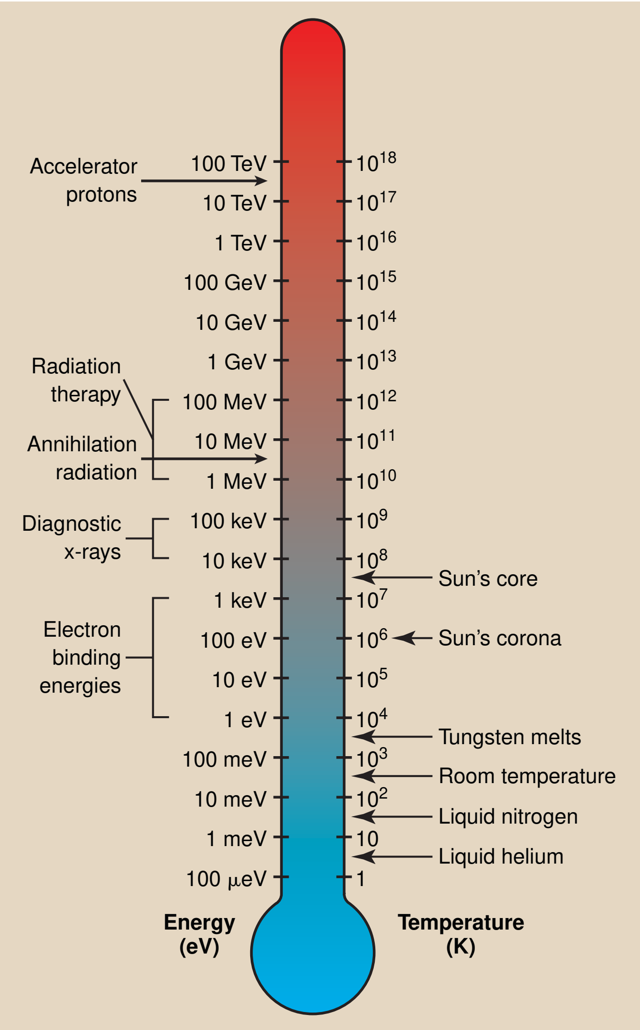


FIGURE 2.14 The energy thermometer scales temperature and energy together.

SUMMARY

This chapter introduces primary mathematics, physics, and standards of measurement as necessary for radiologic science.

Basic algebra and the use of fractions, decimals, and significant figures is presented. The various number systems are introduced, as well as the rules for significant figures and exponents. Graphing as it is required for radiologic science is illustrated.

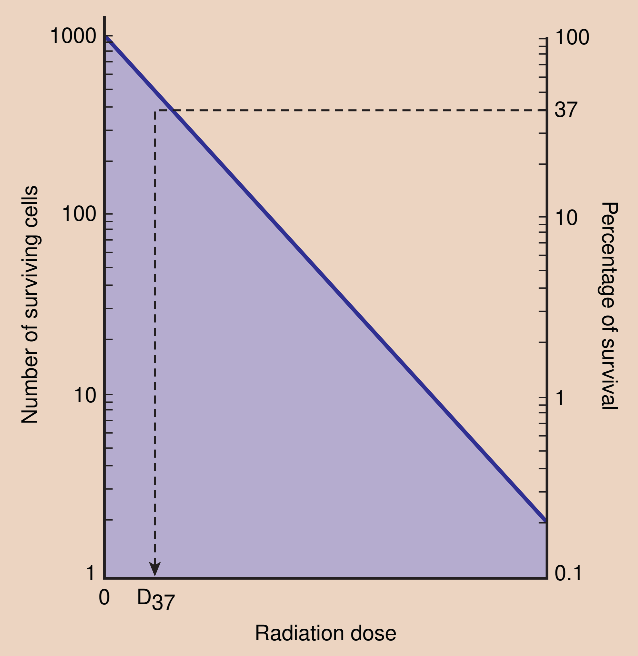
Mass, length, and time are the basic units of physics, and it is shown here how these units are used to describe the special units of radiologic science.

Newton's laws of motion are described as they relate to medical imaging. Newton was first to properly describe the concepts of mechanics each of which are discussed here.

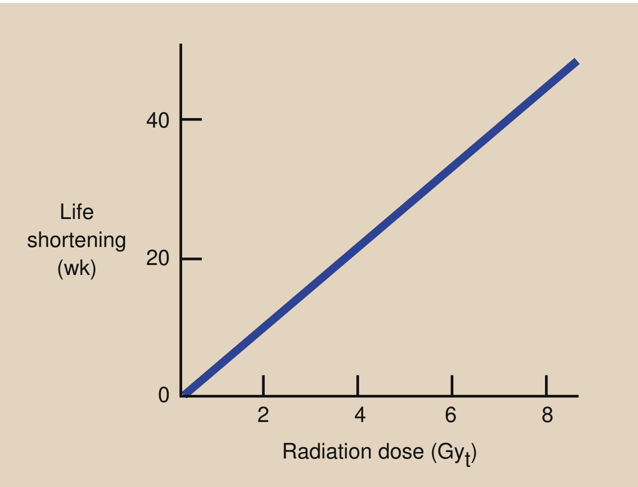
CHALLENGE QUESTIONS

1. Perform the following mathematic problems with fractions. Express each answer in a proper fraction.
   a. 1/2 + 2/3 =
   b. 7/8 − 1/4 =
   c. 1/6 × 1/2 =
   d. 3/4 ÷ 1/8 =
2. Using the ratio 2.54 cm/in, convert 72 into cm. Round the answer to the correct number of significant digits.
3. Convert the following fractions to decimals.
   a. 3/10
   b. 53/100
   c. 40/1000
4. Perform the following mathematic problems with decimals. Round each answer to the correct number of significant digits.
   a. 3.0045 + 2.25 + 8.002 =
   b. 124.78 − 6.5 =
   c. 3.14 × 0.0115 =
   d. 75.25 ÷ 3.11 =
5. Solve using the rules of algebra.
   a. Given: mA × time in seconds = mAs
      200 mA × _____ seconds = 8 mAs
   b. $\frac{x}{877\ \mu Gy_a} = \frac{200\ mAs}{400\ mAs}$
   c. Given grid ratio = $\frac{\text{height of lead strips}}{\text{interspace between lead strips}}$

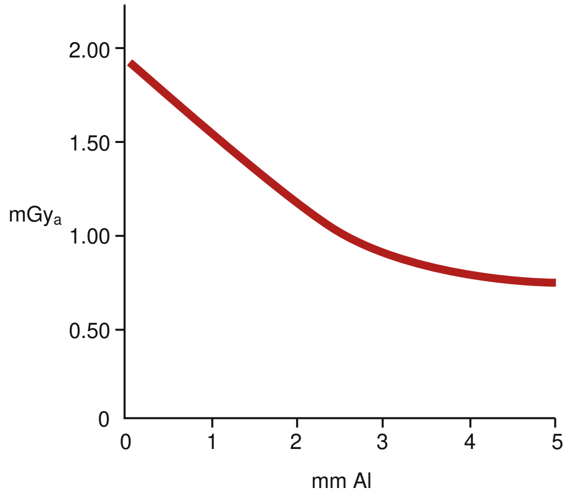
   If the lead strip height of a given grid is 2 mm and the interspace distance is 0.25 mm, what is the grid ratio?
6. Convert to exponential form.
   a. 625,000,000
   b. 820
   c. 5/1000
   d. 0.000125



7. In the dose-response graph above, showing the results of the irradiation of 1000 cells, the y-axis is a ______________________________ (linear, logarithmic) scale.
8. The dose-response graph above demonstrates a(n) ______________________________ (inverse, direct) relationship between radiation dose and the number of surviving cells.



9. In the previous dose-response graph, showing the results of life shortening after chronic irradiation, the y-axis is a ______________________________ (liner, logarithmic) scale.
10. The dose-response graph above demonstrates a(n) ______________________________ (inverse, direct) relationship between chronic radiation dose and life shortening.



11. In the previous graph of added filtration (mm Al) on beam intensity (mGy_a), ______________ mm Al is required to reduce the beam intensity to 1.00 mGy_a.
12. State the three base quantities and the SI unit of measure for each base quantity.
13. What are the four special quantities of radiation measurement?
14. State Newton's three laws of motion.
15. Define power.
16. Define energy.
17. State the law of conservation of energy.
18. Define kinetic energy and potential energy.
19. ___________________ is the kinetic energy of the random motion of molecules.
20. List the three methods of heat transfer systems.

The answers to the Challenge Questions can be found by logging on to our website at http://evolve.elsevier.com.

CHAPTER

3

The Structure of Matter

OBJECTIVES

At the completion of this chapter, the student should be able to do the following:

1. Relate the history of the atom.
2. Identify the structure of the atom.
3. Describe electron shells and instability within atomic structure.
4. Discuss radioactivity and the characteristics of alpha and beta particles.
5. Explain the difference between two forms of ionizing radiation: particulate and electromagnetic.

OUTLINE

THIS CHAPTER moves from the study of energy and force to the basis of matter itself. What composes matter? What is the magnitude of matter?

From the inner space of the atom to the outer space of the universe, there is an enormous range in the size of matter. More than 40 orders of magnitude are needed to identify objects as small as the atom and as large as the universe. Because matter spans such a large magnitude, exponential form is used to express the measurements of objects. Fig. 3.1 shows the orders of magnitude and illustrates how matter in our surroundings varies in size.

The atom is the building block of the radiographer's understanding of the interaction between ionizing radiation and matter. This chapter explains what happens when energy in the form of an x-ray interacts with tissue. Although tissue has an extremely complex structure, it is made up of atoms and combinations of atoms. By examining the structure of atoms, we can learn what happens when the structure is changed.

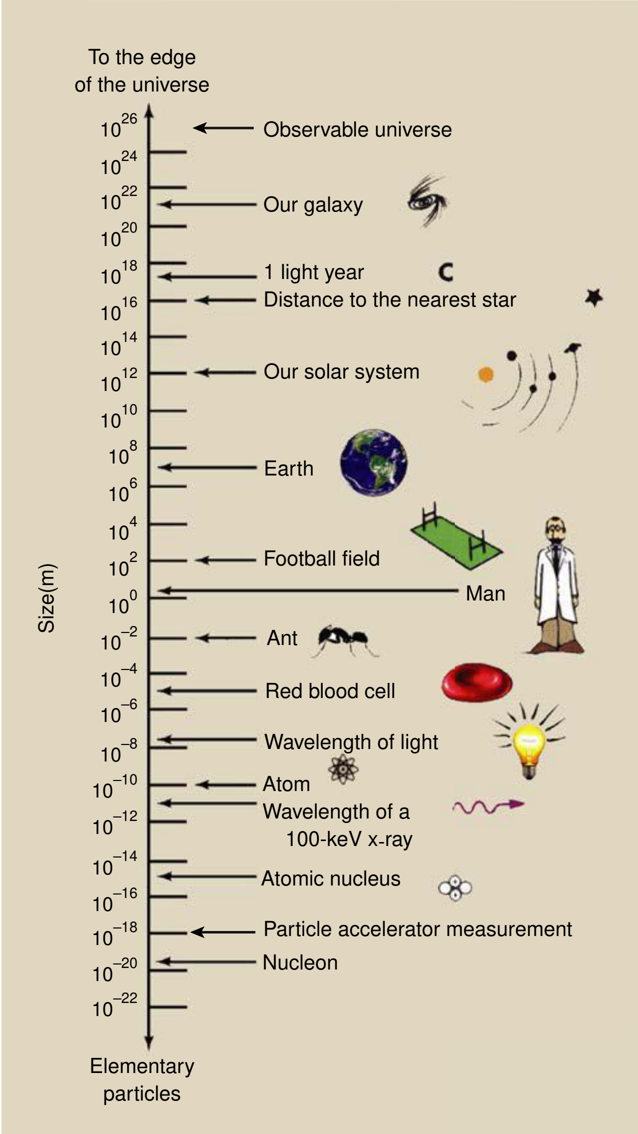


FIGURE 3.1 The size of objects varies enormously. The range of sizes in nature requires that scientific notation be used because more than 40 orders of magnitude are necessary.

An atom is the smallest particle that has all the properties of an element.

CENTURIES OF DISCOVERY

Greek Atom

One of civilization's most pronounced continuing scientific investigations has sought to determine precisely the structure of matter. The earliest recorded reference to this investigation comes from the Greeks several hundred years BC.

Pythagoras, 6th century BC, and Archimedes three centuries later thought that matter was composed of four **substances**: earth, water, air, and fire. According to them, all matter could be described as combinations of these four basic substances in various proportions, modified by four basic **essences**: wet, dry, hot, and cold. Fig. 3.2 shows how this theory of matter was represented at that time.

The Greeks used the term **atom**, meaning "indivisible" [a (not) + temon (cut)] to describe the smallest part of the four substances of matter. Each type of atom was represented by a symbol (Fig. 3.3A). Currently, 118 substances or **elements** have been identified; 92 are naturally occurring, and the additional 26 have been artificially produced in high-energy particle accelerators.

We now know that the atom is the smallest particle of matter that has the properties of an element. Many particles are much smaller than the atom; these are called subatomic particles.

Dalton Atom

The Greek description of the structure of matter persisted for hundreds of years. In fact, it formed the theoretical basis for the vain efforts by medieval alchemists to transform lead into gold. It was not until the 19th century that the foundation for modern atomic theory was laid. In 1808, John Dalton, an English schoolteacher, published a book summarizing his experiments, which showed that the elements could be classified according to integral values of atomic mass.

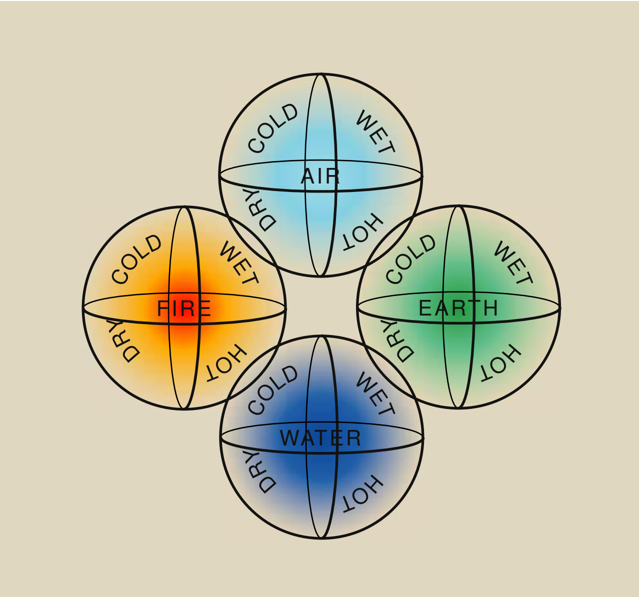


FIGURE 3.2 Representation of the substances and essences of matter as viewed by the ancient Greeks.

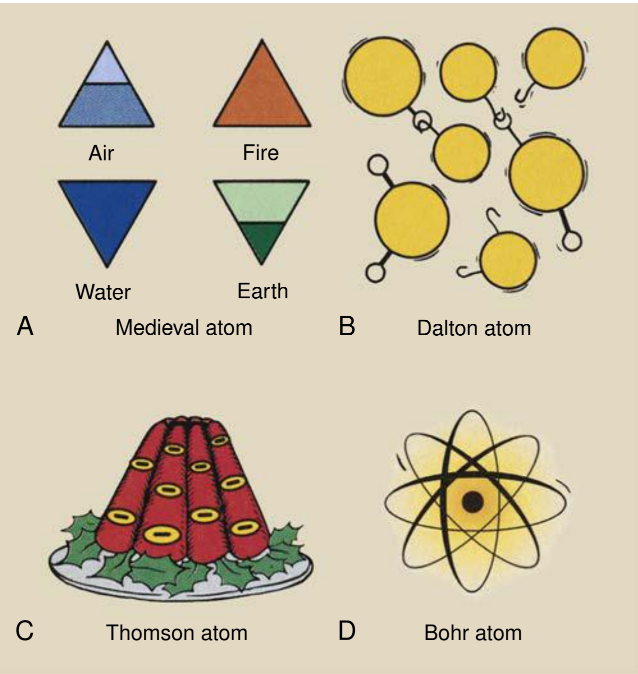


FIGURE 3.3 Through the years, the atom has been represented by many symbols. (A) The Greeks envisioned four different atoms, representing air, fire, earth, and water. These triangular symbols were adopted by medieval alchemists. (B) Dalton's atoms had hooks and eyes to account for chemical combination. (C) Thomson's model of the atom has been described as a plum pudding, with the plums representing the electrons. (D) The Bohr atom has a small, dense, positively charged nucleus surrounded by electrons at precise energy levels.

According to Dalton, an element was composed of identical atoms that reacted the same way chemically. For example, all oxygen atoms were alike. They looked alike, they were constructed alike, and they reacted alike. However, they were very different from atoms of any other element.

The physical combination of one type of atom with another was visualized as being an eye-and-hook affair (see Fig. 3.3B). The size and number of the eyes and hooks were different for each element.

Some 50 years after Dalton's work, a Russian scholar, Dmitri Mendeleev, showed that if the elements were arranged in order of increasing atomic mass, a periodic repetition of similar chemical properties occurred. At that time, approximately 65 elements had been identified. Mendeleev's work resulted in the first **periodic table of the elements**. Although there were many holes in Mendeleev's table, it showed that all the then-known elements could be placed in one of eight groups.

Fig. 3.4 is a rendering of the periodic table of elements. Each block represents an element. The superscript is the atomic number. The subscript is the elemental mass.

> All elements are arranged into eight groups as shown in the periodic table of elements.

All elements in the same group (i.e., column) react chemically in a similar fashion and have similar physical properties. Except for hydrogen, the elements of group I, called the alkali metals, are all soft metals that combine readily with oxygen and react violently with water. The elements of group VII, called halogens, are easily vaporized and combine with metals to form water-soluble salts. Group VIII elements, called the noble gases, are highly resistant to reaction with other elements.

These elemental groupings are determined by the placement of electrons in each atom. This is considered more fully later.

Thomson Atom

After the publication of Mendeleev's periodic table, additional elements were separated and identified, and the periodic table slowly became filled. However, knowledge of the structure of atoms remained scanty.

Before the turn of the 20th century, atoms were considered indivisible. The only difference between the atoms of one element and the atoms of another was their mass. Through the efforts of many scientists, it slowly became apparent that there was an electrical nature to the structure of an atom.

In the late 1890s, while investigating the physical properties of **cathode rays** (**electrons**), J.J. Thomson concluded that electrons were an integral part of all atoms. He described the atom as looking something like a plum pudding, in which the plums represented negative electric charges (electrons) and the pudding was a shapeless mass of uniform positive electrification