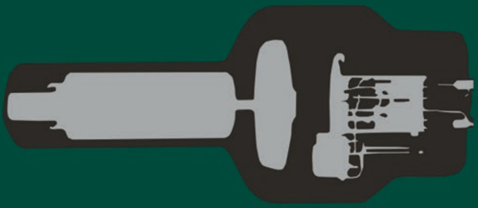
TENTH EDITION

SELMAN'S THE FUNDAMENTALS OF IMAGING PHYSICS AND RADIOBIOLOGY



VICTOR WHITE, PH.D., RT (R)

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Copy of Roentgen's radiograph of his wife's "hand with rings," made soon after his discovery of x-rays in November 1895 in Wurzburg, Germany. (See Glasser O. *Dr. W. C. Roentgen*, 2nd ed., Charles C Thomas, 1958, Springfield, p. 39.)

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SELMAN'S
THE FUNDAMENTALS
OF
IMAGING PHYSICS
AND
RADIOBIOLOGY

By

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Dedicated first, and foremost, to all my medical imaging students: past, present, and future.

Also dedicated to my father, Robert. G. White and high school physics instructor, Larry Armstrong; great mentors and retired teachers, formerly of Taylorville High School in Taylorville, IL, and to Steven B. Dowd, Ed.D, my former Radiography Program Director.

Also dedicated to Dan Bar, D.O., Michael Rafati, M.D., Sharon Hall, M.D., Hector Stella, M.D., and Ben Roberts, MFA, RT (R)(CT)(T), some of the best clinicians and academicians that I have had the pleasure of working with over the years.

Also dedicated to friends and colleagues Craig Reed, Andrea Decker, Jenna Andujar, BAS, RT (R), and Melanie Schmidt, BAS, RT (R), who all offered useful advice, helped with contracts, and/or provided illustrations regarding completion of this textbook.

Finally, dedicated to Max Lee Newlin, RT (R), a great person, radiographer, and student mentor who left us much too soon.

PREFACE

A number of significant changes have been made in this tenth edition. Color photographs and new illustrations have been provided for a number of existing chapters and for the new chapters in this book. Revisions and updates have been completed for Chapters 1 through 28, whereas Chapters 29 to 33 are all new.

The $E = MC^2$ formula has been added to Chapter 3. An updated Periodic Table of the Elements has been added to Chapter 4. A photograph of a modern rotating anode x-ray tube, a diagram of the photodisintegration effect, and the half-life formula have been added to Chapter 12. A new photograph of a rotating anode has been added to Chapter 13, along with some heat unit problems and a diagram of a new type of x-ray tube being developed. In Chapter 14, a new photograph of a modern x-ray control panel has been added. In Chapter 15, a table showing the relationship of screen speed number and screen speed types has been added. In Chapter 20, a new photograph of a Vidicon tube and diagrams of fluoroscopy units and C-Arms have been added. In Chapter 21, a xeromammogram image has been added. In Chapter 22, new mammography, breast US, and breast MRI images, along with photographs of modern mammography equipment and digital mammography quality assurance items have been added. In Chapter 23, information regarding medical and nonmedical computer languages and data have been added. Chapter 24 is significantly revised. Chapter 25 has been significantly revised and updated with new formulas, new diagrams, and CT images. In Chapter 26, images concerning types of nuclear reactors that produce power and radionuclides, diagrams of different types of radiation detectors, and PET diagrams are provided. In Chapter 27, new tables regarding the Acute Radiation Syndrome (ARS) and cancer model data have been provided. In Chapter 28, updated tables about annual dose equivalency, organ system radiation exposure, a photograph of a Luxel® OSL dosimeter, diagrams and data regarding various radiation detectors and current radiobiology practice have been added. Chapter 29, Bone Densitometry, is a completely new chapter. Chapter 30, Magnetic Resonance Imaging, is now its own thoroughly revised chapter. Chapter 31, Ultrasound, is now its own thoroughly revised chapter. Chapter 32, Fusion Imaging, is a completely new chapter. Chapter 33, Molecular Imaging, is a completely new chapter.

In addition, an increased focus has been placed on computed radiography and digital imaging (Indirect and Direct Digital Radiography) to adapt to current technology and ARRT (R) Board exam topics. Chapters related to film processing, the darkroom, and film-screen technology have been maintained because this technology is still used in rural and other facilities worldwide and is still included on the ARRT State Exam for Limited X-Ray Machine Operators (LXMOs).

Additional questions have been added to the end of most chapters, and the answers or locations in the textbook where the answers can be found for all questions are now included in this edition.

I would like to thank Radiology Administrators Michael Wright, Michael Klein, Stuart Schwab, Michelle Walker, and Chief MRI Technologist Terri Camp at Billings Clinic in Billings, MT, for allowing me to take photographs of their MRI Department and related MRI equipment. I would also like to thank St. Vincent's Healthcare Radiology Department Administrator Aubrey Brennemann for allowing me to take photographs of ultrasound machines, CT units, and Mammography units at St. Vincent's Healthcare in Billings, MT. I would especially like to thank Jenna Andujar, BAS, RT (R), for her expert help and assistance in obtaining photographs of the DXA unit, DXA equipment, and a Luxel® OSL Dosimeter from St. Vincent's Healthcare.

Finally, I would like to express my sincere gratitude to Michael Thomas, president of Charles C Thomas, Publisher, Ltd., for his great patience and understanding, and his most competent staff, particularly Michael Fagg, Cindy Marcy, and Sharon Moorman, for their superb help with my illustrations and the publication of this tenth edition of Selman's *The Fundamentals of Imaging Physics and Radiobiology.*

Victor N. White, PhD, RT (R)

INTRODUCTION

This, the tenth edition of Selman's *The Fundamentals of Imaging Physics and Radiobiology*, is the continuation of a seminal work in radiation physics and radiation biology first published by Joseph Selman, MD, in 1954 by Charles C Thomas, Publisher, Ltd., Springfield, IL.

A brief history about the originating author of this book is now in order. Dr. Joseph Selman was born August 25, 1915, in Albany, New York, and passed away on October 31, 2010, in Plano, Texas. Dr. Selman was a widely respected physician and an author of many medical textbooks. He was also one of the founders of the East Texas Cancer Center in Tyler, Texas, in 1951. Editions of this book start with the inaugural edition in 1954. The second edition was published in 1957, the third edition in 1961, the fourth edition in 1965, the fifth edition in 1972, the sixth edition in 1977, the seventh edition in 1985, the eighth edition in 1994, and the ninth edition in 2000. This coauthor happened to use the sixth edition of this book while a radiologic technology student in the St. John's Hospital/Lincoln Land Community College Radiologic Technology Program in Springfield, IL, graduating in 1985.

In this tenth edition, published in 2020, the overall style of Dr. Selman is still present, but, with any revision, the style of the current author is also present. In essence, my *raison d'être* in revising this book was to better reflect current radiology practice and to honor the work of Dr. Selman. Topics discussed in this textbook deal with the physics of x-radiation, the biological interaction of radiation with matter, and all aspects of imaging equipment and technology commonly found in the modern radiology department. The chapter on computed tomography (CT) has been heavily revised and updated. Protective measures regarding radiation safety and radiation hazards for workers and patients are thoroughly discussed, and new chapters on dual energy x-ray absorptiometry (DXA), magnetic resonance imaging (MRI), ultrasound (US), fusion, and molecular imaging have been added.

This book will be very helpful to students about to take the ARRT (R) registry examination but is not a registry review book per se. This book also serves as a good overview of radiologic imaging physics for radiographers and other medical professionals.

V.N.W.

CONTENTS

SELMAN'S
THE FUNDAMENTALS OF IMAGING PHYSICS AND RADIOBIOLOGY

Chapter 1

SIMPLIFIED MATHEMATICS

Learning Objectives

After completing this chapter, the reader will be able to:

- Define mathematics and the differences between arithmetic, algebra, and plane geometry.
- Describe ratio and proportion.
- Describe differences between charts and graphs.
- Describe differences between small and large numbers.
- Describe logarithms.
- Answer questions and solve the problems at the end of the chapter.

ALL OF THE PHYSICAL SCIENCES have in common a firm basis in mathematics. This is no less true of radiologic physics, an important branch of the physical sciences. Clearly, then, in approaching a course in radiologic physics you, as a student radiographer, graduate student, or radiology resident, should find your path smoothed by an adequate background in the appropriate areas of mathematics.

We shall assume here that you have had at least basic exposure to mathematics, although this may vary widely from place to place. However, realizing that much of this material may have become hazy with time, we shall review the simple but necessary aspects of arithmetic, algebra, ratio and proportion, and plane geometry. Such a review should be beneficial in at least two ways. First, it should make it easier to understand the basic principles and concepts of radiologic physics. Second, it should aid in the solution of such everyday problems as conversion of radiographic techniques, interpretation of tube rating charts, determination of radiographic magnification, and many others that may arise from time to time.

The discussion will be subdivided as follows: (1) arithmetic, (2) algebra, (3) ratio and proportion, (4) geometry, (5) graphs and charts, (6) large and small numbers and (7) logarithms. Only fundamental principles will be included in this chapter.

ARITHMETIC

Arithmetic is calculation or problem-solving by means of definite numbers. We shall assume that you are familiar with addition, subtraction, multiplication, and division and shall therefore omit these operations.

Fractions

In arithmetic, ***a fraction may be defined as one or more equal parts of a unit***. For example, $\frac{1}{2}$, $\frac{1}{3}$, and $\frac{2}{5}$ are fractions. The quantity below the line is called the ***denominator***; it indicates the number of equal parts into which the unit is divided. The quantity above the line is the ***numerator***; it indicates the number of equal parts taken. Thus, if a pie were divided into three equal parts, the denominator would be 3; and if two of these parts were taken, the numerator would be 2, so, the two segments would represent $\frac{2}{3}$ of the pie.

Fractions represent ***the division of one quantity by another***. This extends the concept of fractions to expressions in which the numerator is larger than the denominator, as in the fraction $\frac{5}{2}$.

If the numerator is smaller than the denominator, as $\frac{3}{5}$, we have a ***proper fraction***. If the numerator is larger than the denominator, as $\frac{5}{3}$, we have an ***improper fraction***, because $5 \div 3 = 1\frac{2}{3}$, which is really an integer plus a fraction.

In ***adding*** fractions, all of which have the ***same*** denominator, add all the numerators first and then place the sum over the denominator:

$$\frac{2}{7}+\frac{3}{7}+\frac{6}{7}+\frac{5}{7}=\frac{2+3+6+5}{7}=\frac{16}{7}$$

$$\frac{16}{7}=2\frac{2}{7}$$

Subtraction of fractions having identical denominators follows the same rule:

$$\frac{6}{7}-\frac{4}{7}=\frac{6-4}{7}=\frac{2}{7}$$

If fractions are added or subtracted, and the denominators are ***different***, then the ***least common denominator*** must be found. This is the smallest number which is exactly divisible by all the denominators. Thus,

$$\frac{1}{2}+\frac{2}{3}-\frac{3}{4}=?$$

The smallest number which is divided exactly by each denominator is 12. Place 12 in the denominator of a new fraction:

$$\frac{\square}{12}$$

Divide the denominator of each of the fractions in the old equation into 12, and then multiply the answer by the numerator of that fraction; each result is then placed in the numerator of the new fraction:

$$\frac{6+8-9}{12}=\frac{5}{12}$$

Multiplying fractions means taking their product. To multiply fractions, take the product of the numerators and place it over the product of the denominators,

$$\frac{4}{5}\times\frac{3}{10}=\frac{4\times 3}{5\times 10}=\frac{12}{50}$$

The resulting fraction can be reduced by dividing the numerator and the denominator by the same number, in this case, 2:

$$\frac{12}{50}\div\frac{2}{2}=\frac{6}{25}$$

which cannot be further simplified.

Note that when the numerator and the denominator are both multiplied or divided by the same number, the value of the fraction does not change.

For instance,

$$\frac{3}{5}\times\frac{2}{2}=\frac{6}{10}$$

$$\textit{is the same as } \frac{3}{5}\times 1=\frac{3}{5}$$

When two fractions are to be divided, as $\frac{4}{5} \div \frac{3}{7}$, the fraction that is to be divided is the ***dividend*** and the fraction that does the dividing is called the ***divisor***. In this case, $\frac{4}{5}$ is the dividend and $\frac{3}{7}$ the divisor. The rule is to invert the divisor (called "taking the reciprocal") and multiply the dividend by it:

$$\frac{4}{5}\div\frac{3}{7}$$

$$\frac{4}{5}\times\frac{7}{3}=\frac{28}{15}=1\frac{13}{15}$$

Percent

A special type of fraction, ***percent***, is represented by the sign % to indicate that the number standing with it is to be divided by 100. Thus, 95% = 95/100. We do not use percentages directly in mathematical computations but first convert them to fractions or decimals. For instance,

150 × 40% is changed to 150 × 40/100
or 150 × 2/5 or 150 × 0.40.

All these expressions equal 60.

Decimal Fractions

Our common method of representing numbers as multiples of ten is embodied in the

decimal system. A ***decimal fraction*** has as its denominator 10, or 10 raised to some power such as 100, 1000, 10,000, etc. The denominator is symbolized by a dot in a certain position. For example, the decimal 0.2 = 2/10; 0.02 = 2/100; 0.002 = 2/1000, etc. Decimals can be multiplied or divided, but care must be taken to place the decimal point in the proper position:

```
  2.24
ψ 1.25
  1120
  448
 224
2.8000
```

First, add the total number of digits to the right of the decimal points in the numbers being multiplied, which in this case turns out to be four. Then point off four places from the right in the answer to determine the correct position of the decimal point. The decimal system is used everywhere in science and in the vast majority of countries in daily life.

Significant Figures

The precision (reproducibility of results) of any type of measurement is limited by the design of the measuring instrument. For example, a scale calibrated in grams as shown in Figure 1.1 allows an estimate to the nearest tenth of a gram. Thus, the scale in Figure 1.1 reads 8.4 g. The last figure, 0.4, is estimated and is the ***last significant figure***—that is, it is the last meaningful digit. Obviously, no greater precision is possible with this particular instrument. To improve precision, the scale would have to show a greater number of subdivisions.

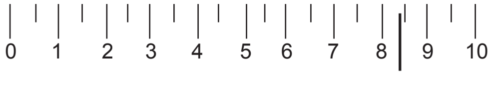

Figure 1.1. With this calibrated scale, we can estimate to the nearest tenth. Thus, the position of the pointer indicates 8.4 units, the 0.4 being the last significant figure.

Significant figures are used in various mathematical operations. For example, in addition:

Item 1	98.26 g
Item 2	1.350 g
Item 3	260.1 g
	359.710 g

Notice that three digits appear after the decimal point in the answer. But in item (3), there is only one digit, 1, after the decimal point; beyond this, the digits are unknown. Therefore, the digits after the 7 in the answer imply more than is known, since the answer can be no more precise than the least precise item being added. In this case, the answer should be properly stated as 359.7. In addition and subtraction, the answer can have no more significant figures after the decimal point than the item with the ***least number of significant figures after its decimal point***.

A different situation exists in multiplication and division. Here, the total number of significant figures in the answer equals that in the items having the ***least total number of significant figures***. For example, in

```
  25.23  cm
ψ  1.21  cm
   2523
  5046
 2523
30.5283  cm²
```

1.21 cm has fewer significant figures—three in all—so the answer should have three significant figures and be read as 30.5 (dropping the 0.0283).

In general, to ***round off*** significant figures, observe the following rule: if the digit following the last significant figure is equal to or greater than 5, the last significant figure is increased by 1; if less than 5, it is unchanged. The rule is applied in the following examples:

45.157 is rounded to 45.16
45.155 is rounded to 45.16
45.153 is rounded to 45.15

where the answer is to be expressed in four significant figures.

ALGEBRA

The word ***algebra***, derived from the Arabic language, connotes that branch of mathematics which deals with the relationship of quantities usually represented by letters of the alphabet—Roman, Greek, or Hebrew.

Operations. Mathematical operations with ***letter symbols*** are the same as with ***numerals***, since both are symbolic representations of numbers which, in themselves, are abstract concepts. For example, the concept "four" may be represented by 4, 2^2, 2 × 2, 2 + 2, or 3 + 1; or by the letter x if the value of x is specifically designated to represent "four." In algebra, just as in arithmetic, the fundamental operations include addition, subtraction, multiplication, and division; and there are fractions, proportions, and equations. Algebra provides a method of finding an unknown quantity when the relationship of certain known quantities is specified.

Algebraic operations are indicated by the same symbols as in arithmetic:

+ (plus) add
/ (minus) subtract
× (times) multiply
÷ (divided by) divide
= equals

To indicate ***addition*** in algebra, use the general expression

$$x + y \qquad (1)$$

The symbols x and y, called ***variables***, may represent any number or quantity. Thus, if $x = 4$ and $y = 7$, then, substituting these values in equation (1),

$$4 + 7 = 11$$

Similarly, to indicate ***subtraction*** in algebra, use the general expression

$$x / y$$

If $x = 9$ and $y = 5$, then 9 / 5 = 4

Notice that algebraic symbols may represent whole numbers, fractions, zero, and negative numbers among others. Negative numbers are those whose value is less than zero and are designated as / x. In algebraic terms, add a positive and a negative number as follows:

$$x + / y$$

If $x = 8$ and / y = / 3, then

$$8 + / 3$$

is the same as

$$8 / 3 = 5$$

The + sign is omitted in the designation of positive numbers, being reserved to indicate the operation of addition.

On the other hand, to subtract a negative quantity from a positive one

$$x / / y$$

If $x = 4$ and / y = / 6, then

$$4 / / 6$$

is the same as

$$4 + 6 = 10$$

Multiplication in algebra follows the same rules as in arithmetic. However, in the multiplication of letter symbols the × sign is omitted, $x \times y$ being written as xy. If $x = 3$ and $y = 5$, then substituting in the expression xy,

$$3 \times 5 = 15$$

Division in algebra is customarily expressed as a fraction. Thus, $x \div y$ is written as x/y. If $x = 3$ and $y = 5$, then

$$3 \div 5 = 3/5$$

When two negative quantities are multiplied or divided, the answer is positive. Thus, / x × / y = xy and / x// y = x/y. When a positive and a negative quantity are multiplied or divided, the answer is negative; thus, x × / y = / xy, and x ÷ / y = / x/y.

In solving an algebraic expression consisting of a collection of ***terms*** we must perform the indicated ***multiplication and division first*** and then carry out the indicated addition and subtraction. An example will clarify this:

$$ab + c/d \,/\, f = ?$$

Suppose $a = 2$, $b = 3$, $c = 4$, $d = 8$, and $f = 5$. Substituting in the preceding expression,

$$2 \times 3 + \frac{4}{8} - 5 = ?$$

Performing ***multiplication and division first***,

$$6 + \frac{4}{8} - 5 = ?$$

Then, performing addition and subtraction,

$$6\frac{4}{8} - 5 = 1\frac{4}{8} = 1\frac{1}{2}$$

A parenthesis inclosing a group of terms indicates that all of the terms inside the parenthesis are to be multiplied by the term outside the parenthesis. This is simplified by performing all the indicated operations in correct sequence—inside the parenthesis first—and then multiplying the result by the quantity outside the parenthesis. For example,

$$6\,(8 \,/\, 4 + 3 \times 2) =$$
$$6\,(8 \,/\, 4 + 6) =$$
$$6 \times 10 = 60$$

Equations. The simpler algebraic equations can be solved without difficulty by the application of basic rules. You can easily verify these rules by substituting numerals. In the equation

$$a + b = c + d \qquad (2)$$

$a + b$ is called the ***left side*** and $c + d$ the ***right side***. Each letter is called a term. If any quantity is added to one side of the equation, the same quantity must be added to the other side in order for this to remain an equation. Similarly, if any quantity is subtracted from one side, the same quantity must be subtracted from the other side. To simplify the concept of the equation, we may picture it as a see-saw as in Figure 1.2. If persons of equal weight are placed at each end, the board will remain horizontal—the equation is balanced. If a second person is now added to one end of the see-saw, a person of similar weight must be added to the other end in order to keep the board level.

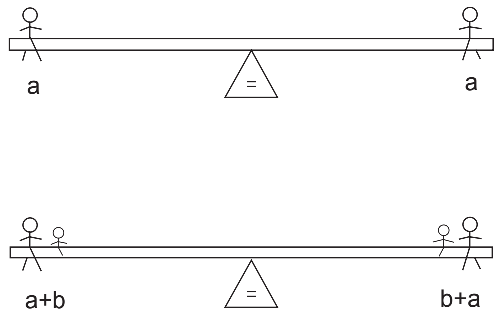

Figure 1.2. Analogy of algebraic equation to a see-saw.

Return again to the simple equation:

$$a + b = c + d$$

in which each term is a variable. If any three of the variables are known, the fourth can be found. Suppose, a is 3, b is 4, c is 1, and d is unknown. Substituting these values in the equation,

$$3 + 4 = 1 + d$$

How can d be found? Simply rearrange the equation so that d is alone, that is, ***the only term in its side***. In this case, subtract 1 from both sides of the equation. However, a mathematical short cut can be used: ***a term may be transposed from one side of an equation to the other side, provided it is given the opposite sign***. Following this rule, 1 becomes a minus 1 when moved to the left side. Thus,

$$3 + 4 \,/\, 1 = d$$
$$6 = d$$
$$\text{or,} \quad d = 6$$

Usually, in solving algebraic equations, rearrange the terms before substituting their numerical values. In the equation $a + b = c + d$ to find d, transpose c to the left side and change its sign.

$$a + b \,/\, c = d$$
$$\text{or,} \quad d = a + b \,/\, c$$

(Reversing both sides of an equation does not alter its equality.)

In algebraic equations in which terms are multiplied or divided, analogous rules apply. For example, equation

$$x = y/z$$

may be solved for y by multiplying both sides by z,

$$xz = yz/z$$

$$xz = y$$

or,

$$y = xz$$

The same result may be obtained by moving z from the denominator of the right side to the numerator of the left side. Thus, we have the short-cut rule for cross-multiplication: ***if the denominator of one side of an equation is moved, it multiplies the numerator of the other side and, conversely, if the numerator of one side is moved, it multiplies the denominator of the other side***.

Suppose that in the equation $x = y/z$, x and y are known, then z is solved as follows: move z into the numerator of the opposite side as a multiplier,

$$xz = y$$

and move x into the denominator of the right side as a multiplier, and

$$z \ ? \ y/x \qquad (3)$$

The above rule can be readily tested. Suppose that y is 12 and x is 3. Substituting in equation (3),

$$z = \frac{12}{3}$$

$$z \ ? \ 4$$

$$4 = \frac{12}{3} \qquad (4)$$

If we wish to move 3, we must place it in the numerator of the left side of equations (4),

$$4 \times 3 \ ? \ 12 \qquad (4a)$$

Note that numerical equations (4) and (4a) balance.

Now, referring again to equation (4), suppose we wish to move 12. We must place it in the denominator of the left side

$$\frac{4}{12} = \frac{1}{3}$$

Again, it is evident that the equation balances.

RATIO AND PROPORTION

A ***ratio*** is a fixed relationship between two quantities, simply indicating how many times larger or smaller one quantity is relative to another. It has essentially the same meaning as a fraction. One symbol that expresses a ratio is the colon (:). Thus, *a:b* is read "*a* is to *b*." Or, 1:2 is read "1 is to 2." In modern mathematics, ratios are usually represented as fractions:

$a{:}b$ is the same as a/b

1:2 is the same as $\frac{1}{2}$

As noted above, the fraction $\frac{1}{2}$ indicates that the numerator is $\frac{1}{2}$ as large as the denominator. Similarly, $\frac{2}{3}$ indicates that the numerator is $\frac{2}{3}$ as large as the denominator.

The meaning of ratio is important to the technologist because it underlies the concept of ***proportion***, defined as ***an expression showing that two given ratios are equal***. Thus, we may have an algebraic proportion,

$$a/b = c/d \qquad (5)$$

which is read "*a* is to *b* as *c* is to *d*." The same idea can also be represented numerically. For example,

$$\frac{3}{6} = \frac{4}{8}$$

If any three terms of a proportion are known, the fourth may easily be determined. Suppose in proportion (5) a is 2, b is 4, d is 8, and c is to be found. Then,

$$\frac{2}{4} = \frac{c}{8}$$

Moving 8 to the numerator of the left side (cross multiplying),

$$\frac{2 \times 8}{4} = c$$

$$c = \frac{16}{4} = 4$$

There are three general types of proportions that pertain to radiography.