

# CONTENTS

INTRODUCTION .....xi

## UNIT 1 • A Framework .....xiv

### CHAPTER 1 FOUNDATIONS OF PHYSICS .....xvi

1A	Why Study Physics?	1
1B	What is Physics?	5
1C	How Do Physicists Work?	16

#### FACETS

Thomas Samuel Kuhn: Philosopher of Science	8
Limitations of Science	12

### CHAPTER 2 MEASUREMENT .....22

*Dominion Modeling: Measuring the Speed of Light*

2A	Dimensions of Physics	23
2B	Principles of Measurement	31
2C	Truth in Measurements and Calculations	36
2D	Problem Solving	41

#### FACETS

Just a Second	26
Fine-Tuning Measurements—Vernier Scales	35

## UNIT 2 • Classical Mechanics .....46

### CHAPTER 3 MOTION IN ONE DIMENSION .....48

*Dominion Modeling: Stopping Distance*

3A	Describing Motion	49
3B	Equations of Motion	61

#### FACET

Hypersonic Jets SCRAM!!!	56
--------------------------	----

### CHAPTER 4 VECTORS AND SCALARS .....72

*Dominion Science: Accurate Hurricane Models*

4A	Properties of Vectors and Scalars	73
4B	Operations with Vectors: Geometric Techniques	76
4C	Operations with Vectors: Mathematical Techniques	79

### CHAPTER 5 MOTION IN A PLANE .....92

*Dominion Science: Humanitarian Aid*

5A	Kinematics of Two-Dimensional Motion	93
5B	Projections	98

#### FACETS

Shot Put Release Angles	107
Biography: Sir Isaac Newton	110

### CHAPTER 6 DYNAMICS .....112

*Dominion Science: Aircraft Carrier Flight Operations*

6A	The History of Dynamics	113
6B	Forces	116
6C	Newton's Laws of Motion	123

#### FACETS

Flight and Newton's Third Law	130
Biography: Aristotle	135

**CHAPTER 7 CIRCULAR MOTION** ..... 136

*Dominion Modeling: Saturn's Moons*

7A	Circular Motion	138
7B	Dynamics of Circular Motion	146
7C	Universal Gravitation	151

**FACET**

Roller Coasters	162
-----------------	-----

**CHAPTER 8 APPLYING NEWTON'S LAWS** ..... 164

*Dominion Science: Head-On Collisions*

8A	Simplifying Problems	165
8B	Transmitting Mechanical Forces	168
8C	Friction	176
8D	More Applications	181

**FACET**

Artificial Gravity	191
--------------------	-----

**CHAPTER 9 WORK AND ENERGY** ..... 194

*Dominion Science: A Renewable Energy Resource*

9A	Work	196
9B	Energy	202
9C	Total Mechanical Energy	211

**CHAPTER 10 CONSERVATION OF ENERGY** ..... 218

*Dominion Science: Elevator Safety*

10A	Total Mechanical Energy	219
10B	Simple Machines	226

**FACET**

Conserving Energy	225
-------------------	-----

**CHAPTER 11 MOMENTUM** ..... 238

*Dominion Science: Car Accident Injuries and Fatalities*

11A	Principles of Momentum	239
11B	Collisions	246
11C	Center of Mass and Angular Momentum	257

**FACETS**

The Ubiquitous Turbine	242
Gravity Assists	255

**CHAPTER 12 PERIODIC MOTION** ..... 264

*Dominion Modeling: Mach Speed*

12A	Simple Harmonic Motion	266
12B	Periodic Motion and the Pendulum	270
12C	Oscillations in the Real World	277
12D	Waves	280

**FACET**

Foucault Pendulum	274
-------------------	-----

**UNIT 3 • Thermodynamics and Matter** ..... 290

**CHAPTER 13 PROPERTIES OF MATTER** ..... 292

*Dominion Science: Replacing Asbestos*

13A	Theories of Matter	293
13B	States of Matter	299

**FACETS**

Ice Skating	303
Relative Humidity	307

<b>CHAPTER 14 EXPANSION AND TEMPERATURE</b> .....	<b>312</b>	
<i>Dominion Science: Infant Respiratory Distress</i>		
14A Thermal Properties .....	313	<b>FACETS</b>
14B Measuring Temperature .....	319	Ball and Ring 319
14C Gas Laws .....	324	Biography: Count Rumford 335
		Biography: James Joule 336
<b>CHAPTER 15 THERMAL ENERGY AND HEAT</b> .....	<b>338</b>	
<i>Dominion Modeling: Metals and Heat</i>		
15A Theories of Heat .....	339	<b>FACET</b>
15B Thermal Energy and Matter .....	342	Biography: Nicolas Sadi Carnot 357
15C Mechanisms for Heat Transfer .....	352	
<b>CHAPTER 16 THERMODYNAMIC LAWS</b> .....	<b>358</b>	
<i>Dominion Science: Miserable Heat</i>		
16A The Zeroth and First Laws .....	359	<b>FACET</b>
16B The Second and Third Laws .....	367	Growth and the Second Law 378
16C Entropy and Its Consequences .....	374	
<b>CHAPTER 17 FLUID MECHANICS</b> .....	<b>382</b>	
<i>Dominion Science: Homespun Energy</i>		
17A Hydrostatics: Fluids at Rest .....	383	<b>FACETS</b>
17B Hydrodynamics: Fluids in Motion .....	396	Maple Syrup Hydrometers 395
		Aerodynamically Designed Cars 405
<b>UNIT 4 • Electromagnetics</b> .....	<b>410</b>	
<b>CHAPTER 18 ELECTRIC CHARGE</b> .....	<b>412</b>	
<i>Dominion Modeling: Fundamental Electricity</i>		
18A Electrification .....	413	<b>FACETS</b>
18B Detecting Electric Charge .....	419	Biography: William Gilbert 415
		Static Electricity 420
		Biography: Michael Faraday 427
<b>CHAPTER 19 ELECTRIC FIELDS</b> .....	<b>428</b>	
<i>Dominion Science: Nanovision</i>		
19A Modeling the Electric Field .....	429	<b>FACET</b>
19B Capacitors .....	436	Kinds of Capacitors 442
<b>CHAPTER 20 ELECTRODYNAMICS</b> .....	<b>446</b>	
<i>Dominion Science: Transcontinental Telephone</i>		
20A Current, Voltage, and Resistance .....	447	<b>FACET</b>
20B Electrical Circuits .....	454	Fuel Cells 472
20C Semiconductors and Transistors .....	463	
<b>CHAPTER 21 MAGNETISM</b> .....	<b>474</b>	
<i>Dominion Modeling: Understanding the Electron</i>		
21A Describing Magnetism .....	475	<b>FACET</b>
21B Electromagnetism and Charges .....	482	Paleomagnetism and the Age of the Earth 483
21C Electromagnetism and Conductors .....	491	



**CHAPTER 22 ELECTROMAGNETISM** ..... 498

*Dominion Science: An Electrifying Idea*

22A	Currents and Magnetic Fields	499
22B	Alternating Current	506
22C	AC Circuit Characteristics	513

**FACETS**

Diesel Locomotives	520
Biography: James Clerk Maxwell	521

**UNIT 5 • Geometric Optics and Light** ..... 522

**CHAPTER 23 LIGHT AND REFLECTION** ..... 524

*Dominion Modeling: Reflecting on Albedo*

23A	Light and the Electromagnetic Spectrum	525
23B	Sources and Propagation of Light	529
23C	Reflection and Mirrors	535

**FACET**

Biography: Christiaan Huygens	533
-------------------------------	-----

**CHAPTER 24 REFRACTION** ..... 550

*Dominion Modeling: Refraction and Glass Composition*

24A	Theory of Refraction	551
24B	Application of Refraction—Lenses	559

**FACET**

Fresnel Lenses	570
----------------	-----

**CHAPTER 25 WAVE OPTICS** ..... 572

*Dominion Science: Busting Counterfeiters*

25A	Wave Interference	573
25B	Diffraction	584
25C	Polarization of Light	589

**FACETS**

Biography: Thomas Young	576
Lasers	582
Optical Testing	593

**CHAPTER 26 USING LIGHT** ..... 596

*Dominion Science: A Better Picture*

26A	Intensity and Color	597
26B	Optical Instruments	606

**FACET**

Microscopy	607
------------	-----

**UNIT 6 • Modern Physics** ..... 616

**CHAPTER 27 RELATIVITY** ..... 618

*Dominion Science: "Relatively" Accurate GPS*

27A	Galilean Relativity	619
27B	Special Relativity	625
27C	General Relativity	634

**FACETS**

Biography: Albert Einstein	624
Gravitational Red Shift	637

**CHAPTER 28 QUANTUM PHYSICS** ..... 640

*Dominion Science: Information Security*

28A	Quantum Theory	641
28B	Quantum Mechanics and the Atom	646
28C	Modern Atomic Models	652

**FACETS**

Biography: Max Planck	643
Electron Microscope	654
Biography: Niels Bohr	661

**CHAPTER 29 NUCLEAR PHYSICS** ..... 662

*Dominion Modeling: Scrolls Out of Time*

29A	Radiation and Radioactivity	663
29B	Radioactive Decay	671
29C	Nuclear Reactions	678
29D	Subatomic Particles	684

**FACETS**

Radioactive Decay Halos	674
Cosmic Rays	692

Appendix A	Base and Derived Units of the SI	694
Appendix B	Commonly Used Unit Abbreviations	695
Appendix C	Unit Conversions	696
Appendix D	Physical Constants	697
Appendix E	Planetary and Astronomical Data	698
Appendix F	Moments of Inertia for Selected Regular Objects	699
Appendix G	Mathematical Reference	700
Appendix H	Periodic Table of the Elements	708
Appendix I	Prefixes for Powers of Ten	709
Appendix J	Greek Alphabet	709
Glossary		710
Index		729
Acknowledgments		740
Photograph Credits		741

4A	Properties of Vectors and Scalars	73
4B	Operations with Vectors: Geometric Techniques	76
4C	Operations with Vectors: Mathematical Techniques	79



This NASA space shuttle, shortly after liftoff, had an increasing speed in a specific direction—straight up.



# Vectors and Scalars

# 4

## DOMINION SCIENCE PROBLEM

### *Accurate Hurricane Models*

Hurricanes and cyclones caused almost 2 million deaths in the last two centuries. If you have never experienced one of these storms, consider yourself fortunate. Hurricanes are huge rotating storm systems in the earth's atmosphere that form over warm oceans in tropical or subtropical areas of the world. The winds in these storms exhibit complex motion in three dimensions. The air in a hurricane not only rotates but also spirals into the hurricane's eye from its periphery, rises vertically in the eye, and then spirals outward over the top of the storm. Wind speeds of over 320 km/h (200 mi/h) have been recorded for hurricanes that have made landfall in the United States.

But extreme winds are not the most dangerous aspect of a hurricane. Most deaths are caused by hurricane *storm surges* that inundate coastal areas with many meters of water, allowing huge ocean waves to assault human habitations far from the beach. A storm surge is the abnormally high sea level caused by the adverse combination of low air pressure, high winds piling water onshore, and a high tide. Often in the aftermath of a storm, disease and famine in the disaster area claim even more lives. How can we better model hurricanes to improve forecast accuracy and to more effectively evacuate people out of harm's way?



4-1 On May 2, 2008, cyclone Nargis smashed into the country of Myanmar (formerly known as Burma) in Southeast Asia. More than 2000 square miles were flooded, and an estimated 25 000 to 60 000 people were dead or missing.

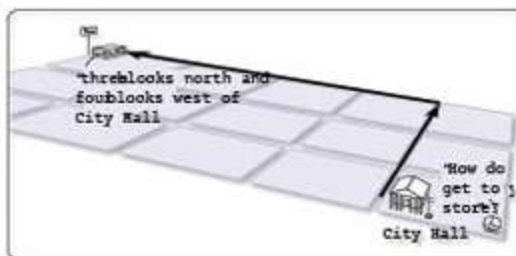
## 4A PROPERTIES OF VECTORS AND SCALARS

### 4.1 Defining Vectors and Scalars

A manager gives a customer directions to her store: "Three blocks north and four blocks west of City Hall." The customer's trip can be represented by two arrows on a map, each having a specific length and direction.

An artillery officer knows that the muzzle velocity of a fired cannon projectile is 930 m/s. He must raise the barrel of his cannon to an elevation of  $33^\circ$  in order to hit a target. The initial speed of the projectile can be represented by a long arrow labeled 930 m/s at an angle of  $33^\circ$  above a horizontal line.

An engineer for a tire manufacturing company is designing a new, low-profile radial tire. In order to understand



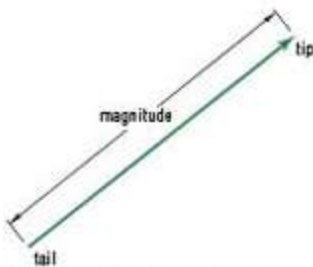
4-2 Each leg of the trip to the store is a vector.



4-3 The velocity vector describes both speed and direction.

The *magnitude* of a quantity is the absolute value of its numerical value. As such, magnitudes are always positive. It is important to remember that while all magnitudes of vectors are scalars, not all scalars are magnitudes of vectors.

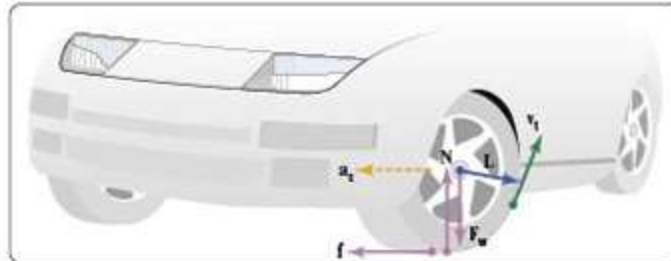
The magnitude of  $A$  is written  $A$  or  $|A|$ . The magnitude of a vector is also called its modulus. The magnitude of a vector may be indicated by a numerical label or graphically indicated by the relative length of the vector arrow.



4-5 The essential parts of a vector diagram

The *vector angle* ( $\theta$ ) is the direction of the vector in relation to its *reference direction*, the direction of zero angle.

how the tire will respond to hard braking, he sketches a diagram of the various forces at work on the tire. He draws arrows representing the weight of the vehicle, the angular momentum of the wheel, braking torque, and the tire's friction with the road. Large quantities are represented by long arrows and small ones by short arrows. The diagram helps the engineer understand the dynamics needed to create a computer model of the tire design.



4-4 Each quantity in the diagram is represented by a vector.

In each case above, vectors are used to study quantities that have two pieces of information—a specific numerical value and a direction. Physicists use vectors to study dimensions such as displacement, velocity, force, acceleration, and magnetic fields. Vectors are drawn as arrows on *vector diagrams*.

Physicists also work with scalars. A scalar is a quantity that can be described completely by only a single numerical piece of information. Time, mass, volume, and temperature are all scalars because, unlike vectors, they have no direction associated with them. Some scalars are only positive, such as mass and time. Others, such as temperature, may be positive or negative, depending on the instant of measurement.

A vector symbol is printed with boldface roman type,  $A$ . Since writing boldface letters is difficult, you may use a regular letter with an arrow over it,  $\vec{A}$ . Upright lines around the vector symbol,  $|A|$ , stand for its absolute value and specify its magnitude. As a shorthand notation for the magnitude, either the italicized letter or the absolute value sign will be used; that is,

$$A = |A| \text{ (handwritten, } A \text{ or } |A| \text{)}.$$

The symbol  $=$  means “is defined as.”

## 4.2 Vector Angles

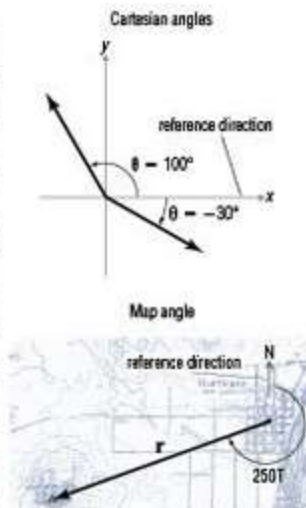
Vectors in diagrams provide important information. The tail of the arrow can indicate the starting point of motion or the point at which a force is physically applied. The length of the arrow is proportional to the magnitude of the vector quantity. Vector diagrams also include directional information indicated by the orientation of the arrow. The *vector angle*, labeled with the Greek letter  $\theta$ , is given a numerical value in degrees or radians measured from a fixed direction. This *reference direction* is usually determined by convention or is selected for convenience in working the problem. This is especially important in two- and three-dimensional vectors. For one-dimensional vectors, direction can be indicated by a plus or minus sign, as stated in Chapter 3.

There are some *conventions* (generally agreed-upon rules) for establishing reference directions for angular measurement. This will be especially applicable to two-dimensional motion, which you will study in the next chapter. In the



Cartesian (two-dimensional) plane, the reference direction is the positive  $x$ -axis. Positive angles are measured counterclockwise and negative angles are measured clockwise around the origin. There is no limit to the size of geometric angles. An angle can be measured in either degrees or radians.

Map directions are always referenced to geographic north, which by convention is located at the *top* of the map or diagram. Angles referenced to true north are indicated by a capital "T" in place of the degree symbol. Map directions are usually measured clockwise from north. For example, 315T is northwest. When using north as the reference direction, angles are always positive and are reported only in degrees from 0T to 360T. This textbook will always give map directions using three digits (which is standard practice for navigational purposes). In this system, north is 000T, northeast is 045T, south is 180T, and so on. On the other hand, if a problem gives an angle with the degree symbol (e.g.,  $120^\circ$ ), then you know that a Cartesian reference direction is being used.



4-6 The method for measuring vector angles depends on the kind of angle.



4-7 This compass rose shows the cardinal and intercardinal directions, as well as degrees.

### 4.3 Transporting Vectors

Drawing accurate vector diagrams requires a protractor and a ruler. For most physics problems, it is sufficient to sketch the approximate magnitude and orientation of each vector. Unless specifically requested, sketches don't have to be made exactly to scale.

Vectors are equal if they have both the same magnitude and the same direction. Examine vectors **A** and **B** in Figure 4-8.

Even though they are at different locations in the diagram, they have identical magnitudes and they point in the same direction, so  $\mathbf{A} = \mathbf{B}$ . Remember that vectors are models of the physical quantities that they represent. If necessary for the sake of a problem solution, it is perfectly permissible to transport a vector from one location to another in a diagram as long as you maintain its original length and orientation (see Figure 4-9).

A marine biologist is periodically monitoring the location of a submerged humpback whale (*Megaptera novaeangliae*) using a sonic transponder. He plots its position at three different times on a nautical chart. The whale's position with time is shown in Figure 4-10. The distance the whale moves between the first and second positions is represented by the length of the line segment between  $P_1$  and  $P_2$ , written  $P_1P_2$ . The whale's *displacement* is indicated by an arrow drawn from  $P_1$  to  $P_2$  (labeled  $\vec{P_1P_2}$ ). Displacement is a vector quantity because it specifies both distance and direction. Distance is a scalar because only the magnitude of the displacement, a single piece of information, is given.

Map direction angles referenced to true north are followed by the letter "T."

Modern directional compass scales are subdivided into  $360^\circ$ . The four principal compass directions, or *cardinal directions*, are represented by angles that are  $90^\circ$  apart: north is 000T, east is 090T, south is 180T, and west is 270T. *Intercardinal directions* (NE, SE, SW, and NW) are  $45^\circ$  from their associated cardinal directions.



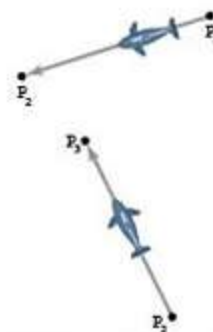
4-8 Equal vectors



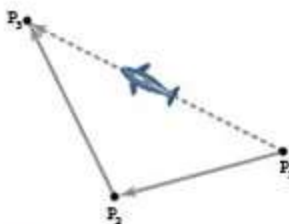
4-9 Vector transport

#### Problem-Solving Strategy 4.1

Vectors in a diagram can be transported from one point to another as long as their lengths and orientations remain unchanged.



4-10 Positions and displacement of a whale



4-11 Positions and displacement of a whale

#### 4A Objectives

After completing this section, I can

- ✓ differentiate between vectors and scalars.
- ✓ describe the properties of a vector.
- ✓ write the correct symbols for vector and scalar quantities.
- ✓ identify the vector angle according to the kind of reference direction specified.

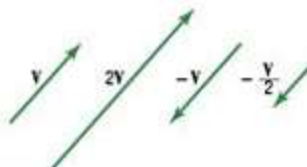
If the whale moves on to  $P_3$ , the total distance that it traveled through the water from  $P_1$  is the sum of the distances  $P_1P_2$  and  $P_2P_3$ . Since the total distance is length alone, it is still just a scalar quantity. The whale's total displacement, however, is the vector from  $P_1$  to  $P_3$  (see Figure 4-11). The length of this vector is clearly different from the distance that the whale traveled. Vectors cannot be added by simple arithmetic. Fortunately, vector addition is not difficult to understand. You will learn this important skill in Section 4B.

### 4A Section Review

- What is the key difference between scalar and vector quantities?
- State whether the following quantities are scalars, vectors, or neither.
 

a. force	e. distance	i. mass
b. one-way sign	f. displacement	j. temperature
c. pressure	g. velocity	k. Wednesday
d. $\pi$ (3.14 . . .)	h. speed	l. density
- When dealing with vectors, what is the difference between  $B$  and  $B$ ? Write another symbol that is equivalent to  $B$ .
- Compare and contrast the properties of angles measured in a Cartesian coordinate system to those measured on a map.
- Why can you transport a vector from one place to another in a vector diagram?

The sum or difference of two or more vectors is called the **resultant**.



4-12 Scalar multiples of vector  $V$

## 4B OPERATIONS WITH VECTORS: GEOMETRIC TECHNIQUES

When more than one quantity is involved in a problem, vectors often need to be added, subtracted, or multiplied. They may be multiplied and divided by scalars as well. Mathematicians have developed methods to simplify these operations and yield useful results. The geometric techniques of vector math can be done quickly with only a ruler and a pencil.

### 4.4 Adding Equal Vectors by Scalar Multiplication

The simplest case of vector addition is adding a vector equal to itself. Graphically, this is accomplished by placing the tail of the second vector at the tip of the first. Their sum is the vector drawn from the tail of the first vector to the tip of the second. The vector sum, called the **resultant**, is twice as long as the original vector and is oriented in the same direction.

$$\mathbf{V} + \mathbf{V} = 2\mathbf{V}$$

The bold plus sign indicates vector addition. Note that this vector sum is also the product of a scalar number and the original vector. When a vector is multiplied by a positive scalar number, its length (magnitude) changes but its direction stays the same. The magnitude of vector  $2V$  is  $2V$ .

In Figure 4-12, if  $V$  is a vector 6 units long,  $2V$  would be a vector 12 units long pointing in the same direction as  $V$ . If the scalar multiplier is negative, the resulting vector points in the opposite direction from the original. Thus,  $-V$  (that is,  $-1 \times V$ ) is a vector 6 units long pointing in the opposite direction from  $V$ . Scalar coefficients may also be fractions, so  $-\frac{1}{2}V$  (or  $-V/2$ ) is a vector 3 units long oriented opposite to  $V$ .