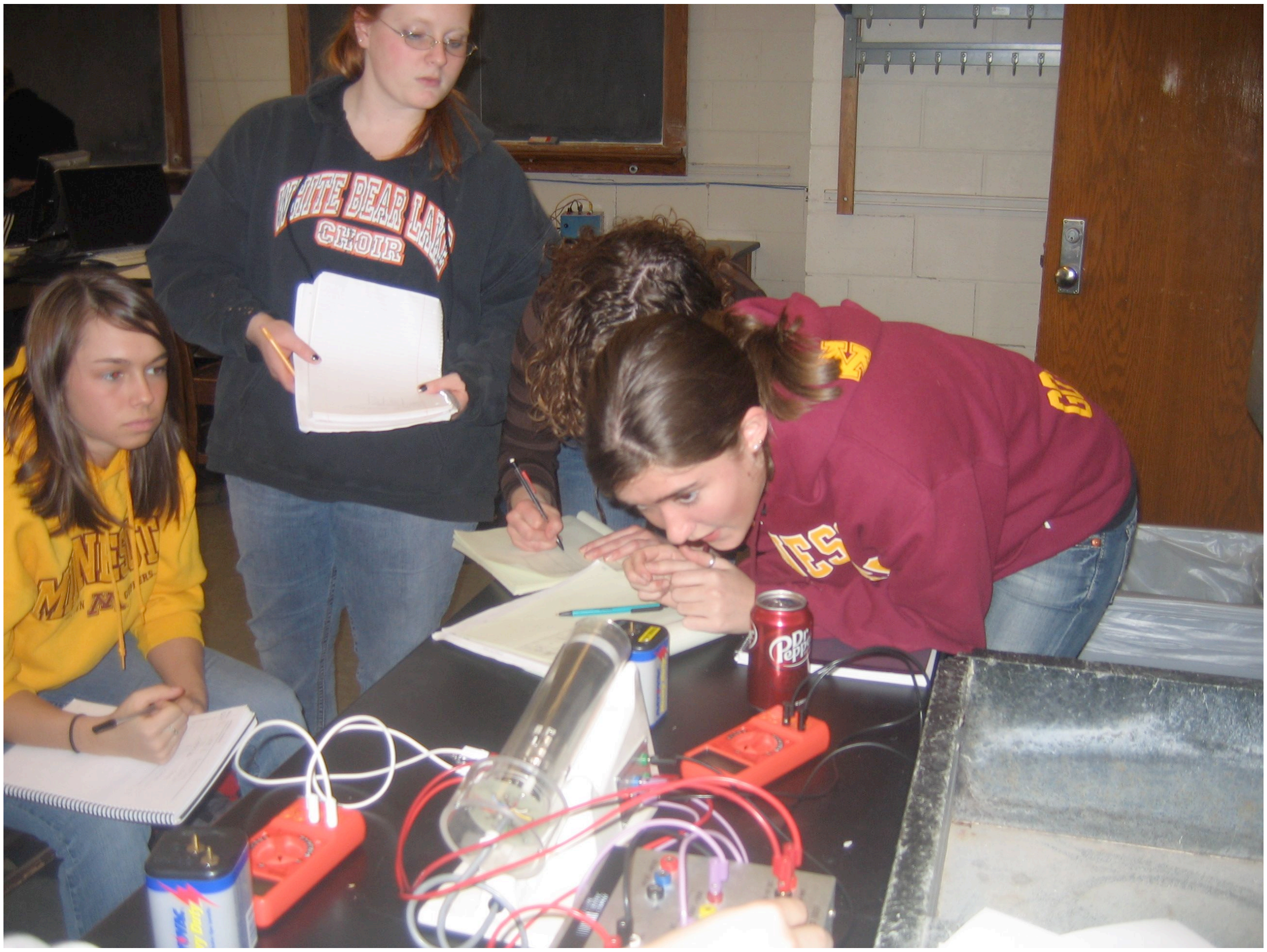

College Ready Physics Standards: A Look to the Future

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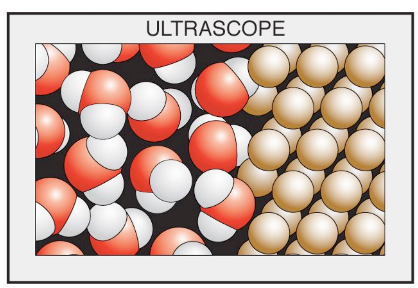
STANDARD 1
INTERACTIONS, SCALE, AND MODELS

Changes in the natural world are the result of interactions. The description, explanation, and prediction of interactions depend on the size and time scale and our models of the structure of matter. For objects moving very fast, the macro (human) scale ideas of absolute time and space must be revised.

Students understand that at the macro (human) scale❖ (length and time larger than about 10^{-6} and smaller than about 10^{+10}) descriptions, explanations, and predictions of the changes that occur during all events (simple interactions, multiple simultaneous interactions, and complex interaction chains) depend on defining a time interval and a system of interest. Macro-scale objects are identified by their properties – how they interact with our senses or measuring instruments, and the substances that make up objects are identified by unique sets of properties.

Different mental models are useful at the atomic scale ($\sim 10^{-10}$ m) and subatomic scale ($\leq 10^{-15}$ m). At the atomic scale, the small-particle model of matter is a useful for explaining the physical properties of substances, such as the state (solid, liquid, or gas) of a substance at room temperature. At the core of this model is the idea that the strength of the attraction between the particles (atoms and molecules) of a substance is different for different substances, ranging from very weak to strong. The atom consists of electrons, protons, and neutrons, and the physical and chemical properties of elements depend on the number of protons in the nucleus and the configuration of its electrons. At the subatomic scale, the quantum mechanical model is useful for describing, explaining and predicting the interaction of subatomic particles with macro-scale objects, including measuring instruments.

At the scale of the nucleus ($\sim 10^{-15}$ m), the force that holds the protons and neutrons together in the nucleus is much stronger than the electric force that holds the electrons and nucleus together in the atom. Consequently, much larger amounts of energy can be transferred out of a system during nuclear interactions than during chemical interactions, which only involve the outermost electrons of an atom or molecule.



Interface between water and a metal.

Objective 1.1: Interactions, Systems, and Scale (Grades 5-8)

Students understand that observed changes in our world are the result of interactions. The description, explanation, and prediction of interactions depend on the defined system and defined time interval, and the distance and time scale involved [cosmic, macro (human), and the atomic and subatomic domains of magnitude].

Objective 1.2: Interactions and Properties (Grades 5-8)

Students understand that at the macro (human) scale, the properties of objects are qualitative or quantitative descriptions of how the object interacts with other objects or systems. Properties that do not depend on the amount of material can be used to identify the material.

Objective 1.3: Interactions and Atomic and Subatomic Models (Grades 5-8 and 9-12)

Students understand that different mental models are useful at the atomic scale (small particle model of matter) and subatomic scale (quantum mechanics) for describing, explaining and predicting events, processes, and the properties of systems.

Objective 1.4: Interactions and Objects Moving *Very* Fast (Grades 9-12)

Students understand that the Newtonian ideas about absolute space and time are incorrect, as Einstein demonstrated with his special theory of relativity.

❖ Underlined words and phrases are defined in the glossary.

OBJECTIVE 1.1
INTERACTIONS, SYSTEMS, AND SCALE (Grades 5-8)

Students understand that observed changes in our world are the result of interactions. The description, explanation, and prediction of interactions depend on the defined system and defined time interval, and the distance and time scale involved [cosmic, macro (human), and the atomic and subatomic domains of magnitude].

Clarification. The ideas in this objective are used throughout physics in both the grades 5 - 8 and grades 9 - 12. When considering any type of qualitative or quantitative problem, one defines the time interval, the system of interest, including boundaries, and identifies interactions within the system and between the system and its surroundings.

Elementary Foundations

By the end of grade 4, students know that:

1. An object can change in various ways, such as in size, weight, color, or temperature. Some features of things may stay the same even when other features change. [BSL 11C/P3a*]

2. People can keep track of some things, seeing where they come from and where they go. [BSL 11C/P2]

3. In things that are made up of many parts, the parts usually influence one another. [BSL 11A/E1]

4. Something may not work well (or at all) if a part of it is missing, broken, worn out, mismatched, or misconnected. [BSL 11A/E2]

Grades 5 - 8

Clarification. Students are introduced to the central theme of interactions and to the idea that the description of an event can be different for different systems of interest and/or time intervals. This idea is developed further in Objective 1.2. Students are also introduced to domains of magnitude of size and time. [Note: Interactions and systems of interest can be introduced in grades 5 - 6. Consideration of distance and time scales should be introduced in later grades 7 – 8.]

BOUNDARY.† *Events are limited to simple, everyday activities. System inputs and outputs should be limited to materials unless energy has been introduced (see Standard 4).*

ESSENTIAL KNOWLEDGE✶

Students know, apply, and reason with the following concepts in the learning outcomes:

M.1.1.1 Scientists describe and explain observed changes in terms of interactions. Two objects (which can be a defined quantity of a solid, liquid or gas) interact when they act on or influence each other to cause some effect. The evidence of the interaction is usually the effect -- an observed change in one or both objects (e.g., change in the motion, change in properties such as mass, volume, temperature, shape, and texture).

M.1.1.2 Sometimes an event or process involves a single interaction between two objects; sometimes it involves complex chains of interactions and/or multiple simultaneous interactions. Some events are very short, while others are very long.

M.1.1.3 Scientists use the concept of a *system* to help in their study of processes and events. By defining a system of interest and a time interval, any inputs, outputs, and changes within the system can be tracked. A real boundary (e.g., surface of cup) or an imaginary boundary (e.g. food-oxygen system in humans) separates the system of interest from the surroundings. The system of interest can be a single object, two interacting objects, or a larger system with subsystems (e.g., car-engine system).

† For further background and instructional guidance, including restrictions in the scope of the content for the learning outcomes for each objective, see Instructional Guidance for Standards 1 (page 77).

✶ For further clarification of the essential knowledge statements and learning outcomes for each objective, see the *Tables of Common Student Conceptual Difficulties* in Instructional Guidance for Standard 1.

M.1.1.4 The interaction description of the same event is different for different defined systems and/or time intervals.

M.1.1.5 A closed (isolated) system does not interact with its surroundings: materials and energy cannot get into or out of the system. Most systems of interest in our everyday lives are open systems. Materials and energy can be transferred into or out of the system. [SSCS, page 101]

M.1.1.6 When defining time intervals and systems of interest, it is convenient to think about three *domains of magnitude* in size (distance in meters) and time (in seconds); the macro (human) domain, the cosmic domain, and the atomic and subatomic domains.[1]

a. The macro (human) domain (distance and time larger than about 10^{-6} and smaller than about 10^{+10}) corresponds roughly with what can be perceived and measured with either human senses or simple instruments (e.g., optical microscopes and telescopes).

b. The cosmic domain (distance and time larger than about 10^{+10}) is so great it is almost beyond imagination, and requires instruments or procedures that depend on long chains of reasoning to understand how they work.

c. Similarly, the atomic and subatomic domains (distance and time < 10^{-6} and < 10^{-14} respectively) are tiny beyond imagination and it requires a great deal of physics knowledge to understand the measurement instruments.

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Represent simple events, in words and/or diagrams, by identifying the interacting objects/systems (or a successive chain of interactions between pairs of objects) and the evidence of these interactions for a defined system and time interval.
- Give examples of systems that consist of subsystems; identify the objects in the subsystems.
- Recognize when the interaction description of the same event is different for different defined systems and/or time intervals.
- Analyze simple mechanical devices in terms of interactions and evidence of interactions, system and subsystems, boundaries, and inputs and outputs. Describe what the various parts are for; estimate (predict) what the effect of making a change in one part of a device would have on the device as a whole.
- Define the time interval and system of interest for a study, including subsystems, the boundaries of the system, the objects in the surroundings that interact with the system of interest, and the inputs and/or outputs of the system during the defined time interval. Justify the usefulness of a choice of a system for the convenience of the study.
- Gives examples of objects or events to add to a chart that shows three domains of magnitude of size and time: atomic and subatomic, macro (human), and cosmic.
- Express numbers like 100, 1,000, and 1,000,000 as powers of ten. [BSL 12B/M9]

Grades 9 - 12

None. Learning outcomes and essential knowledge of interactions, systems, and scales are included in other standards and objectives at the grades 9 - 12 level.

[1] The idea of domains of magnitude came from Robert Karplus's book *Interactions: A Model Approach* (1969, 2003)

OBJECTIVE 1.2
INTERACTIONS AND PROPERTIES (Grades 5-8)

Students understand that at the macro (human) scale, the properties of objects are qualitative or quantitative descriptions of how the object interacts with other objects or systems. Properties that do not depend on the amount of material can be used to identify the material.

Elementary Foundations

By the end of grade 4, students know that:

1. People use their senses to find out about their surroundings and themselves. Different senses give different information. [BSL 6D/P1*]

2. Objects can be described in terms of their properties. Some properties, such as hardness and flexibility, depend upon what material the object is made of, and some properties, such as size and shape, do not. [BSL 4D/P1*]

3. All materials have certain physical properties, such as strength, hardness, flexibility, durability, resistance to water and fire, and ease of conducting heat. [BSL 4D/E6** (SFAA)]

4. Length can be thought of as unit lengths joined together, area as a collection of unit squares, and volume as a set of unit cubes. Areas of irregular shapes can be found by dividing them into squares and triangles. [BSL 9C/E1] Volumes of irregular shapes can be estimated by building the same shape from unit cubes.

5. Measuring instruments (e.g., clocks, stopwatches, rulers, tape measures, unit squares and cubes, simple balances) can be used to gather accurate information for making scientific comparisons of objects and events and for designing and constructing things that will work properly. [BSL 3A/E3]

6. Air is a material that surrounds us and takes up space and whose movement we feel as wind. [BSL 4B/E4*]

Grades 5-8

Clarification. Students begin to develop their skills in precise and accurate measurement (including measurement errors) of the properties of objects. They recognize properties that do not depend on the amount of the substance

RELATED OBJECTIVES: Conservation of Mass, Energy and Charge (2.1)**;** College Board *Standards for College Success: Mathematics and Statistics* MI.3.1 and MII.3.3.

BOUNDARY.† *See Boundary conditions for the learning outcomes in Appendix A.*

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes:

M.1.2.1 A property of an object is a description, qualitative or quantitative, of how the object interacts with other objects (e.g., magnetic materials are materials that are attracted to a magnet).

a. In our everyday life, properties of objects are descriptions of how the objects interact with our senses.

b. The interaction of an object with a measuring instrument (e.g., ruler, thermometer, graduated cylinder, mass balance) provides more reliable information about an object’s properties than our senses alone.

c. A pure substance has a unique set of properties (e.g., melting point, boiling point, density, color, hardness, thermal conductivity) that can be used to identify it. Under all conditions, these properties do not depend on the amount (mass or volume) of the substance. [SSCS, page 97]

M.1.2.2 Volume and mass are two different properties of objects that help us determine the amount of material in an object (e.g., How much mayonnaise is in this jar?).

a. The volume of an object is the number of standard unit cubes that fit inside the object. Volume tells us how much room or space an object takes up. Standard units of volume are cubic centimeters (cm^3), cubic meters (m^3), milliliters (ml), and liters (l). There are different methods of counting the number of unit cubes that fit inside the object.

b. The mass of an object is the number of standard unit masses that balance the object on a mass balance. Standard units of mass are the gram (g) and kilogram (kg).[2]

M.1.2.3 Different gases have different properties, but all gases have volume and mass.] The air in our atmosphere is a mixture of different gases, including oxygen (~20%), nitrogen (~79%), and trace amounts of water vapor, carbon dioxide, and other gases (~1%).

M.1.2.4 When measurements are performed, a true (or exact) value is never obtained; there is always some uncertainty associated with a measurement. [SSCS, page 97]

a. An uncertainty (± measurement error) should be estimated and reported with each measured value. Estimations depend on the precision of the instrument (e.g., 20.5 ± 0.5 ^{o}C).

b. A quantity should be measured several times (trials) and the average (mean) calculated. There is always some variation in measured values. An uncertainty should be estimated and reported with the average (e.g., 105.4 grams ± 2 grams).

M.1.2.5 The density of any object can be measured and calculated by dividing the mass of the object by the volume of the object (D = M/V). For objects made of a (pure) uniform substance, density is the mass of each unit volume of the substance, and is the same for all samples of the substance. Density is different for different substances.

LEARNING OUTCOMES

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Give real-world examples of how instruments are better than using our senses to make scientific observations (e.g. temperature, density, mass, volume).
- Draw interaction chains for determining different properties of objects.
- Measure time intervals, lengths, surface areas, mass, and temperature of different objects, estimate the measurement errors, and report each value with its measurement error (e.g., 105.4 grams ± 1.7 grams).
- Measure, using different methods, the volume of gases and liquids, the inside volume of solid containers, and the volume of regular and irregular solid objects; estimate the measurement errors and report the value and the measurement error. [SSCS, page 96]
- Investigate the relationship between the mass and the volume of different substances. (a) Develop an appropriate method of measuring the mass and the volume of different amounts of a substance. (b) Record measurements of the mass and the volume of different amounts of the substance, and organize this data in a table with estimated measurement errors. (c) Construct a graph, using collected data, to show the relationship between mass and volume, and find a best-fit representation. (d) Use the relationship between mass and volume to define density. Calculate the density of the substance. (e) Compare the densities of different substances. Explain why density can be used to help identify an unknown substance.
- Calculate the mass of different objects by using a given value of volume or measuring the volume, and using the mathematical relationship for density and a table of densities. Similarly, calculate the volume of different objects by using a given value of mass or measuring the mass, and using the mathematical relationship for density and a table of densities. [SSCS, page 96]
- Describe a substance in terms of its properties (e.g., temperature, state, density, thermal conductivity, color, hardness and magnetic properties). Identify which properties of a substance are dependent on the amount of the sample and which are not. [SSCS, page 96]

[2] Only gravitational mass is used in these standards. The distinction between gravitational and inertia mass is a college-level topic.

LEARNING OUTCOMES (5-8), continued

- Identify unknown but familiar substances from descriptions of sets of properties of the unknown substances (including melting or boiling temperatures and density), using knowledge of substances, a table of densities, and a table of melting and boiling temperatures.

- Give examples of evidence that supports the idea that gases have mass and volume, and different gases (e.g., oxygen, nitrogen, hydrogen, carbon dioxide) have different properties. [SSCS, page 96]

Grades 9-12

The quantitative measurement of properties in the grade band 9-12 are embedded in the other objectives.

OBJECTIVE 1.3
INTERACTIONS AND ATOMIC AND SUBATOMIC MODELS (Grades 5-8 and Grades 9-12)

Students understand that different mental models are useful at the atomic scale (small particle model of matter) and subatomic scale (quantum mechanics) for describing, explaining and predicting events, processes, and the properties of systems.

Clarification. In grades 5 - 8, students are introduced to the small-particle model of substances (matter). They begin to develop fluency in using the model to explain different physical properties of room temperature gases, liquids, and solids. Students in grades 9 - 12 are introduced to some qualitative ideas in quantum mechanics.

Elementary Foundations

By the end of grade 4, students know that:

1. Science is a process of trying to figure out how the world works by making careful observations and trying to make sense of those observations. [BSL 1A/E2**] Scientists' explanations about what happens in the world come partly from what they observe, partly from what they think. [BSL1B/E3a]

2. A model of something is similar to, but not exactly like, the thing being modeled. Some models, like toys, are physically similar to what they are representing, but others are not. [BSL 11B/P]

3. Geometric figures, diagrams, sketches, number sequences, graphs, number lines, maps, and oral and written descriptions can be used to represent objects, events, and processes in the real world. [BSL 11B/E2*]

4. Representations and models are very useful for communicating ideas about objects, events, processes, and interactions. When using a representation or model to communicate about something, it is important to keep in mind how it is different from the thing being represented or modeled. [BSL 11B/E4*]

5. Materials may be composed of parts that are too small to be seen without magnification. [BSL4D/E3]

Grades 5 - 8

Clarification. In grades 5 - 8, the nature of the interaction forces between the particles in the small-particle model is not specified, but if students have already studied electrical forces (Objective 3.4) the fact that this force is electrical in nature can be discussed.

RELATED OBJECTIVES: Contact Interactions Forces (3.3); Heating and Cooling Interactions and Energy (4.5)

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes:

M.1.3.1 Collections of small pieces (sand, powders, marbles, sugar cubes) may have properties that the individual pieces do not. [BSL4D/E7** (ASL)]

M.1.3.2 Scientists find it useful to compare a new idea about a system, process, or event with something that is familiar. The thing that is familiar is called an analogue model of the system, process, or event. Analogue models can be physical (e.g., small model car in wind tunnel), verbal, and/or visual. [Same as in Objective 2.1]

M.1.3.3 Theories often make use of a set of related ideas that are simplified and idealized – without the complexities of the full theory. This set of simplified, idealized ideas is a mental model.

M.1.3.4 All models have some similarities but also some differences from the real thing. Deciding what kind of model to use depends on its purpose: (1) to help us initially make sense of (understand) the ideas in a mental model, or (2) to help us figure out how a system or process works. A model is considered useful when the difference(s) between the model and the things they represent are not important *for the purpose of the model*.

M.1.3.5 A useful mental model of substances (gas, liquid, or solid) that helps us make sense of the physical properties of substances is:

a. Substances are made up of a huge number of very tiny <u>particles</u> (atoms or molecules). The particles are too small to see with a visible-light microscope.

b. All particles of a (pure) substance have identical mass, volume, and shape, but are different from the particles of all other substances.

c. There is nothing between the particles of a substance (the space is empty of stuff).

d. The particles move continually in all directions with a large range of speeds.

e. The interaction between the particles of a substance is an attraction when they are relatively far apart, and a repulsion when very close during collisions.

f. The strength of the attractive forces between particles is different for different substances, ranging from very weak to strong.

M.1.3.6 The small-particle idea that the strength of the attractive forces between particles is different for different substances helps us explain many physical properties of materials, including *why different substances are a gas, liquid, or solid near room temperature*.

a. When the attractive forces between the particles of a substance are *very weak* (almost none), then the substance is usually a gas near room temperature. Consequently, the particles move (almost) *independently* in all directions with a large range of speeds, and on the average, are far apart compared to the size of the particles. The average speed of the particles of air between collisions is about the speed of sound (about 770 miles per hour) at room temperature.

b. When the attractive forces between the particles of a substance are weak to medium, then the substance is usually a liquid near room temperature. In a liquid, the attractive forces are strong enough to keep the particles clumped close together, but weak enough so the particles can bump and slide past each other.

c. When the attractive forces between the particles of a substance are *strong*, then the substance is usually a solid near room temperature. In a solid, the attraction is strong enough so that the particles can only vibrate back and forth about (relatively) fixed positions.

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Investigate and compare, qualitatively, several properties of room temperature solids, liquids, and gases (e.g., shape, volume, how easy they are to pull apart [tensile strength], how easy they are to compress).

- Give real-world examples of collections of small pieces (e.g., sand, powders) that have properties that the individual pieces do not have. From collections of small pieces, construct physical analogue models of the small-particle explanations of the shape and volume properties of liquids and solids. <u>Explain</u> how the physical model is the same as and different from the small particle model ideas.

LEARNING OUTCOMES (5-8), continued

- Rank the strength of the attractions between the particles of three room-temperature (pure) substances (a solid, a liquid and a gas) in order from greatest to least. [SSCS, page 99]
- Give examples of objects to add to a chart that shows the atomic and part of the macro (human) size scale (about 10^{-10} m to 10^{+3} m). Investigate the range in sizes that can be seen with the unaided eye, a visual light microscope, and instruments like the electron microscope.
- Recognize when different visual representations of an idea in the small-particle model of gases, liquids, and/or solids are good or poor for the purpose of helping us understand the model idea. When appropriate, revise the visual representation.
- Recognize when small-particle explanations of different physical properties of room temperature gases, liquids, and solids are good or poor, using the criteria: (a) the explanation links the macroscopic property of the gas, liquid, or solid to the relevant small-particle model idea(s); (b) the explanation is based on the correct small-particle model idea(s), and (c) the explanation is complete (no important small-particle model ideas are missing from the explanation).
- Explain why solids, liquids and gases have different physical properties (e.g., thermal expansion, how easy they are to compress) at room temperature. Justification is based on the small-particle model of substances.

Grades 9 - 12

Clarification. While some quantum mechanics ideas are abstract and rigorous, the purpose of this objective is not deep understanding at the level of manipulating probability functions. The purpose is to leave students with the modern view that photons and subatomic particles do not have wave-like or particle-like properties – it is the probabilities that are wavelike.

RELATED OBJECTIVES: Mechanical Wave Interactions and Energy (4.3); Radiant Energy Interactions (4.4).

***BOUNDARY*.**† *Excluded are the historical wave-particle duality arguments, the uncertainty principle, and de Broglie's wavelength.*

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes:

H.1.3.1 All atoms consist of three subatomic particles, called protons, neutrons, and electrons. Atoms are mostly empty space. Essentially all of the mass of the atom is in a tiny, dense center or *nucleus* of the atom, which contains positively charged protons and neutral neutrons, which have almost the same mass. Electrons are much lighter than the other subatomic particles, are negatively charged, and are within the empty space that surrounds the nucleus. The electron and proton have equal but opposite charges. In neutral atoms, the number of protons is the same as the number of electrons.

H.1.3.2 Electrons in atoms have definite energy levels, with no values in between. Electrons usually occupy the lowest available energy levels (ground state). When an electron moves from one energy level to another, it emits or absorbs a photon that has energy equal to the energy difference between the levels. The energy levels of electrons are different for each element. Consequently, each element has a unique emission spectrum or absorption spectrum. [SSCS, Chemistry, page 116]

H.1.3.3 The theory called quantum mechanics describes, explains, and predicts subatomic interactions. The quantum mechanical consequences of these interactions are sometimes directly visible on the human scale. In quantum mechanics, *interactions* can be modeled as particle-like or wave-like, depending on the number of ways that the interaction can happen. The evidence for these models includes:

a. Experiments with light interacting with single or double slits that result in a diffraction pattern or two-source interference pattern, which are characteristic of the interaction of mechanical waves with slits.

b. Experiments with light interacting with metals (photoelectric effect), which result in data patterns characteristic of the interaction of objects (called photons) with discrete energies interacting with other objects (electrons of the metal atoms);

ESSENTIAL KNOWLEDGE (9-12), continued

c. Experiments with electrons interacting with crystals (whose atomic structure acts like slits) resulting in diffraction or interference patterns, which are characteristic of the interaction of mechanical waves with slits; and

d. Experiments with high-energy particles interacting with materials that result in data patterns characteristic of the interaction of discrete objects.

H.1.3.4 At the macro (human) scale, the properties[3] of an object are descriptions of how the object interacts with other objects, including measurement instruments, and it appears that the effect of the measuring instrument is insignificant. On the other hand, the properties of objects are among the quantities that define interactions (e.g., charges and masses are part of force laws and energy equations). This paradox causes no difficulty until we reach the scale of very small "objects," like electrons and photons. At this scale, the presence of measurement instruments changes the result of an interaction. We cannot ask questions such as: which slit did the particle (e.g., electron or a photon) go through? We cannot determine precisely both the momentum and the position of an object at the same time. All we can calculate are probabilities.

H.1.3.5 A simplified quantum mechanical mental model of interactions is that there is a set of rules for adding up the probabilities of all possible paths a particle (e.g., photon, electron, or other subatomic particle) could follow from one location to another. The probabilities have the same mathematical form as a wave that changes with time.

a. Sometimes the probabilities add in such a way that the final location of a particle is the same as predicted from classical mechanics (e.g., light travels in straight lines, the laws of reflection and the refraction of light).

b. Sometimes the sum of probabilities result is a probability "cloud" for the final location of the subatomic particle. The thicker the probability cloud, then the more likely (probable) it is to find the subatomic particle at that location at any given time. The thinner the cloud, then the less likely it is to find the particle at that location at any given time. For the two-slit experiment, the probability cloud for a photon or electron is the same as the observed interference pattern.

c. The electrons in an atom do not orbit the nucleus. The sum of the probabilities for the location of a specific electron in an atom is a probability cloud (called an *orbital*). The shape of the probability cloud differs for different electrons in an atom.

H.1.3.6 There are pairs of quantities that can be measured and obtained individually, but never at the same time (e.g., momentum and position, energy and time). You can know one precisely, but then you will know nothing about the other and vice versa. This is called the principle of complementarity.

H.1.3.7 Light and subatomic particles are not particles at one time and waves at another, nor do they have innate particle-like and/or wave-like properties. They are neither particles nor waves. An analogy for quantum mechanics is the flight of a baseball. The path of the baseball is not due to an innate "ballness" property; the path depends of the interactions of the ball with its surroundings (the air and the Earth), and is different in different surroundings (i.e., in the space station). Similarly, the path of an electron (or photon or other subatomic particle) does not depend on whether the electron is a particle, a wave, or something else. The path depends on the interaction of the electron with its surroundings, including measurement instruments. The path of a particle to some final location is described in terms a set of rules for interactions – classical mechanics "rules" or laws for the baseball, and quantum mechanics rules for summing probabilities for subatomic particles.[4]

LEARNING OUTCOMES*

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Compare and contrast the mass, charge and location of protons, neutrons and electrons in an atom. [SSCS, page 155]

[3] At this level, students do not need to develop a deeper understanding of the meaning of the properties of subatomic particles (e.g., color, strangeness, and so on).

[4] The flight of a baseball analogy is an adaptation of a personal communication from Ken Heller.

LEARNING OUTCOMES (9-12), continued

- Explain, using absorption and emission spectra, how this evidence supports the idea that electrons have discrete energy levels. Justification includes the use of analogue models and visual representations, and a discussion of how emission and absorption spectra arise, why these spectra are unique to each element, and how these spectra are limited to a set of discrete energies. Compare the spectra of elements to standard spectra in order to identify elements in stars. [SSCS, Chemistry, page 115]
- Justify, based on evidence, the particle model and the wave model of *interactions* of light and subatomic particles with macro (human) scale objects and instruments.
- Compare the effect of a measuring instrument on the results of an interaction at the macro (human) scale and at the subatomic scale.
- Identify, from different pictures of a probability cloud, the regions where a photon or electron is most likely to be found, and justify using knowledge of probability clouds.
- Explain why we cannot say that light and electrons are sometimes particles and sometimes waves, or that that they each have both wavelike and particle-like properties. Justification is based on knowledge of the quantum mechanical model of interactions with subatomic particles.

OBJECTIVE 1.4
INTERACTIONS AND OBJECTS MOVING *VERY* FAST (Grades 9 - 12)

Students understand that the Newtonian ideas about absolute space and time are incorrect, as Einstein demonstrated with his special theory of relativity.

Clarification. The knowledge about the special theory of relativity is qualitative and limited to a few consequences of relativity (time dilation, length contraction, addition of velocities, and space-time). The purpose is not deep understanding of relativity, but an introduction to a different way of thinking about space and time

RELATED OBJECTIVES:
Interactions, Forces, and Motion (3.2). Forces and Fields (5.1)

BOUNDARY.† *Evidence is limited to historical experiments for time dilation and length contraction.*

ESSENTIAL KNOWLEDGE

Students reason with and apply the following concepts in the learning outcomes:

H.1.4.1 While Newton's laws of motion, including the universal law of gravitation, can be used to explain and predict many physical events and have many practical applications, they are not correct for objects traveling near the speed of light. In these cases, Einstein's special theory of relativity must be applied.

H.1.4.1 Newtonian physics is based on the assumption that space and time are absolute and independent. Newton assumed that space itself is a fixed (stationary) reference frame from which all motion can be determined absolutely, and time is constant, progressing at a fixed rate at all locations in space.

H.1.4.1 Einstein's special theory of relativity overthrows Newtonian notions of absolute space and time, although the effects are only noticeable for objects moving very fast -- a significant fraction of the speed of light). The theory is based on two postulates:

a. *The Principle of Relativity*. The laws of physics are the same in all uniformly moving coordinate systems (inertial frames of reference). So there is there is no absolute time or motion.

b. *The Constancy of Speed of Light in Vacuum.* The speed of light in vacuum has the same value *c* in all uniformly moving coordinate systems. So there is no coordinate system that is at absolute rest.

H.1.4.1 The consequences of the special relativity postulates have been experimentally verified (including the Michelson-Morley experiment). For example:

a. When an object (with mass) is in motion, the passage of time, measured with a clock (including a biological clock like pulse rate), is slowed. Only a person that is in a different frame of reference from the object would be able to detect the slowing of time - as far as the object is concerned, in its frame of reference, the passage of time is the same. This phenomenon is referred to as time dilation.

b. When an object (with mass) is in motion, its measured length shrinks in the direction of its motion. Only a person that is in a different frame of reference from the object would be able to detect the shrinking - as far as the object is concerned, in its frame of reference, its size remains the same. This phenomenon is referred to as length contraction.

c. Relative velocities of uniformly moving observers never exceed the speed of light. For example if a rocket is moving at 2/3 of the speed of light relative to an observer, and the rocket fires a missile at 2/3 of the speed of light relative to the rocket, the missile does not exceed the speed of light relative to the observer.

d. Time cannot be separated from space because the *rate at which time passes depends on an object's velocity relative to the speed of light*. The concept of space-time combines space and time within a single coordinate system, typically with 4 dimensions: length, width, height, and time. The space-time coordinate grid is used to locate "events" rather than just points in space.

Learning Outcomes

Ways in which students engage with and apply the essential knowledge in order to understand the objective:

- Investigate the experimental evidence for time dilation, length contraction, and/or the rules for the addition of velocities in special relativity. Explain how the evidence supports the theory.
- Explain why a stationary observer measures the light clock in a fast-moving system as running slow. Justification includes appropriate diagrams of what an observer in the moving system measures and what the stationary observer measures.
- Explain why a stationary observer measures the distance between objects in a fast-moving system as shorter. Justification includes appropriate diagrams of what an observer in the moving system measures and what the stationary observer measures.
- Evaluate explanations of special relativity as good or poor based on the criteria: (a) the explanation links the evidence to the statement in the explanation; (b) the explanation is based on the correct special relativity idea(s); (c) the explanation is complete (no important special relativity ideas are missing from the explanation); and (d) the explanation is logical.
- Describe the difference between Newtonian space and time and relativistic space-time, using the consequences of the special theory of relativity.