**DISCIPLINARY CORE IDEAS—PHYSICAL SCIENCES**

**Core Idea PS1: Matter and Its Interactions**

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**PS1.B: Chemical Reactions**

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Core Idea PS1 **Matter and Its Interactions**

*How can one explain the structure, properties, and interactions of matter?*

The existence of atoms, now supported by evidence from modern instruments,

was first postulated as a model that could explain both qualitative and quantitative

observations about matter (e.g., Brownian motion, ratios of reactants and

products in chemical reactions). Matter can be understood in terms of the types

of atoms present and the interactions both between and within them. The states

(i.e., solid, liquid, gas, or plasma), properties (e.g., hardness, conductivity), and

reactions (both physical and chemical) of matter can be described and predicted

based on the types, interactions, and motions of the atoms within it. Chemical

reactions, which underlie so many observed phenomena in living and nonliving

systems alike, conserve the number of atoms of each type but change their

arrangement into molecules. Nuclear reactions involve changes in the types of

atomic nuclei present and are key to the energy release from the sun and the balance

of isotopes in matter.

**PS1.A: STRUCTURE AND PROPERTIES OF MATTER**

*How do particles combine to form the variety of matter one observes?*

While too small to be seen with visible light, atoms have substructures of their

own. They have a small central region or nucleus—containing protons and

neutrons—surrounded by a larger region containing electrons. The number of protons

in the atomic nucleus (atomic number) is the defining characteristic of each

element; different isotopes of the same element differ in the number of neutrons

only. Despite the immense variation and number of substances, there are only

some 100 different stable elements.

Each element has characteristic chemical properties. The periodic table, a

systematic representation of known elements, is organized horizontally by increasing

atomic number and vertically by families of elements with related chemical

properties. The development of the periodic table (which occurred well before

atomic substructure was understood) was a major advance, as its patterns suggested

and led to the identification of additional elements with particular properties.

Moreover, the table’s patterns are now recognized as related to the atom’s

outermost electron patterns, which play an important role in explaining chemical

reactivity and bond formation, and the periodic table continues to be a useful way

to organize this information.

The substructure of atoms determines how they combine and rearrange to

form all of the world’s substances. Electrical attractions and repulsions between

charged particles (i.e., atomic nuclei and electrons) in matter explain the structure

of atoms and the forces between atoms that cause them to form molecules

(via chemical bonds), which range in size from two to thousands of atoms (e.g.,

in biological molecules such as proteins). Atoms also combine due to these forces

to form extended structures, such as crystals or metals.

The varied properties (e.g., hardness, conductivity) of the materials one encounters, both natural and manufactured, can be understood in terms of the atomic and molecular constituents present and the forces within and between them.

Within matter, atoms and their constituents are constantly in motion. The arrangement and motion of atoms vary in characteristic ways, depending on the substance and its current state (e.g., solid, liquid). Chemical composition, temperature, and pressure affect such arrangements and motions of atoms, as well as the ways in which they interact. Under a given set of conditions, the state and some properties (e.g., density, elasticity, viscosity) are the same for different bulk quantities of a substance, whereas other properties (e.g., volume, mass) provide measures of the size of the sample at hand.

Materials can be characterized by their intensive measureable properties.

Different materials with different properties are suited to different uses. The ability

to image and manipulate placement of individual atoms in tiny structures allows

for the design of new types of materials with particular desired functionality (e.g.,

plastics, nanoparticles). Moreover, the modern explanation of how particular

atoms influence the properties of materials or molecules is critical to understanding

the physical and chemical functioning of biological systems.

*Grade Band Endpoints for PS1.A*

***By the end of grade 2*.** Different kinds of matter exist (e.g., wood, metal, water),

and many of them can be either solid or liquid, depending on temperature.

Matter can be described and classified by its observable properties (e.g., visual,

aural, textural), by its uses, and by whether it occurs naturally or is manufactured.

Different properties are suited to different purposes. A great variety of

objects can be built up from a small set of pieces (e.g., blocks, construction

sets). Objects or samples of a substance can be weighed, and their size can

be described and measured. (Boundary: volume is introduced only for liquid

measure.)

***By the end of grade 5.*** Matter of any type can be subdivided into particles that

are too small to see, but even then the matter still exists and can be detected by

other means (e.g., by weighing or by its effects on other objects). For example,

a model showing that gases are made from matter particles that are too small

to see and are moving freely around in space can explain many observations,

including the inflation and shape of a balloon; the effects of air on larger particles

or objects (e.g., leaves in wind, dust suspended in air); and the appearance

of visible scale water droplets in condensation, fog, and, by extension, also in

clouds or the contrails of a jet. The amount (weight) of matter is conserved

when it changes form, even in transitions in which it seems to vanish (e.g., sugar

in solution, evaporation in a closed container). Measurements of a variety of

properties (e.g., hardness, reflectivity) can be used to identify particular materials.

(Boundary: At this grade level, mass and weight are not distinguished, and

no attempt is made to define the unseen particles or explain the atomic-scale

mechanism of evaporation and condensation.)

***By the end of grade 8.*** All substances are made from some 100 different types of

atoms, which combine with one another in various ways. Atoms form molecules

that range in size from two to thousands of atoms. Pure substances are made from

a single type of atom or molecule; each pure substance has characteristic physical

and chemical properties (for any bulk quantity under given conditions) that can be

used to identify it.

Gases and liquids are made of molecules or inert atoms that are moving

about relative to each other. In a liquid, the molecules are constantly in contact

with each other; in a gas, they are widely spaced except when they happen to

collide. In a solid, atoms are closely spaced and vibrate in position but do not

change relative locations. Solids may be formed from molecules, or they may be

extended structures with repeating subunits (e.g., crystals). The changes of state

that occur with variations in temperature or pressure can be described and predicted

using these models of matter. (Boundary: Predictions here are qualitative,

not quantitative.)

***By the end of grade 12.*** Each atom has a charged substructure consisting of a

nucleus, which is made of protons and neutrons, surrounded by electrons. The

periodic table orders elements horizontally by the number of protons in the atom’s

nucleus and places those with similar chemical properties in columns. The repeating

patterns of this table reflect patterns of outer electron states. The structure

and interactions of matter at the bulk scale are determined by electrical forces

within and between atoms. Stable forms of matter are those in which the electric

and magnetic field energy is minimized. A stable molecule has less energy, by an

amount known as the binding energy, than the same set of atoms separated; one

must provide at least this energy in order to take the molecule apart.

**PS1.B: CHEMICAL REACTIONS**

*How do substances combine or change (react) to make new substances? How does*

*one characterize and explain these reactions and make predictions about them?*

Many substances react chemically with other substances to form new substances

with different properties. This change in properties results from the ways in which

atoms from the original substances are combined and rearranged in the new substances.

However, the total number of each type of atom is conserved (does not

change) in any chemical process, and thus mass does not change either. The property

of conservation can be used, along with knowledge of the chemical properties

of particular elements, to describe and predict the outcomes of reactions. Changes

in matter in which the molecules do not change, but their positions and their

motion relative to each other do change also occur (e.g., the forming of a solution,

a change of state). Such changes are generally easier to reverse (return to original

conditions) than chemical changes.

“Collision theory” provides a qualitative model for explaining the rates of

chemical reactions. Higher rates occur at higher temperatures because atoms are

typically moving faster and thus collisions are more frequent; also, a larger fraction

of the collisions have sufficient energy to initiate the process. Although a

solution or a gas may have constant chemical composition—that is, be in a steady

state—chemical reactions may be occurring within it that are dynamically balanced

with reactions in opposite directions proceeding at equal rates.

Any chemical process involves a change in chemical bonds and the related

bond energies and thus in the total chemical binding energy. This change is

matched by a difference between the total kinetic energy of the set of reactant

molecules before the collision and that of the set of product molecules after the

collision (conservation of energy). Some reactions release energy (e.g., burning fuel

in the presence of oxygen), and others require energy input (e.g., synthesis of sugars

from carbon dioxide and water).

Understanding chemical reactions and the properties of elements is essential

not only to the physical sciences but also is foundational knowledge for the life

sciences and the earth and space sciences. The cycling of matter and associated

transfers of energy in systems, of any scale, depend on physical and chemical processes.

The reactivity of hydrogen ions gives rise to many biological and geophysical

phenomena. The capacity of carbon atoms to form the backbone of extended

molecular structures is essential to the chemistry of life. The carbon cycle involves

transfers between carbon in the atmosphere—in the form of carbon dioxide—and

carbon in living matter or formerly living matter (including fossil fuels). The proportion

of oxygen molecules (i.e., oxygen in the form O2) in the atmosphere also

changes in this cycle.

*Grade Band Endpoints for PS1.B*

***By the end of grade 2.*** Heating or cooling a substance may cause changes that can

be observed. Sometimes these changes are reversible (e.g., melting and freezing),

and sometimes they are not (e.g., baking a cake, burning fuel).

***By the end of grade 5.*** When two or more different substances are mixed,

a new substance with different properties may be formed; such occurrences

depend on the substances and the temperature. No matter what reaction or

change in properties occurs, the total weight of the substances does not change.

(Boundary: Mass and weight are not distinguished at this grade level.)

***By the end of grade 8.*** Substances react chemically in characteristic ways. In a

chemical process, the atoms that make up the original substances are regrouped

into different molecules, and these new substances have different properties from

those of the reactants. The total number of each type of atom is conserved, and

thus the mass does not change. Some chemical reactions release energy, others

store energy.

***By the end of grade 12.*** Chemical processes, their rates, and whether or not energy

is stored or released can be understood in terms of the collisions of molecules

and the rearrangements of atoms into new molecules, with consequent changes

in total binding energy (i.e., the sum of all bond energies in the set of molecules)

that are matched by changes in kinetic energy. In many situations, a dynamic and

condition-dependent balance between a reaction and the reverse reaction determines

the numbers of all types of molecules present.

The fact that atoms are conserved, together with knowledge of the chemical

properties of the elements involved, can be used to describe and predict chemical

reactions. Chemical processes and properties of materials underlie many important

biological and geophysical phenomena.