Microgravity Science Primer

We experience many manifestations of gravity on a day to day basis. If we drop something, it falls toward Earth. If we release a rock in a container of water, the rock settles to the bottom of the container. We experience other effects of gravity regularly, although we may not think of gravity as playing a role.

Consider what happens when a container of water is heated from below. As the water on the bottom is heated by conduction through the container, it becomes less dense than the un-heated, cooler water. Because of gravity, the cooler, more dense water sinks to the bottom of the container and the heated water rises to the top due to buoyancy. A circulation pattern is produced that mixes the hot water with the colder water. This is an example of buoyancy driven (or gravity driven) convection. The convection causes the water to be heated more quickly and uniformly than if it were heated by conduction alone. This is the same density driven convection process to which we refer when we state matter-of-factly that “hot air rises.”

In addition to mixing, density differences can also cause things to differentially settle through a process called sedimentation. In this process, the more dense components of mixtures of immiscible fluids or solid particles in fluids settle to the bottom of a container due to gravity. If you fill a bucket with very wet mud, and then leave the bucket sitting on the ground, over time the more dense soil particles will sink to the bottom of the bucket due to gravity, leaving a layer of water on top. When you pick up a bottle of Italian salad dressing from the grocery store shelf, you see several different layers in the bottle. The dense solids have settled to the bottom, the vinegar forms a middle layer, and the least dense oil is on top.

Science Standards
Δ ☐ Physical Science
Δ ☐ Unifying Concepts and Processes

Heat transfer occurs through one of three processes or a combination of the three. Conduction is the flow of heat through a body from an area of higher temperature to an area of lower temperature. Molecules in the hot region increase their vibrational energy as they are heated. As they collide with molecules with lower vibrational energy (cooler ones), some of the vibrational energy is passed to the cooler ones, their energy is increased, and heat is passed on.

Heat transfer by convection is the movement of heat by motion of a fluid. This motion can be the result of some force, such as a pump circulating heated water, and is referred to as forced convection. If the motion is the result of differences in density (thermal or compositional), the convection is referred to as buoyancy-driven, density-driven, or natural convection.

Radiation is the emission of energy from the surface of a body. Energy is emitted in the form of electromagnetic waves or photons (packets of light). The character (wavelength, energy of photons, etc.) of the radiation depends on the temperature, surface area, and characteristics of the body emitting the energy. Electromagnetic waves travel with the speed of light through empty space and are absorbed (and/or reflected) by objects they fall on, thus transferring heat. An excellent example of radiative heating is the sun’s heat that we experience on Earth.

Mathematics Standards
Δ ☐ Mathematical Connections

Science Standards
Δ ☐ Earth and Space Science
Δ ☐ Physical Science
Δ ☐ Unifying Concepts and Processes

The mass of a body divided by its volume is its average density.

Science Standards
Δ ☐ Physical Science
Δ ☐ Unifying Concepts and Processes

When two or more liquids are immiscible they do not mix chemically.
Gravity can also mask some phenomena that scientists wish to study. An example is the process of diffusion. Diffusion is the intermingling of solids, liquids, and gases due to differences in composition. Such intermingling occurs in many situations, but diffusion effects can be easily hidden by stronger convective mixing. As an example, imagine a large room in which all air circulation systems are turned off and in which a group of women are spaced ten feet apart standing in a line. If an open container of ammonia were placed in front of the first woman in line and each woman raised her hand when she smelled the ammonia, it would take a considerable amount of time before everyone raised her hand. Also, the hand raising would occur sequentially along the line from closest to the ammonia to furthest from the ammonia. If the same experiment were performed with a fan circulating air in the room, the hands would be raised more quickly, and not necessarily in the same order. In the latter case, mixing of the ammonia gas with the air in the room is due to both diffusion and convection (forced convection due to the fan) and the effects of the two processes cannot be easily separated. In a similar manner, buoyancy driven convection can mask diffusive mixing of components in scientific experiments.

Some behavior of liquids can also be masked by gravity. If you pour a liquid into a container on Earth, the liquid conforms to the bottom of the container due to gravity. Depending on the shape of the container and on the properties of the container and the liquid, some of the liquid may creep up the walls or become depressed along the walls due to the interrelated phenomena of surface tension, adhesion, cohesion, and capillarity.

The resulting curved surface may be familiar to anyone who has measured water in a small diameter glass container (the water cups upward) or has looked at the level of mercury in a glass thermometer (the mercury cups downward). The distance the contact
line between the liquid and the container moves up or down the container wall is affected by gravity.

Experiments performed on Earth often take advantage of the effects of gravity discussed. For many experiments, however, these effects tend to make the execution of experiments or the analysis of experimental results difficult and sometimes even impossible. Therefore, many researchers design experiments to be performed under microgravity conditions. The different scientific research areas that are studied in microgravity include biotechnology, combustion science, fluid physics, fundamental physics, and materials science. Each of these areas, or disciplines, is discussed below. The discipline is defined, some of the specific effects of gravity that illustrate the benefits of microgravity research are discussed, and some examples of current research are presented. In addition, a brief discussion of the microgravity environment of orbiting spacecraft is provided as an introduction to the application of microgravity research to the exploration and development of space.

The Microgravity Environment of Orbiting Spacecraft

While freefall reduces the effects of gravity, being in an orbiting laboratory introduces other accelerations that cause effects that are indistinguishable from those due to gravity. When a spacecraft is in orbit around Earth, the orbit is actually defined by the path of the center of mass of the spacecraft around the center of Earth. Any object in a location other than on the line traversed by the center of mass of the spacecraft is actually in a different orbit around Earth. Because of this, all objects not attached to the spacecraft move relative to the orbiter center of mass. Other relative motions of unattached objects are related to aerodynamic drag on the

Capillarity can be defined as the attraction a fluid has for itself versus the attraction it has for a solid surface (usually the fluid’s container). The surface tension $\sigma$ in a liquid-liquid or liquid-gas system is the fluids’ tendency to resist an increase in surface area. Surface tension is temperature dependent. Surface tension, capillarity, adhesion, and cohesion work together to drive the contact angle $\theta$ between a solid-liquid interface and liquid-liquid interface when a small diameter tube is dipped into a liquid.

When the contact angle $\theta=0$, the liquid “wets” the tube completely. When $0^\circ<\theta<90^\circ$ (an acute angle), the liquid rises in the tube; when $\theta>90^\circ$ (an obtuse angle), the liquid is depressed in the tube and does not wet the walls. The distance between the liquid surface in the container and in the tube is $h=2\sigma\cos\theta/\rho g$ where $r$ is the radius of the tube ($D/2$), $\rho$ is the density of the liquid, and $g$ is the acceleration due to gravity.

Mathematics Standards
- Functions
- Geometry
- Geometry from a Synthetic Perspective

Science Standards
- Science and Technology
- Science in Personal and Social Perspectives
- Unifying Concepts and Processes

Something that is concave is curved inward like the inner surface of a sphere. Something that is convex is curved like the outer surface of a sphere. A variety of concave and convex lenses and mirrors are used in the design of eyeglasses, magnifying glasses, cameras, microscopes, and telescopes. In the example in the text, water cupping upward produces a concave surface; mercury cupping downward produces a convex surface.
Mathematics Standards

Δ Computation and Estimation
Δ Mathematical Connections
Δ Mathematics as Communication
Δ Measurement

Science Standards

Grades 5-8 (Δ); Grades 9-12 (☑)

Δ Physical Science
Δ Science and Technology
Δ Unifying Concepts and Processes

**Quasi-steady accelerations** in spacecraft are related to the position in the spacecraft, aerodynamic drag, and vehicle rotation. For the Space Shuttle Orbiters, these accelerations are on the order of $10^{-6}$ g and vary with the orbital frequency.

Mathematics Standards

Δ Computation and Estimation
Δ Mathematical Connections
Δ Mathematics as Communication
Δ Measurement

Science Standards

Δ Physical Science
Δ Science and Technology
Δ Unifying Concepts and Processes

*g-jitter* indicates the vibrations experienced by microgravity experiments (for example on parabolic aircraft and the Space Shuttle) that cause effects similar to those that would be caused by a time-varying gravitational field.

The combined acceleration levels that result from the quasi-steady and vibratory contributions are generally referred to as **g-jitter** because their effects are similar to those that would be caused by a time-varying gravitational field. Typical sources for vibrations are experiment and spacecraft fans and pumps, motion of centrifuges, and thruster firings. With a crew onboard to conduct experiments, additional vibrations can result from crew activities.

The combined acceleration levels that result from the quasi-steady and vibratory contributions are generally referred to as the microgravity environment of the spacecraft. On the Space Shuttles, the types of vibration-causing operations discussed above tend to create a cumulative background microgravity environment of about $10^{-4}$ g, considering contributions for all frequencies below 250 Hz.

**Biotechnology**

Biotechnology is an applied biological science that involves the research, manipulation, and
manufacturing of biological molecules, tissues, and living organisms. With a critical and expanding role in health, agriculture, and environmental protection, biotechnology is expected to have a significant impact on our economy and our lives in the next century. Microgravity research focuses on three principal areas—protein crystal growth, mammalian cell and tissue culture, and fundamental biotechnology.

Gravity significantly influences attempts to grow protein crystals and mammalian cell tissue on Earth. Initial research indicates that protein crystals grown in microgravity can yield substantially better structural information than can be obtained from crystals grown on Earth. Proteins consist of thousands—or in the case of viruses, millions—of atoms, which are weakly bound together, forming large molecules. On Earth, buoyancy-induced convection and sedimentation may inhibit crystal growth. In microgravity, convection and sedimentation are significantly reduced, allowing for the creation of structurally better and larger crystals.

The absence of sedimentation means that protein crystals do not sink to the bottom of their growth container as they do on Earth. Consequently, they are not as likely to be affected by other crystals growing in the solution. Because convective flows are also greatly reduced in microgravity, crystals grow in a much more quiescent environment, which may be responsible for the improved structural order of space-grown crystals. Knowledge gained from studying the process of protein crystal growth under microgravity conditions will have implications for protein crystal growth experiments on Earth.

Research also shows that mammalian cells—particularly normal cells—are sensitive to conditions found in ground-based facilities used to culture (grow) them. Fluid flows caused by gravity can separate the cells from each other,
severely limiting the number of cells that will aggregate (come and stay together). But tissue samples grown in microgravity are much larger and more representative of the way in which tissues are actually produced inside the human body. This suggests that better control of the stresses exerted on cells and tissues can play an important role in their culture. These stresses are greatly reduced in microgravity.

**Protein Crystal Growth**

The human body contains over 100,000 different proteins. These proteins play important roles in the everyday functions of the body, such as the transport of oxygen and chemicals in the blood, the formation of the major components of muscle and skin, and the fighting of disease. Researchers in this area seek to determine the structures of these proteins, to understand how a protein’s structure affects its function, and ultimately to design drugs that intercede in protein activities (penicillin is a well-known example of a drug that works by blocking a protein’s function).

Determining protein structure is the key to the design and development of effective drugs.

The main purpose in growing protein crystals is to advance our knowledge of biological molecular structures. Researchers can use microgravity to help overcome a significant stumbling block in the determination of molecular structures: the difficulty of growing crystals suitable for structural analysis. Scientists use X-ray diffraction to determine the three-dimensional molecular structure of a protein. They can calculate the location of the atoms that make up the protein based on the intensity and position of the spots formed by the diffracted X-rays. From high resolution diffraction data, scientists can describe a protein’s structure on a molecular scale and determine the parts of the protein that are important to its functions. Using computer analysis, scientists can create and manipulate three-dimensional models of the protein and examine the intricacies of its structure to create a drug that “fits” into a protein’s active site, like inserting a key into a lock to “turn off” the

*Crystallized protein lysozyme after dialysis to remove small molecule contaminants.*
protein’s function. But X-ray diffraction requires large, homogeneous crystals (about the size of a grain of table salt) for analysis. Unfortunately, crystals grown in Earth’s gravity often have internal defects that make analysis by X-ray diffraction difficult or impossible. Space Shuttle missions have shown that crystals of some proteins (and other complex biological molecules such as viruses) grown on orbit are larger and have fewer defects than those grown on Earth. The improved data from the space-grown crystals significantly enhance scientists’ understanding of the protein’s structure and this information can be used to support structure-based drug design.

Scientists strive for a better understanding of the fundamental mechanisms by which proteins form crystals. A central goal of microgravity protein crystal growth experiments is to determine the basic science that controls how proteins interact and order themselves during the process of crystallization. To accomplish this goal, NASA has brought together scientists from the protein crystallography community, traditional crystal growers, and other physical scientists to form a multidisciplinary team in order to address the problems in a comprehensive manner.

**Mammalian Cell and Tissue Culture**

Mammalian cell tissue culturing is a major area of research for the biotechnology community. Tissue culturing is one of the basic tools of medical research and is key to developing future medical technologies such as ex vivo (outside of the body) therapy design and tissue transplantation. To date, medical science has been unable to fully culture human tissue to the mature states of differentiation found in the body.

The study of normal and cancerous mammalian tissue growth holds enormous promise for applications in medicine. However, conventional static tissue culture methods form flat sheets of growing cells (due to their settling on the bottom of the container) that differ in appearance and function from their three-dimensional counterparts.

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**Science Standards**

- Physical Science
- Unifying Concepts and Processes

A substance that is homogeneous is uniform in structure and/or composition.

*Three different types of protein crystals grown on the Space Shuttle Columbia in 1995: satellite tobacco mosaic virus, lysozyme, and thaumatin.*
Differentiation is the process (or the result of that process) by which cells and/or tissues undergo a progressive specialization of form or function.

The forces acting on a surface can be separated into components perpendicular (normal) to and tangential to the surface. The normal force causes a normal stress and the tangential force is responsible for a tangential, or shear, stress acting on the surface. Shear forces cause contiguous parts of a structure or liquid to slide relative to each other.

In cooperation with the medical community, the bioreactor design is being used to prepare better models of human colon, prostate, breast, and ovarian tumors. Cells grown in conventional culture systems may not differentiate to form a tumor typical of cancer. In the bioreactor, however, these tumors grow into specimens that resemble the original tumor. Similar results have been observed with normal human tissues as well. Cartilage, bone marrow, heart muscle, skeletal muscle, pancreatic islet cells, liver cells, and kidney cells are examples of the normal tissues currently being grown in rotating bioreactors by investigators. In addition,
laboratory models of heart and kidney diseases, as well as viral infections (including Norwalk virus and Human Immunodeficiency Virus (HIV)) are currently being developed using a modified NASA bioreactor experiment design with slight variations in experimental technique and some adjustments to hardware. Continued use of the bioreactor can improve our knowledge of normal and cancerous tissue development. NASA is beginning to explore the possibility of culturing tissues in microgravity, where even greater reduction in stresses on growing tissue samples may allow much larger tissue masses to develop. A bioreactor is in use on the Russian Space Station Mir in preparation for the International Space Station.

**Fundamental Biotechnology**

*Electrophoresis* has been studied on a dozen Space Shuttle flights and has led to additional research in fluid physics in the area of electrohydrodynamics. Phase partitioning experiments, which use interfacial energy (the energy change associated with the contact between two different materials) as the means of separation, have flown on six missions.

**Combustion Science**

Combustion, or burning, is a rapid, self-sustaining chemical reaction that releases a significant amount of heat. Examples of common combustion processes are burning candles, forest fires, log fires, the burning of natural gas in home furnaces, and the burning of gasoline in internal combustion engines. For combustion to occur, three things must normally be present: a fuel, an oxidizer, and an ignition stimulus. Fuels can be solid, liquid, or gas. Examples of solid fuels include filter paper, wood, and coal. Liquid fuels include gasoline and kerosene. Propane and hydrogen are examples of gaseous fuels. Oxidizers can be solid (such as ammonium perchlorate, which is used in Space Shuttle booster rockets), liquid (like hydrogen peroxide), or gaseous.

Science Standards

Δ Physical Science
Δ Science and Technology
Δ Sciences in Personal and Social Perspectives
Δ Unifying Concepts and Processes

*Electrophoresis* is the separation of a substance based on the electrical charge of the molecule and its motion in an applied electric field.

Science Standards

Δ Physical Science
Δ Science and Technology
Δ Sciences in Personal and Social Perspectives
Δ Unifying Concepts and Processes

An exception to the standard combustion process is hypergolic combustion. In this situation, a fuel and an oxidizer spontaneously react on contact without the need for an ignition stimulus. The jets used to maintain and change the Shuttle’s orientation when in orbit are powered by hypergolic reactions.
Air, which contains oxygen, is a particularly common oxidizer. An electrical spark is an example of an ignition stimulus.

Combustion is a key element in many of modern society’s critical technologies. Electric power production, home heating, ground transportation, spacecraft and aircraft propulsion, and materials processing are all examples in which combustion is used to convert chemical energy to thermal energy. Although combustion, which accounts for approximately 85 percent of the world’s energy usage, is vital to our current way of life, it poses great challenges to maintaining a healthy environment. Improved understanding of combustion will help us deal better with the problems of pollutants, atmospheric change and global warming, unwanted fires and explosions, and the incineration of hazardous wastes. Despite vigorous scientific examination for over a century, researchers still lack full understanding of many fundamental combustion processes.

Some objectives of microgravity combustion science research are to enhance our understanding of the fundamental combustion phenomena that are affected by gravity, to use research results to advance combustion science and technology on Earth, and to address issues of fire safety in space. NASA microgravity combustion science research combines the results of experiments conducted in ground-based microgravity facilities and orbiting laboratories and studies how flames ignite, spread, and extinguish (go out) under microgravity conditions.

Research in microgravity permits a new range of combustion experiments in which buoyancy-induced flows and sedimentation are virtually eliminated. The effects of gravitational forces often impede combustion studies performed on Earth. For example, combustion generally produces hot gas (due to the energy released in the reaction), which is less dense that the cooler gases around it. In Earth's gravity, the
hot gas is pushed up by the denser surrounding gases. As the hot gas rises, it creates buoyancy-induced flow that promotes the mixing of the unburned fuel, oxidizer, and combustion products.

The ability to significantly reduce gravity-driven flows in microgravity helps scientists in several ways. One advantage is that the “quieter” and more symmetric microgravity environment makes the experiments easier to model (describe mathematically), thus providing a better arena for testing theories. In addition, eliminating buoyancy-induced flows allows scientists to study phenomena that are obscured by the effects of gravity, such as the underlying mechanisms of fuel and heat transport during combustion processes. Because buoyancy effects are nearly eliminated in microgravity, experiments of longer duration and larger scale are possible, and more detailed observation and examination of important combustion processes can occur.

Scientists often desire an even mixture of the component parts of fuels so that models developed for their experiments can use simplified sets of equations to represent the processes that occur. Sedimentation affects combustion experiments involving particles or droplets because, as the components of greater density sink in a gas or liquid, their movement relative to the other particles creates an asymmetrical flow around the dropping particles. This can complicate the interpretation of experimental results. On Earth, scientists must resort to mechanical supports, levitators, and stirring devices to keep fuels mixed, while fluids in microgravity stay more evenly mixed without sticking together, colliding, or dispersing unevenly.

Mathematics Standards

- Computation and Estimation
- Discrete Mathematics
- Mathematical Connections
- Mathematics as Communication
- Mathematics as Problem Solving
- Mathematics as Reasoning

Science Standards

- Physical Science
- Science as Inquiry
- Science and Technology
- Unifying Concepts and Processes

The creation and use of mathematical models is a key element of science, engineering, and technology. Modeling begins with identifying the physical and chemical phenomena involved in an experiment. Associated mathematical equations such as equations of motion are then identified. These governing equations are solved in order to predict important aspects of the experiment behavior, using appropriate values of experiment parameters such as density, composition, temperature, and pressure. Simple mathematical models can be solved by hand, while more complex experiments are generally modeled using sophisticated algorithms on high speed computers.

In microgravity research, scientists use modeling in preparation for flight experiments and in analysis of the results. Models and experiment procedures are fine-tuned based on comparisons between model predictions and the results of ground-based microgravity experiments (for example, drop facilities and parabolic aircraft flights). This preliminary work allows researchers to best take advantage of space flight opportunities.
To date, combustion science researchers have demonstrated major differences in the structures of various types of flames burning under microgravity conditions and under 1 g conditions. In addition to the practical implications of these results in combustion efficiency, pollutant control, and flammability, these studies establish that better understanding of the individual processes involved in the overall combustion process can be obtained by comparing results from microgravity and Earth gravity tests. One clear example of the advantage of these comparison tests is in the area of fire safety. Most smoke detectors have been designed to detect soot particles in the air, but the sizes of soot particles produced in 1 g are different from those produced in microgravity environments. This means that smoke-detecting equipment must be redesigned for use on spacecraft to ensure the safety of equipment and crew.

Comparisons of research in microgravity and in 1 g have also led to improvements in combustion technology on Earth that may reduce pollutants and improve fuel efficiency. Technological advances include a system that measures the composition of gas emissions from factory smoke stacks so that they can be monitored. In addition, a monitor for ammonia, which is one gas that poses dangers to air quality, is already being produced and is available for industrial use. Engineers have also designed a device that allows natural gas appliances to operate more efficiently while simultaneously reducing air pollution. This may be used in home furnaces, industrial processing furnaces, and water heaters in the future. Another new technology is the use of advanced optical diagnostics and lasers to better define the processes of soot formation so that soot-control strategies can be developed. Devices have also been developed to measure percentages of soot in exhausts from all types of engines and combustors, including those in automobiles and airplanes.
The combustion science program supports experiments in the following research areas:

**Premixed Gas Flames**
In premixed gas flame research, the fuel and oxidizer gases are completely mixed prior to ignition. Scientists are interested in flame speed (the rate at which the flame zone travels away from the ignition source and into the unreacted mixture) as a function of both the type of fuel and oxidizer used and the oxidizer-to-fuel ratio. With sufficiently high or low ratios, the flame does not move into the unreacted mixture; these critical ratios are referred to as lower and upper flammability limits and are of considerable interest in terms of both safety and fundamental science. Gravity can strongly affect both flame speed and flammability limits, chiefly through buoyancy effects. Scientists in this area are also researching gravity's effects on the stability, extinction, structure, and shape of premixed gas flames.

**Gaseous Diffusion Flames**
In this area of research, the fuel and oxidizer gases are initially separate. They tend to diffuse into each other and will react at their interface upon ignition. The structure of these flames under microgravity conditions is quite different than on Earth because of buoyancy-induced flows caused by Earth's gravity. Scientists study flammability limits, burning rates, and how diffusion flame structure affects soot formation. Within this area, results of studies of the behavior of gas-jet flames in a microgravity environment, both in transition and in turbulent flows, are being used to develop models with potential applications in creating effective strategies to control soot formation in many practical applications.

**Liquid Fuel Droplets and Sprays**
In this research area, scientists study the combustion of individual liquid fuel droplets suspended in an oxidizing gas (air, for example). For these experiments, investigators commonly use fuels.
such as heptane, kerosene, and methanol. Gravity hinders fundamental studies of droplet combustion on Earth due to flows induced by high-density droplets that sink and buoyancy-induced upward acceleration of hot combustion products relative to the surrounding gas. These flows cause drops to burn unevenly, making it difficult for scientists to draw meaningful conclusions from their experiments.

This area of study also includes the investigation of the combustion of sprays and ordered arrays of fuel droplets in a microgravity environment for an improved understanding of interactions between individual burning droplets in sprays. Knowledge of spray combustion processes resulting from these studies should lead to major improvements in the design of combustors using liquid fuels.

**Fuel Particles and Dust Clouds**

This area is particularly important in terms of fire safety because clouds of coal dust have the potential to cause mine explosions and grain-dust clouds can cause silos and grain elevators to explode. It is particularly difficult to study the fundamental combustion characteristics of fuel-dust clouds under normal gravity because initially well-dispersed dust clouds quickly settle due to density differences between the particles and the surrounding gas. Because particles stick together and collide during the sedimentation process, they form nonuniform fuel-air ratios throughout the cloud. In microgravity, fuel-dust clouds remain evenly mixed, allowing scientists to study them with much greater experimental control with a goal of mitigating coal mine and grain elevator hazards.

**Flame Spread Along Surfaces**

An important factor in fire safety is inhibiting the spread of flames along both solid and liquid surfaces. Flame spread involves the reaction between an oxidizer gas and a condensed-phase fuel or the vapor produced by the “cooking” of
such a fuel. Research has revealed major differences in ignition and flame-spreading characteristics of liquid and solid fuels under microgravity and normal gravity conditions. Material flammability tests in 1 g, which are strongly affected by buoyancy-induced flows, do not match results obtained in microgravity. It is therefore useful to study both flame spread and material flammability characteristics in microgravity to ensure fire safety in environments with various levels of gravity. The knowledge gained from these studies may also lead to better understanding of dangerous combustion reactions on Earth. Microgravity experiments eliminate complexities associated with buoyancy effects, providing a more fundamental scenario for the development of flame-spreading theories.

Smoldering Combustion
Smoldering combustion is a relatively slow, nonflaming combustion process involving an oxidizer gas and a porous solid fuel. Well-known examples of smoldering combustion are “burning” cigarettes and cigars. Smoldering combustion can also occur on much larger scales with fuels such as polyurethane foam. When a porous fuel smolders for a long period of time, it can create a large volume of gasified fuels, which are ready to react suddenly if a breeze or some other oxidizer flow occurs. This incites the fuel to make the transition to full-fledged combustion, often leading to disastrous fires (like those involving mattresses or sofa cushions). Since heat is generated slowly in this process, the rate of combustion is quite sensitive to heat exchange; therefore, buoyancy effects are particularly important. Accordingly, smoldering combustion is expected to behave quite differently in the absence of gravity.

Combustion Synthesis
Combustion synthesis, a relatively new area of research, involves creating new materials through a combustion process and is closely tied to work in materials science. One area of particular interest is referred to as self-deflagrating high-
temperaturesynthesis. This occurs when two materials—usually two solids—are mixed together, are reactive with one another, and create a reaction that gives off a large amount of heat. Once the reaction is started, the flame will propagate through a pressed mixture of these particles, resulting in a new material. Much of the initial research in this groundbreaking area involves changing variables such as composition, pressure, and preheat temperature. Manipulating these factors leads to interesting variations in the properties of materials created through the synthesis process.

Flame processes are also being used to create fullerenes and nanoparticles. Fullerenes, a new form of carbon, are expensive to produce at this time and cannot be produced in large quantities, but scientists predict more uses for them will be developed as they become more readily available. Nanoparticles (super-small particles) are also of great interest to materials scientists due to the changes in the microstructure of compacted materials that can be produced by sintering, which results in improved properties of the final products. These nanoparticles can thus be used to form better pressed composite materials.

**Fluid Physics**

A fluid is any material that flows in response to an applied force; thus, both liquids and gases are fluids. Some arrangements of solids can also exhibit fluid-like behaviors; granular systems (such as soil) can respond to forces, like those induced by earthquakes or floods, with a flow-like shift in the arrangement of solid particles and the air or liquids that fill the spaces between them. Fluid physicists seek to better understand the physical principles governing fluids, including how fluids flow under the influence of energy, such as heat or electricity; how particles and gas bubbles suspended in a fluid interact with and change the properties of the fluid; how fluids interact with solid boundaries; and how fluids change phase, either from fluid to solid or from one fluid phase to another. Fluid phenomena studied...
range in scale from microscopic to atmospheric and include everything from the transport of cells in the human body to changes in the composition of the atmosphere.

The universal nature of fluid phenomena makes their study fundamental to science and engineering. Understanding the fluid-like behavior of soils under stress will help civil engineers design safe buildings in earthquake-prone areas. Materials engineers can benefit from a better grasp of how the structure and properties of a solid metal are determined by fluid behavior during its formation. And knowledge of the flow characteristics of vapor-liquid mixtures is useful in designing power plants to ensure maximum stability and performance. The work of fluid physics researchers often applies to the work of other microgravity scientists.

**Complex Fluids**

This research area focuses on the unique properties of complex fluids, which include colloids, gels, magneto-rheological fluids, foams, and granular systems.

Colloids are suspensions of finely divided solids or liquids in fluids. Some examples of colloidal dispersions are aerosols (liquid droplets in gas), smoke (solid particles in gas), and paint (solid in liquid). Gels are colloidal mixtures of liquids and solids in which the solids have linked together to form a continuous network, becoming very viscous (resistant to flow). Magneto-rheological fluids consist of suspensions of colloidal particles. Each particle contains many tiny, randomly oriented magnetic grains and an externally applied magnetic field can orient the magnetic grains into chains. These chains may further coalesce into larger-scale structures in the suspension, thereby dramatically increasing the viscosity of the suspension. This increase, however, is totally reversed when the magnetic field is turned off.

Side views of water and airflowing through a clearpipe. At 1g, the air stays on top. In microgravity, the air can form a core down the center of the pipe.
A foam is a nonuniform dispersion of gas bubbles in a relatively small volume of liquid that contains surface-active macromolecules, or surfactants (agents that reduce the surface tension of liquids). Foams have striking properties in that they are neither solid, liquid, nor vapor, yet they exhibit features of all three. Important uses for customdesigned foams include detergents, cosmetics, foods, fire extinguishing, oil recovery, and many physical and chemical separation techniques. Unintentional generation of foam, on the other hand, is a common problem affecting the efficiency and speed of a vast number of industrial processes involving the mixing or agitation of multicomponent liquids. It also occurs in polluted natural waters and in the treatment of wastewater. In all cases, control of foam rheology and stability is required.

Examples of granular systems include soil and polystyrene beads, which are often used as packing material. Granular systems are made up of a series of similar objects that can be as small as a grain of sand or as large as a boulder. Although granular systems are primarily composed of solid particles, their behavior can be fluid-like. The strength of a granular system is based upon the friction between and geometric interlocking of individual particles, but under certain forces or stresses, such as those induced by earthquakes, these systems exhibit fluidic behavior.

Studying complex fluids in microgravity allows for the analysis of fluid phenomena often masked by the effects of gravity. For example, researchers are particularly interested in the phase transitions of colloids, such as when a liquid changes to a solid. These transitions are easier to observe in microgravity. Foams, which are particularly sensitive to gravity, are more stable (and can therefore be more closely studied for longer periods of time) in microgravity. In magneto-rheological fluids, controlling rheology induced by a magnetic field has many potential applications, from shock absorbers and clutch controls for cars to robotic joint controls. Under the force...
of Earth’s gravity, the magnetic particles in these fluids often fall out of suspension due to sedimentation, but in microgravity this problem is eliminated. Investigations of the behavior of granular systems, which have previously been hampered by Earth’s gravity, are more feasible in microgravity because they do not settle as they do on Earth.

**Multiphase Flow and Heat Transfer**

This research area, which has applications in the engineering of heat transfer systems and gas purification systems, focuses on complex problems of fluid flow in varying conditions. Scientists are seeking to add to their currently limited knowledge of how gravity-dependent processes, such as boiling and steam condensation, occur in microgravity. Boiling is known to be an efficient way to transfer large amounts of heat, and as such, it is often used for cooling and for energy conversion systems. In space applications, boiling is preferable to other types of energy conversion systems because it is efficient and the apparatus needed to generate power is smaller.

Another of the mechanisms by which energy and matter move through liquids and gases is diffusive transport. The way atoms and molecules diffuse, or move slowly, through a liquid or gas is due primarily to differences in concentration or temperature. Researchers use microgravity to study diffusion in complex systems, a process that would normally be eclipsed by the force of gravity.

Understanding the physics of multiphase flow and heat transfer will enable scientists to extend the range of human capabilities in space and will enhance the ability of engineers to solve problems on Earth as well. Applications of this research may include more effective air conditioning and refrigeration systems and improvements in power plants that could reduce the cost of generating electricity.
Interfacial Phenomena

Research in this area focuses on how an interface, like the boundary between a solid and a liquid, acquires and maintains its shape. Interface dynamics relate to the interaction of surfaces in response to heating, cooling, and chemical influences. A better understanding of this topic will contribute to improved materials processing and other applications.

Interfacial phenomena, such as the wetting and spreading of two immiscible liquids or the spreading of fluid across a solid surface, are ubiquitous in nature and technology. Duck feathers and waterproof tents repel water because the wetting properties of the surfaces of their fibers prevent water from displacing the air in the gaps between the fibers. In contrast, water spontaneously displaces air in the gaps of a sponge or filter paper. Technologies that rely on dousing surfaces with fluids like agricultural insecticides, lubricants, or paints depend on the wetting behavior of liquids and solids. Wetting is also a dominant factor in materials processing techniques, including film and spray coating, liquid injection from an orifice, and crystal growth. Interfaces dominate the properties and behavior of advanced composite materials, where wetting of the constituent materials dictates the processing of such materials. Understanding and controlling wetting and spreading pose both scientific and technological challenges.

In reduced gravity, wetting determines the configuration and location of fluid interfaces, thus greatly influencing, if not dominating, the behavior of multiphase fluid systems. This environment provides scientists with an excellent opportunity to study wetting and surface tension forces that are normally masked by the force of Earth’s gravity. This research also provides information that can help improve the design of space engineering systems strongly affected by wetting, including liquid-fuel supply tanks, two-phase heat transfer and/or storage loops, and fluids management devices for life support purposes.

Comparison of thermocapillary flows on Earth (top) and in microgravity (bottom). The flow pattern (indicated by the white areas) in the Earth-based experiments is only evident on the fluid’s surface, while the flow pattern in microgravity encompasses the entire fluid.
Dynamics and Stability
This broad area of research includes drop dynamics, capillarity, and magneto/electrohydrodynamics.

Drop dynamics research deals with the behavior of liquid drops and gas bubbles under the influence of external forces and chemical effects. Research in drop dynamics ranges from the study of rain in the atmosphere to the investigation of chemical processes. A potential application of these studies is in the realm of materials processing. In forming solid materials from liquids in space, it is usually important to create pure and/or uniform solids—gas bubbles and drops of foreign liquids are undesirable. Yet due to the microgravity environment, these bubbles and drops of substances of lower densities would not “rise to the top” the way they would if they were on the ground, which makes extraction of the bubbles difficult. Researchers are attempting to resolve this problem in order to facilitate better materials processing in space.

Scientists are also interested in studying single bubbles and drops as models for other natural systems. The perfect spheres formed by bubbles and drops in microgravity (due to the dominance of surface tension forces) are an easy fit to theoretical models of behavior—fewer adjustments need to be made for the shape of the model. Investigators can manipulate the spherical drops using sound and other impulses, creating an interactive model for processes such as atom fissioning.

Capillarity refers to a class of effects that depend on surface tension. The shape a liquid assumes in a liquid-liquid or liquid-gas system is controlled by surface tension forces at the interface. Small disturbances in the balance of molecular energies at these boundaries or within the bulk of the liquid can cause shifts in the liquid’s position and shape within a container (such as a fuel tank) or in a containing material (such as soil). These changes, or capillary effects, often occur in liquids on Earth.
Joule heating occurs when electric current flows through a material. This is how an electric toaster works.

Researchers observe the float package and data rack of a superfluid helium experiment on a parabolic aircraft flight.

Science Standards

- Physical Science
- Science and Technology
- Unifying Concepts and Processes

Joule heating occurs when electric current flows through a material. This is how an electric toaster works.


but are to some degree masked or minimized by the stronger force of gravity. In microgravity, however, capillary effects become prominent. The study of capillary phenomena in microgravity will enable researchers to better understand and predict fluid configurational changes both on Earth and in low-gravity environments.

Microgravity fluid physics researchers also study the effects of magnetic and electric fields on fluid flows, or magneto/electrohydrodynamics. Promising microgravity research subjects in this area include weak fluid flows, such as those found in poorly conducting fluids in a magnetic field, and Joule heating. In Earth's gravity, Joule heating causes buoyancy-driven flows which, in turn, obscure its effects. In microgravity, however, buoyancy-driven flows are nearly eliminated, so researchers are not only able to study the effects of Joule heating, but they can also observe other processes involving applied electric fields, such as electrophoresis.

Fundamental Physics

Physics is a major part of fundamental science where the ultimate goal is to establish a unified description of the basic laws that govern our world. At present fundamental physics includes low temperature physics, condensed matter physics (the study of solids and liquids), laser cooling and atomic physics, and gravitational and relativistic physics. A unifying characteristic of these research areas is that they address fundamental issues which transcend the boundaries of a particular field of science.

The majority of experiments in fundamental physics are extensions of investigations in Earth-based laboratories. The microgravity experiment in these cases presents an opportunity to extend a set of measurements beyond what can be done on Earth, often by several orders of magnitude. This extension can lead either to a more precise confirmation of our previous understanding of a problem,
or it can yield fundamentally new insight or discovery. The remainder of fundamental physics research involves tests of the fundamental laws which govern our universe. Investigations aim at enhancing our understanding of the most basic aspects of physical laws, and as such may well have the most profound and lasting longrange impact on mankind’s existence on Earth and in space.

There are many examples of how fundamental science has had an impact on the average person. Basic research in condensed matter physics to explain the behavior of semiconductors led to the development of transistors which are now used in communication devices, and which produce ever more prevalent and capable computer technology. Research in low temperature physics to explore the properties of fluids at very low temperatures led to advanced magnetic resonance techniques that have brought extremely detailed magnetic resonance imaging to the medical doctor, so today much exploratory surgery can be avoided. A less widely appreciated part played by fundamental science in today’s world has been the need to communicate large quantities of data from physics experiments to collaborators at many locations around the world. Satisfying this need was instrumental in the development of the Internet and the World Wide Web.

Fundamental physics research benefits from both the reduction in gravity’s effects in Earth-orbit and from the use of gravity as a variable parameter. In condensed matter physics, the physics of critical points has been studied under microgravity conditions. This field needs microgravity because the ability to approach a critical point in the Earthbound laboratory is limited by the uniformity of the sample which is spoiled by hydrostatic pressure variations. One of the important issues in condensed matter physics is the nature of the interface between solids and fluids. The boundary conditions at this interface have an influence on macroscopic phenomena, including wetting. The microscopic aspects of the system near the critical point is the temperature at which the differences between liquids and gases disappear. Above that temperature, the liquid smoothly transforms to the gaseous state; boiling disappears.

Science Standards

\( \Delta \) Physical Science
\( \Delta \) Science and Technology
\( \Delta \) Unifying Concepts and Processes

Hydrostatic pressure is the result of the weight of a material above the point of measurement.
There are three temperature scales commonly used in the world. The Kelvin scale, the Celsius temperature scale, and the Fahrenheit scale. The SI unit for temperature is the Kelvin. In most scientific laboratories, temperatures are measured and recorded in Kelvin's or degrees Celsius. The Celsius scale is used for weather reporting in most of the world. The United States and some other countries use the Fahrenheit scale for weather reporting.

The Kelvin scale is defined around the triple point of water (solid ice, liquid water, and water vapor coexist in thermal equilibrium) which is assigned the temperature 273.16 K. This is equal to 0.01°C and 32.02°F. Absolute zero, the coldest anything can get, is 0 K, -273.15°C, and -459.67°F.

Questions for Discussion

• How do you convert between these different temperature scales?
• What are the boiling and freezing points of water on all these scales, at 1 atm pressure?

Among the most important goals of such research is the improvement of ultra-high precision clocks. These clocks not only provide the standard by which we tell time, but are crucial to the way we communicate and navigate on Earth, in the air, and in space. Laser cooled atoms have significantly improved the accuracy and precision of clocks because these atoms move very slowly and they remain in a given observation volume for very long times. However, observation times in these clocks are still affected by gravity. Because of the effects of gravity, the atoms used in these clocks ultimately fall out of the observation region due to their own weight. Increased observation times are possible in microgravity and can result in further improvements in precision of at least one or two orders of magnitude.

Indeed, clocks are central to the study of general relativity and in questions concerning the very nature of gravity itself. The motivation for space
based clocks is not only tied to the improved performance expected in a microgravity environment but also these clocks will have access to different positions in space than are available on Earth. An important example of this physics is revealed in the comparison of an Earth-based clock with a space-based clock. This comparison provides a direct measurement of the gravitational redshift. Tests of Einstein's theories of relativity and of other theories of gravitation serve as a foundation for understanding how matter and space-time itself behave at large length scales and under extreme conditions. The freefall environment of orbit, the use of low temperature techniques, and the use of high precision frequency standards offer opportunities to perform improved tests of these theories. Direct tests of gravitation theories and other fundamental theories, including the Law of Universal Gravitation, can be performed in a microgravity environment.

**Materials Science**

Materials science is an extremely broad field that encompasses the study of all materials. Materials scientists seek to understand the formation, structure, and properties of materials on various scales, ranging from the atomic to microscopic to macroscopic (large enough to be visible). Establishing quantitative and predictive relationships between the way a material is produced (processing), its structure (how the atoms are arranged), and its properties is fundamental to the study of materials.

Materials exist in two forms: solids and fluids. Solids can be subdivided into two categories—crystalline and noncrystalline (amorphous)—based on the internal arrangement of their atoms or molecules. Metals (such as copper, steel and lead), ceramics (such as aluminum oxide and magnesium oxide), and semiconductors (such as silicon and gallium arsenide) are all crystalline solids because their atoms form an ordered
Science Standards

△ □ Physical Science
△ □ Science and Technology
△ □ Unifying Concepts and Processes

A semiconductor is a substance, such as germanium and silicon, that is a poor electrical conductor at room temperature but is improved by minute additions of certain substances (dopants) or by the application of heat, light, or voltage; a material with a forbidden energy gap less than 3 eV.

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One principal objective of microgravity materials science research is to gain a better understanding of how gravity-driven phenomena affect the solidification and crystal growth of materials. Buoyancy-driven convection, sedimentation, and hydrostatic pressure can create defects (irregularities) in the internal structure of materials, which in turn alter their properties.

The virtual absence of gravity-dependent phenomena in microgravity allows researchers to study underlying events that are normally obscured by the effects of gravity and which are therefore difficult or impossible to study quantitatively on Earth. For example, in microgravity, where buoyancy-driven convection is greatly reduced, scientists can carefully and quantitatively study segregation, a phenomenon that influences the distribution of a solid’s components as it forms from a liquid or gas.

Microgravity also supports an alternative approach to studying materials called containerless processing. Containerless processing has an advantage over normal processing in that containers can contaminate the materials being processed inside them. In addition, there are some cases in which there are no containers that will withstand the very high temperatures and corrosive environments needed to work with certain materials. Containerless processing, in which acoustic, electromagnetic, or electrostatic forces are used to position and manipulate a sample, thereby eliminating the need for a container, is an attractive solution to these problems.

Furthermore, microgravity requires much smaller forces to control the position of containerless samples, so the materials being studied are not
disturbed as much as they would be if they were levitated on Earth.

Materials science research in microgravity leads to a better understanding of how materials are formed and how the properties of materials are influenced by their formation. Researchers are particularly interested in increasing their fundamental knowledge of the physics and chemistry of phase changes (when a material changes from liquid to solid, gas to solid, etc.). This knowledge is applied to designing better process-control strategies and production facilities in laboratories on Earth. In addition, microgravity experimentation will eventually enable the production of limited quantities of high-quality materials and of materials that exhibit unique properties for use as benchmarks.

Microgravity researchers are interested in studying various methods of crystallization, including solidification (like freezing water to make ice cubes), crystallization from solution (the way rock candy is made from a solution of sugar and water), and crystal growth from the vapor (like frost forming in a freezer). These processes all involve fluids, which are the materials that are most influenced by gravitational effects. Examining these methods of transforming liquids or gases into a solid in microgravity gives researchers insight into other influential processes at work in the crystallization process.

**Electronic Materials**
Electronic materials play an important role in the operation of computers, medical instruments, power systems, and communications systems. Semiconductors are well-known examples of electronic materials and are a main target of microgravity materials science research. Applications include creating crystals for use in X-ray, gamma-ray, and infrared detectors, lasers, computer chips, and solar cells. Each of these devices depends on the ability to manipulate the crystalline and chemical structure (perfection) of

Schematic diagram of a multizone furnace used to grow semiconductor materials on the Shuttle. A mechanism moves an existing crystal through the temperature zones, melting the sample then cooling it so that it solidifies. In other furnace designs, the heating mechanism moves and the sample is stationary. What are the advantages and disadvantages of each approach?
Questions for Discussion

- What is an ordinary drinking glass made from?
- What different things are added to glass to change its properties?
- What natural processes produce glasses?
- What are the differences between how glasses and crystalline solids fracture?

the material, which can be strongly influenced by gravity as crystals are formed.

The properties of electronic materials are directly related to the degree of chemical and crystalline perfection present in the materials. However, perfect crystals are not normally the ultimate goal. For example, the presence of just a few impurities in some electronic materials can change their ability to conduct electricity by over a million times. By carefully controlling crystalline defects and the introduction of desirable impurities to the crystals, scientists and engineers can design better electronic devices with a wide range of applications.

Glasses and Ceramics

A glass is any material that is formed without a long range ordered arrangement of atoms. Some materials that usually take crystalline forms, like metals, can also be forced to form as glasses by rapidly cooling molten materials to a temperature far below their normal solidification point. When the material solidifies, it freezes so quickly that its atoms or molecules do not have time to arrange themselves systematically.

Ceramics are inorganic nonmetallic materials that can be extraordinarily strong at very high temperatures, performing far better than metallic systems under certain circumstances. They will have many more applications when important fundamental problems can be solved. If a ceramic turbine blade, for example, could operate at high temperatures while maintaining its strength, it would provide overall thermodynamic efficiencies and fuel efficiencies that would revolutionize transportation. The problem with ceramics is that when they fail, they fail catastrophically, breaking in an irreparable manner.

Glasses and ceramics are generally unable to absorb the impacts that metals can; instead, they crack under great force or stress (whereas metals generally bend before they break). An important part of ceramics and glass research in
Microgravity involves controlling the minute flaws that govern how these materials fail. From information obtained through microgravity research, scientists hope to be able to control the processing of ceramics so that they can, during processing, prevent the formation of imperfections that lead to catastrophic failure.

Applications for knowledge obtained through research in these areas include improving glass fibers used in telecommunications and creating high-strength, abrasion-resistant crystalline ceramics used for gas turbines, fuel-efficient internal combustion engines, and bioceramic artificial bones, joints, and teeth.

**Metals and Alloys**

Metals and alloys constitute an important category of engineered materials. These materials include structural materials, many types of composites, electrical conductors, and magnetic materials. Research in this area is primarily concerned with advancing the understanding of metals and alloys processing so that structure and, ultimately, properties, can be controlled as the materials are originally formed. By removing the influence of gravity, scientists can more closely observe influential processes in structure formation that occurs during solidification. The properties of metals and alloys are linked to their crystalline and chemical structure; for example, the mechanical strength and corrosion resistance of an alloy are determined by its internal arrangement of atoms, which develops as the metal or alloy solidifies from its molten state.

One aspect of the solidification of metals and alloys that influences their microstructures is the shape of the boundary, or interface, that exists between a liquid and a solid in a solidifying material. During the solidification process, as the rate of solidification increases under the same thermal conditions, the shape of the solidifying interface has been shown to go through a series of transitions. At low rates of growths the interface is planar (flat or smoothly curved.

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**Science Standards**

- Physical Science
- Science and Technology
- Unifying Concepts and Processes

An alloy is a combination of two or more metals.

Magnification of a sample of an aluminum-indium alloy. When the sample is melted then controllably solidifies in the AGHF; the indium forms in cylindrical fibers within a solid aluminum matrix.
Mathematics Standards

- Geometry
  - Geometry from an Algebraic Perspective
  - Geometry from a Synthetic Perspective
- Mathematical Connections
- Mathematics as Communication

Science Standards

- Physical Science
- Unifying Concepts and Processes

One of the important characteristics of a solid is its shape. On a visible scale, the function of some solids may depend on the ability to sit in a stable manner on a surface or to fit tightly into some configuration. On a smaller scale, the structures of crystalline solids are defined by the ordered placement of atoms. The basis of understanding crystalline structure and the shapes of solids is a knowledge of the definitions of two-dimensional shapes (polygons) and three-dimensional solids (polyhedra).

A simple k-sided polygon is defined by connecting k points in a plane with line segments such that no edges intersect except at the defining points (vertices). The sum of the angles in any polygon equals \(2x(k-2)x90^\circ\). Specific names given to some simple polygons are given below.

<table>
<thead>
<tr>
<th>Name</th>
<th># of Sides (k)</th>
</tr>
</thead>
<tbody>
<tr>
<td>triangle</td>
<td>3</td>
</tr>
<tr>
<td>quadrilateral</td>
<td>4</td>
</tr>
<tr>
<td>pentagon</td>
<td>5</td>
</tr>
<tr>
<td>hexagon</td>
<td>6</td>
</tr>
<tr>
<td>heptagon</td>
<td>7</td>
</tr>
<tr>
<td>octagon</td>
<td>8</td>
</tr>
<tr>
<td>nonagon</td>
<td>9</td>
</tr>
<tr>
<td>decagon</td>
<td>10</td>
</tr>
<tr>
<td>undecagon</td>
<td>11</td>
</tr>
<tr>
<td>dodecagon</td>
<td>12</td>
</tr>
</tbody>
</table>

Regular polygons are those for which all the sides are the same length and all the angles are the same. The angles of a regular polygon are defined by \(\theta=(k-2)x180^\circ/k\).

Questions for Discussion

- Discuss special cases of triangles and quadrilaterals such as isosceles triangles, parallelograms, trapezoids.
- What is the common name for a regular triangle? For a regular quadrilateral?
- Is there a general equation for the area of any polygon’?

on a macroscopic scale). As the rate of growth increases, the interface develops a corrugated texture until three dimensional cells (similar in shape to the cells in a beehive but much smaller) form in the solid. A further increase in the rate of growth causes the formation of dendrites. The development of these different interface shapes and the transition from one shape to another is controlled by the morphological stability (shape stability) of the interface. This stability is influenced by many factors. Gravity plays an important role in a number of them. In particular, buoyancy-driven convection can influence the stability and, thus, the shape of the solidifying interface. Data obtained about the conditions under which certain types of solidification boundaries appear can help to explain the formation of the crystalline structure of a material.

Another area of interest in metals and alloys research in microgravity is multiphase solidification. Certain materials, which are known as eutectics and monotectics, transform from a single phase liquid to substances of more than one phase when they are solidified. When these materials are processed on Earth, the resultant substances have a structure that was influenced by gravity either due to buoyancy-driven convection or sedimentation. But when processed in microgravity, theory predicts that the end product should consist of an evenly dispersed, multiphase structure.

Eutectic solidification is when one liquid, of uniform composition, forms with two distinct solid phases. An example of such a material is the alloy manganese-bismuth. Solidifying liquid Mn-Bi results in two different solids, each of which has a chemical composition that differs from the liquid. One solid (the minor phase) is distributed as rods, particles, or layers throughout the other solid (a continuous matrix, or major phase).

Monotectics are similar to eutectics, except that a monotectic liquid solidifies to form a solid and a
liquid (both of which are different in composition from the original liquid). Al-In is a monotectic that starts out as indium dissolved completely in aluminum, but when the alloy is solidified under the appropriate conditions, it forms a solid aluminum matrix with long thin “rods” of liquid indium inside it. As the system cools, the rods of liquid indium freeze into solid rods. The indium rods are dispersed within the structure of the solidified material.

**Polymers**

Polymers are macromolecules (very large molecules) made up of numerous small repeating molecular units called monomers. They appear naturally in wool, silk, and rubber and are manufactured as acrylic, nylon, polyester, and plastic. Polymers are typically composed of long chains of monomers, appearing on the molecular scale as if they had a spine of particular elements such as carbon and nitrogen. The bonding between individual polymer molecules affects the material’s physical properties such as surface tension, miscibility, and solubility. Manipulation of these bonds under microgravity conditions may lead to the development of processes to produce polymers with more uniform and controlled specific properties. Important optoelectronic and photonic applications are emerging for polymers, and many of the properties needed are affected by the polymers’ crystallinity. This crystallinity, which is the extent to which chains of molecules line up with each other when the polymer is formed, may be more easily understood and controlled when removed from the influence of gravity.

Growing polymer crystals is more difficult than growing inorganic crystals (such as metals and alloys) because the individual polymer molecules weigh more and are more structurally complex, which hinders their ability to attach to a growing crystal in the correct position. Yet in microgravity, the process of polymer crystal growth can be studied in a fundamental way, with special attention to the effects of such variables as

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**Regular Polyhedra (or the Platonic Solids) are listed and shown below.**

<table>
<thead>
<tr>
<th>Name</th>
<th>Formed By</th>
</tr>
</thead>
<tbody>
<tr>
<td>tetrahedron</td>
<td>4 triangles</td>
</tr>
<tr>
<td>cube</td>
<td>6 squares</td>
</tr>
<tr>
<td>octahedron</td>
<td>8 triangles</td>
</tr>
<tr>
<td>dodecahedron</td>
<td>12 pentagons</td>
</tr>
<tr>
<td>icosahedron</td>
<td>20 triangles</td>
</tr>
</tbody>
</table>

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**The Five Regular Polyhedra or Platonic Solids**

- Tnp-Tetrahedron; second row left-Cube; second row right-Octahedron; third row left-Dodecahedron; third row right-Icosahedron.

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**Questions for Discussion**

- What do you think of as a cylinder and cone?
- What are the general definitions cylinder and cone?
- What shapes are some mineral samples you have in your classroom?
- Investigate the crystalline structure of halite (rock salt), fluorine, quartz, diamond, iron.

temperature, compositional gradients, and the size of individual polymer units on crystal growth. In addition, just as microgravity enables the growth of larger protein crystals, it may allow researchers to grow single, large polymer crystals for use in studying properties of polymers and determining the effects of crystal defects on those properties.

**Microgravity Research and Exploration**

There is one endeavor for which microgravity research is essential. That is the goal of exploring new frontiers of space and using the Moon and Mars as stepping stones on our journey. To achieve these goals, we must design effective life support systems, habitation structures, and transportation vehicles. To come up with workable designs, we must have a thorough understanding of how the liquids and gases that we need to sustain human, plant, and animal life can be obtained, transported, and maintained; of how structural materials can be formed in-situ (on site); and of what types of fuels and fuel delivery systems would allow us to get around most efficiently. Microgravity research can provide the insight needed to get us on our way.

The ability to use extraterrestrial resources is a key element in the exploration of the solar system. We believe that we can use the Moon as a research base to develop and improve processes for obtaining gases and water for human life support and plant growth; for creating building materials; and for producing propellants and other products for transportation and power generation. Oxygen extracted from lunar rocks and soils will be used for life support and liquid oxygen fuel. A byproduct of the extraction of oxygen from lunar minerals may be metals and semiconductors such as magnesium, iron, and silicon. Metals produced on the Moon and material mined from the surface will then be used for construction of habitats, successive processing plants, and solar cells.

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**NASA's Enterprise for the Human Exploration and Development of Space**

The goals of this Enterprise are to

- Increase human knowledge of nature’s processes using the space environment,
- Explore and settle the Solar System,
- Achieve routine space travel,
- Enrich life on Earth through people living and working in space.

Microgravity research will contribute to the areas of cryogenic fuel management, spacecraft systems, in-situ resource utilization, power generation and storage, life support, fire safety, space structures, and science exploration.

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**Elemental Percent Weight on Earth and Moon**

<table>
<thead>
<tr>
<th></th>
<th>Earth's Crust</th>
<th>Lunar Highland Soils</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>47</td>
<td>45</td>
</tr>
<tr>
<td>Fe</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Si</td>
<td>28</td>
<td>21</td>
</tr>
<tr>
<td>Mg</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>Ca</td>
<td>4</td>
<td>11</td>
</tr>
<tr>
<td>Al</td>
<td>8</td>
<td>13</td>
</tr>
<tr>
<td>Na</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>K</td>
<td>3</td>
<td>0</td>
</tr>
</tbody>
</table>

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Current research in the areas of microgravity science will guide our path as we develop the means to use the Moon as a stepping stone to Mars. Research into how granular materials behave under reduced gravity conditions will be important when we design equipment to mine and move large amounts of lunar material. The ability to extract gases and metals from minerals requires an understanding of how gases, liquids, and solids of different densities interact in lunar gravity. Building blocks for habitats and other structures can be made from the lunar regolith. Research into sedimentation and sintering under reduced gravity conditions will lead to appropriate manufacturing procedures. Experiments have already been performed on the Space Shuttle to determine how concrete and mortar mixes and cures in microgravity. An understanding of fluid flow and combustion processes is vital for all the materials and gas production facilities that will be used on the Moon and beyond.

Science Standards

Δ  □ Earth and Space Science
Δ  □ Physical Science

Regolith is a layer of powder-like dust and loose rock that rests on bedrock. In the case of the moon, fragmentation of surface rocks by meteorite bombardment created much of the regolith material.