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Microgravity Science Background
For the Student Spaceflight Experiments Program

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1. Introduction

What is microgravity?

There is no lack of gravity in space. In fact, it is gravity that keeps the Space Shuttle and the International Space Station in orbit around Earth. The reason that astronauts have the feeling and appearance of weightlessness is that they, too, are orbiting (falling around) Earth at the same rate as the Space Shuttle or the Station. As a result, an astronaut in an orbiting spacecraft is in freefall and so has no weight because the walls of the spacecraft apply no force to hold the astronaut up against the force of gravity. The term often used to describe this kind of situation is "microgravity," meaning a condition in which the local effects of gravitational forces are extremely small. While there are ways to achieve the effect of microgravity on Earth (such as using drop towers and shafts), the ideal laboratory for conducting these kinds of experiments is in orbit aboard the Space Shuttle and the International Space Station.

Useful resources:

- Blog Post at *Blog on the Universe* providing an excellent, in-depth look at 'weightlessness'—
  Title: *You Want Me to Do What With a Bathroom Scale?* (http://bit.ly/jPOLx)
  Essential Question: *Why are astronauts weightless in space?*
  Concepts: common knowledge regarding the characteristics of weightlessness; the force of gravity exists between any two objects; definition of weight
  Objective: to address the deep misconception that weightlessness is due to a lack of gravity in space; to understand that astronauts APPEAR weightless because they are in a free-falling environment—the space shuttle
  Math skills: none required
  Optional math skills: relation: the Law of Universal Gravitation; calculating the weight of a person in orbit relative to their weight at sea level
  Special features: a link to a powerful middle school lesson on weightlessness; Dr. Jeff's full calculation of a person's weight in orbit versus weight on the surface of Earth in a downloadable PDF.

- NCESSE developed a great grade 5-8 lesson that easily demonstrates that astronauts inside a free falling soda bottle space shuttle appear weightless. The lesson is part of the *Building a Permanent Human Presence in Space* compendium of lessons for NCESSE's *Journey through the Universe* program.

The lesson is titled ***Grade 5-8 Unit, Lesson 1: Weightlessness***, and can be downloaded as a PDF from the *Building a Permanent Human Presence in Space* page (http://bit.ly/9mDAXa). You can also read an overview of the lesson, and see a photograph of it being conducted at an NCESSE Educator Workshop in Muncie Indiana. Go to: http://bit.ly/d45bzT

Why do an experiment in microgravity?
There are two basic reasons to do experiments in microgravity: (1) To test something that normally happens in the presence of gravity, to see if it still happens in the same way in the absence of gravity's effects; and (2) To test something that does NOT normally happen in the presence of gravity, to see whether the lack of influence from gravity will enable it to happen. For example, many animals such as brine shrimp produce eggs that can be dried, and then reactivated later with water. As the animals live their entire lives floating in water, gravity provides an orientation for what is "up". In microgravity, that is not the case. Can larval brine shrimp, which might be an element of a closed ecosystem in a long-duration spaceflight, develop properly in the absence of gravity's effects? As an example of the second reason, pure crystals of various materials can be difficult to grow in gravity, where the force of gravity can overwhelm the intermolecular forces that attach more material to the growing crystal structure. Pure crystalline samples are useful for, among other things, determining the structure of complex molecules like proteins.

What kind of science can be explored in microgravity?
The kinds of science that can be performed in a microgravity environment are limited only by the experimenters' imagination. For the purposes of the Student Spaceflight Experiments Program, there are nine broad categories of science experiments described in brief in the next section that are specifically addressed in the **Master List of Experiment Samples** document—the list of fluids and solids from which students must design their experiments. You can download this document from the Documents Library at the SSEP website (http://ssep.ncesse.org)

2. Categories of Experiments in the Student Spaceflight Experiments Program

2.1. Bacteria
Bacteria can be found in every habitat on Earth, from Earth's crust and soil to the living bodies of plants, animals, and humans. Different types of bacteria interact with their environment in different ways, from performing vital functions in the ecosystem of our planet by recycling nutrients, to contributing to the general well-being of the human body, or causing us severe harm or even death. Bacteria exhibit the same biological phenomena as other living beings, and therefore they are the ideal laboratories for observing how fundamental biological processes may differ in different environments. By observing how bacteria behave under different circumstances also allows us to come up with better means to make sure beneficial bacteria can thrive in different environments where humans operate, while minimizing the effect of harmful bacteria.

Studying the behavior of bacteria in microgravity is important for two reasons. First, studying how the microgravity environment affects the organisms helps us understand better how living organisms adapt to new environments. This can not only improve our understanding of biological processes on the surface of Earth, but also aid in space exploration. The fundamental details of how biological systems work in microgravity is necessary preparation for sending humans out into space for long periods of time. Do basic biological processes operate as we expect, or are there differences? This will help us understand how microgravity may affect humans on long-duration stays at the International Space Station or on future expeditions to Near-Earth Objects (NEOs), asteroids or Mars.

The second reason to study the behavior of bacteria in microgravity is to determine what kind of effect the presence of these organisms might have on the health of the crew in a closed environment such as the Space Shuttle. While significant efforts are made to make space flights as sterile as possible, it is not possible to eliminate all harmful bacteria. Past studies have shown that human immune response appears to be different in microgravity environment, and antibiotics may not work as well in space as they do on Earth. Understanding how bacteria behave in microgravity – whether they are more virulent, and whether they exhibit resistance to antibiotics – will help in planning future long-term space expeditions. Better understanding of the basic behavior of different types of bacteria may also lead to a better ways to prevent infections or treat them on the surface of Earth, as well.

2.2. Cell Biology

The cell is the basic functional unit of life. A typical cell is 10 micrometers (0.0004 inches) in diameter and 1 nanogram ($4x10^{-11}$ ounces) in mass. Organisms may come in many flavors, from unicellular (consisting of a single cell) such as most bacteria, to multicellular, such as humans, who have about 100 trillion cells. Cell biology is the science that studies the properties and structure of cells; their life cycle, division, and death; and their interactions with their environments. Cells typically exhibit the same fundamental biological processes across the range of organisms, though there are specialized cells in multicellular organisms. Understanding the basic behavior of cells and how they react to different external circumstances is important for all biological sciences. Important biological processes take place on the cellular level, and to understand how different environments may affect the human body, it is good to start by studying how the environment may affect the basic biological processes at the cellular level.

Human beings are spending longer periods of time in microgravity environments. At the present time, this experience is restricted to the International Space Station, but the day will come when humans will leave Earth's gravity for long periods of time and quick rescue from an emergency will not be possible. The fundamental details of how biological systems work in microgravity is necessary preparation for sending humans out into space. We need to understand the basic operations of biology in a weightless environment, as well as in the bodies of organisms we bring to space with us, both intentionally – such as experimental animal subjects or animals for food — and unintentionally – such as mold, fungi, and bacteria. The success of human spaceflight over periods of months to even a year for an individual shows that weightlessness is survivable for extended periods. However, we also know that astronauts experience significant bone loss in space. At a more basic level, the human body – all animal bodies – are filled with complex systems that keep bones and joints healthy, that filter contaminants from the air before they reach the lungs, that enable the sense of smell to work, that keep blood supplying oxygen to cells throughout the body, and that fight off infections. In microgravity, do basic biological processes at a cellular level operate as we expect – for example, blood cell production, cellular reproduction (especially critical muscles like the heart) and blood clotting?

On a more general level, understanding how cellular biology may differ in microgravity from the processes on Earth may also help us understand these basic processes better even in our Earth-bound environment. By removing the effect of gravity from cellular behavior, other, more subtle effects may become observable. Observing how cells adapt to the lack of gravity provides great insight into how organisms react to changes in physical circumstances in general. A better understanding of cellular biology may help in many areas of science, biotechnology, and medicine, from making advances in our understanding of many diseases, such as osteoporosis, to developing new vaccines or testing of new drugs.

2.3. Fish and Other Aquatic Life

For current human space flight missions, between Earth's surface and low Earth orbit, food and air are supplied from Earth. For long-duration space flight, it may not be possible to bring sufficient supplies. One of the questions that needs to be answered to plan for long-duration space flight is whether suitable food sources such as fish could be raised in flight.

We know that an amazingly wide variety of animals use common genes to perform common functions – for example, genes involved in the growth of eyes or originating the development of legs in larval or fetal organisms (depending on the mode of reproduction) are very similar. A more recent discovery, however, is that the expression of different genes depends on interactions with the animal's environment in a complex process known as epigenetics. The epigenetic functioning of genes in adult organisms – humans, for example – already is a complex topic. Some day, long-duration space flight will encounter the development of animals from conception. Is it even possible for organisms to produce a fertilized zygote in microgravity? Can a zygote begin to develop properly without the influence of gravity? Ultimately, we may be curious about whether a viable full-grown organism can develop, but first we need to understand the basic beginning of an individual organism's life in microgravity. Are the animals born in space different from those born on Earth? Are there any developmental defects that arise because of the lack of gravity's effects? Fish eggs and embryos – and aquatic life in general – are ideal ways to observe phenomena related to these questions.

Another aspect of study of aquatic life in a microgravity environment is the study of basic biological processes in multicellular organisms. For example, by studying how the regeneration of the body parts of the Planaria worm may differ in a microgravity environment from the process on the surface of Earth may help us understand better how cellular regeneration occurs in microgravity. This is an important consideration for planning long-duration spaceflights, but also may also offer great insight into matters such as tissue engineering on Earth.

2.4. Fluid Diffusion

A fluid is a material that flows in response to an applied force. This means that, even though in our everyday use of the term "fluid" we tend to think of just liquids, both liquids and gases are fluids. Understanding how fluids behave under different circumstances is important for a vast range of disciplines, from technology (such as processes for the fabrication of miniaturized electronics) to engineering (*e.g.,* how air flows over the wing of a plane, or water flows around a bridge), and biology (*e.g.,* understanding the behavior of fluids in the human body.)

On Earth, we are used to seeing fluids behave in certain ways. For example, if you have two fluids in a container, the lower-density fluid (lighter fluid) will rise to the top while the higher-density fluid (heavier fluid) will sink toward the bottom through the process of buoyancy-driven *convection*. It is characterized by bulk motion of the fluid and is entirely driven by gravity. Convection is therefore a "macroscopic", as opposed to microscopic, mixing process. The effect can also be seen in a single fluid, when parts of the fluid become less dense than others; for example, when boiling a pot of water on a stovetop. In this case, as the water heats up at the bottom of the pot, it becomes less dense and rises to the top, while the denser, cooler water sinks to the bottom. Convection is such a dominant force of fluid physics on Earth that it often makes it difficult to observe other important effects, such as surface tension and fluid diffusion.

In the process of *fluid diffusion*, atoms or molecules of a fluid move from an area where they are highly concentrated to an area of low concentration. For example, when food dye is dropped into a beaker of water, diffusion spreads the dye throughout the water. Fluid diffusion is a mixing process produced by the random motion of atoms and molecules on a microscopic level. It is not driven by gravity, but rather by the temperature of the fluid that sets the atoms or molecules into "thermal" motion. On Earth, convection in the water also helps spread the dye, but in microgravity, the effect of gravity is removed, and the process is driven just by diffusion.

Experiments in fluid diffusion in microgravity provide great insight into subtle effects of fluid physics that are often not easily observable on Earth due to gravity-driven convection, which helps us better understand the behavior of fluids in general.

2.5. Food Products

For current human space flight missions, between Earth's surface and low Earth orbit, food is supplied from Earth. To make sure the food products used by the astronauts are safe and remain nutritious throughout the flight, it is important to study the behavior of common foods in space. These studies become even more important for future long-duration space flights, since there may not be chances of replenishing food supplies after the launch, except for what can be grown within the vehicle. Examples of questions that experiments studying the effect of microgravity on common food products can help answer include: Does the way the food products are stored in microgravity affect their nutritional value, or how long they remain consumable? Do beneficial bacteria such as probiotics survive in microgravity? Do harmful bacteria spoil food products at a different rate from the conditions on the surface? The study of how microgravity affects common foods may also help us develop new food products, both for space exploration and for use here on Earth.

2.6. Inorganic Crystal Growth

Solid materials can be divided into two basic categories depending on the arrangement of atoms and molecules in them. In a crystal, individual atoms or molecules align themselves in an orderly, repeating pattern, while in an amorphous material, there is no ordered atomic or molecular internal structure. Metals, ceramics, and semiconductors are examples of crystalline solids, while many polymers and glasses are amorphous solids. You can even grow crystals from organic compounds like proteins (see Section 2.8). Understanding the crystal growth of solid materials is important for many fields of materials science, especially considering the essential roles of semiconductor crystals (materials the electrical conductivity of which are between those of insulators and conductors) in today's electronics-oriented world. Creating high-quality crystals is an important goal for materials science, since better crystals greatly improve crystal performance and can eliminate some causes of defects in devices using semiconductor crystals, for example.

An example of crystallization is when liquid water changes into ice: when water cools, small ice crystals start to form inside it, they grow and fuse together until all of the liquid water has turned into solid ice. The kind of crystal structure formed when any fluid turns into a crystalline solid depends on the chemistry of the fluid, and the conditions under which it is being solidified. When crystals are grown on Earth, gravitational effects such as convection (turbulent rising of low-density materials on top of high-density materials), sedimentation (solid particles settling out of a fluid to the bottom of a container), and hydrostatic pressure cause irregularities in the internal structure of the crystals, which reduces the size and the purity of the crystals. When the same crystals are grown in a microgravity environment, the crystals grow larger and with a higher purity than what can be achieved on Earth. Furthermore, comparing the crystals grown in space and on the ground can help us determine how to make better crystals on Earth.

2.7. Microencapsulation

In microencapsulation, tiny particles or droplets are surrounded by a coating to give the combined packages useful properties, such as isolating the particles from their surroundings, or slowing down their dispersion into the environment. The typical sizes of these microcapsules vary from a few micrometers (1 micrometer = 0.00004 inches) to a few millimeters (1 millimeter = 0.04 inches) and may be made with a wide range of materials including glass, metals, and polymers. If the capsules are spherical in shape, they are sometimes also called microspheres. While microcapsules have numerous applications, from pesticides to textiles, one of their most promising uses is to deliver drugs in a more efficient way to the human body. For example, a drug in a microcapsule can be kept safe from environmental degradation until it is absorbed in the human body, or the capsulation may aid in the release of a drug in a more controlled manner, which may reduce the side effects of medications.

One of the easiest ways to produce microcapsules is to stir together two immiscible fluids (that is, fluids that cannot be mixed to form a homogeneous substance; e.g., oil and water.) One fluid contains the polymer that will be the coating, and the other the contents of the capsule (such as a drug.) When the mixture of the two fluids (emulsion) evaporates, the microcapsules are left behind as a dry powder.

The behavior of fluids is greatly affected by the presence of gravity. For example, convective motions in the fluids can cause eddies that make it more difficult to make uniform, strong microcapsules. In microgravity, these effects are eliminated. The mixture of the two fluids does not have to be stirred constantly but can be left to stabilize. Observing microencapsulation in these circumstances allows for a better understanding of the process in general, which may aid in designing better methods of microencapsulation in Earth-bound laboratories. Furthermore, it also appears that the interaction of the microcapsules with the cells in the human body are influenced by the crystal structure of the polymer coating of the microcapsules. In microgravity, crystals are known to grow larger. As a result, microcapsules developed in microgravity are more uniform, stronger, significantly larger, and so can carry more drug and include more layers than those produced on Earth.

2.8. Protein Crystal Growth

Proteins are essential parts of organisms, and they participate in virtually every process within cells. By understanding the three-dimensional structure of the thousands of proteins that make up the human body, animals, and plants, scientists can determine how these proteins fit within the overall biology of the organism and how they work together. This will aid in the development of new medicines to fight diseases, for example, since many diseases involve proteins either directly or indirectly.

The best way to study the structure of a protein is to have it form a crystal, which can be studied efficiently using methods such as X-ray crystallography to determine its three-dimensional structure. In a protein crystal, individual molecules align themselves in an orderly, repeating pattern. A good example of a crystal (though not a protein crystal) is rock candy. If sugar is dissolved in hot water to the point where no more sugar can be dissolved, the solution is said to be saturated. As the solution cools down, it then contains more sugar than it normally would be able to hold at that temperature — it is said to be supersaturated. If a string is placed in the solution, sugar crystals start forming on the string through a process called precipitation. Over time, the solution will cool to a steady temperature, but water continues to evaporate, and more sugar molecules are forced to crystallize out of solution and onto the existing crystals, forming rock candy. A similar process can be done to form protein crystals: proteins are dissolved in a fluid, and over time, protein crystals form out of the supersaturated solution.

When crystals are grown on Earth, gravitational effects such as convection (turbulent rising of low-density materials on top of high-density materials), sedimentation (solid particles settling out of a fluid to the bottom of a container), and hydrostatic pressure cause irregularities in the internal structure of the crystals, which reduces the size and the purity of the crystals. When the same crystals are grown in a microgravity environment, the crystals grow larger and have a higher purity than what can be achieved on Earth. The higher-quality crystals allow for a more precise determination of their three-dimensional structure using X-ray crystallography, which makes it possible to determine its function in an organism better, which in turn makes it possible to develop new and better medicines to fight diseases.

2.9. Seeds & Plant Studies

Plants perform an incredibly valuable task of transforming carbon dioxide and water and light into oxygen and leaves, stems, seeds, and food – food for animals to eat, and food for the plant's own life functions. For current human space flight missions, between Earth's surface and low Earth orbit, food and air are supplied from Earth. For long-duration space flight, it may not be possible to bring sufficient supplies and to process air by chemical means sufficiently well to preserve a safe air supply. Plant farming – agriculture – may be a necessity in long-duration manned spaceflight, recycling the chemical constituents within a closed ecosystem using light energy supplied by power sources in the spacecraft or from collected sunlight, and providing food for astronauts to use. The only Earth plant that humans regularly eat, however, that does not grow "up" is seaweed. Everything else that we eat has a stem and grows with an orientation defined by gravity. Under microgravity conditions, that will not be true. Can plants grow in space? Can the seeds germinate and develop properly? Can they perform the same functions for which we farm them here on Earth? Will we have to move to different plants to work in the space environment, and are there any plants from Earth that can do what we need them to do in space? Is it even possible for flowering plants, like most food crops, to be pollinated in microgravity, when there is no gravity to encourage pollen grains to slip down into the plant? Seed and plant studies done in microgravity can help us answer these questions crucial to future long-duration spaceflight. Understanding the processes of germination and the early development of plants in microgravity will also provide insight into how these processes may vary in different environments, and so increase our understanding of the processes at a more basic level. This may aid in more Earth-bound applications, as well, such as farming plants in harsh environments here on Earth.