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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 International Space Station in orbit around Earth, the Moon in orbit around Earth, and the Earth in orbit around the Sun. If you could take a bathroom scale to the top of a really tall mountain that rises to the orbit of the Space Station, you'd still weigh 90% of what you weigh on the surface of the Earth.

So why do astronauts in a spacecraft appear to be 'weightless'? Why does it seem to them that gravity is 'turned off'? The reason is that they are orbiting (falling around) Earth just like their spacecraft. Since astronauts and spacecraft are in 'freefall' together, the astronauts appear to be freely floating relative to the interior of the spacecraft. And any physical, chemical, or biological process in such an environment will proceed as if gravity is absent. That's pretty cool. That's physics.

Here's another example that is a bit more familiar. Imagine you're in an elevator at the top of a very high elevator shaft. (Your elevator has emergency brakes so don't worry.) Inside the elevator you are standing on a small chair, which puts you 1 foot above the floor. You decide to walk off the edge of the chair. At the moment you walk off the chair you hit a button on the wall that detaches the cable holding the elevator, and the elevator and you plummet downward together, accelerating under the action of gravity. Now you are accelerating in the direction of the elevator's floor BUT the elevator's floor is accelerating in the same direction, which is away from you. You never get any closer to the floor! What do you see as a passenger inside the elevator? You're not aware of anything moving. Inside the elevator, you are floating a foot above the floor, as if weightless! (OK, time to hit the emergency brakes.)

"Microgravity" is the term often used to describe the environment experienced inside a freely falling spacecraft (a spacecraft only moving under the action of gravity, so no engines turned on, and no atmospheric drag). While there are ways to achieve the effect of microgravity on Earth (such as using drop towers and shafts), the ideal laboratory for conducting microgravity experiments is in orbit aboard the International Space Station where experiments can be conducted with gravity seemingly turned off for long periods of time. It was a main reason for constructing the International Space Station, America's newest National Laboratory.

Useful resources:

- A 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 Addressed: the characteristics of weightlessness; that the force of gravity exists between any two objects; the 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—an orbiting spacecraft
  Math skills: none required
  Optional math skills: understanding the Law of Universal Gravitation; calculating the weight of a person in orbit relative to their weight at sea level
  Special feature: Dr. Jeff's full calculation of a person's weight in orbit versus their weight on the surface of Earth, provided in a downloadable PDF.

- NCESSE developed a great grade 5-8 lesson that easily demonstrates that model astronauts inside a freefalling 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 experiments in microgravity?
There are two basic reasons to do experiments in microgravity: (1) to see if some phenomenon normally observed in the presence of gravity is still observed in the absence of gravity's effects; and (2) test to see whether something will happen in microgravity that normally would NOT happen in the presence of gravity.

As an example of the first reason, brine shrimp live their entire lives floating in water, with gravity providing the buoyant force that causes them to float, and even providing an orientation for what is 'up' versus what is 'down'. Maybe gravity therefore plays a key role in their life cycle and development. So you might want to explore whether larval brine shrimp develop properly in the absence of gravity's effects by sending brine shrimp eggs to the International Space Station to hatch there.

As an example of the second reason, pure crystals of various materials can be difficult to grow on Earth, where the force of gravity can overwhelm the molecular forces that attach more material to the growing crystal structure. But in microgravity you can grow purer crystals. Pure crystalline samples are useful for, among other things, determining the structure of complex molecules like proteins. You might therefore want to explore growing specific crystals on the International Space Station.

What kinds of science can be explored in microgravity?
The kinds of science experiments that can be performed in a microgravity environment are limited only by the experimenters' imagination. For the purposes of the Student Spaceflight Experiments Program (SSEP), there are nine broad categories of science experiments described briefly in the next section.

The document titled **Master List of Experiment Samples** includes examples of materials (fluids and solids), in each of the nine science categories, which have been used in previous spaceflight experiments. You can download this document from the Documents Library found under the "Resources" tab at the SSEP Website (http://ssep.ncesse.org). While student teams are not required to use materials listed in this document, the list may prove a useful starting point in exploring the types of fluids and solids typically considered in the different microgravity science categories described below.

2. Categories of Microgravity Science Experiments

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 organisms might adapt to a seeming loss of gravity. 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 International Space Station. While significant efforts are undertaken to make spaceflight 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 a 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. A better understanding of the basic behavior of different types of bacteria may lead to 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 (4×10^{-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 a diverse range of organisms, though there are specialized cells in multicellular organisms. Understanding the basic biology of cells, and how that biology is affected by changes in the environment is important to all biological sciences. Regarding human spaceflight, to understand how the microgravity environment may affect the human body, one needs to study the impact of microgravity at the cellular level.

The success of human spaceflight over periods of months to even a year for individual astronauts shows that it is possible to survive in microgravity for extended periods of time. However, we also know that astronauts experience significant bone loss in space. At a more basic level, the human body – all animal bodies – require complex systems at the cellular level 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 of critical muscles like the heart), and blood clotting?

Human beings are spending longer periods of time in microgravity environments. At the present time, this experience is restricted to spacecraft in low Earth orbit, but the day will come when humans will venture farther from Earth for long periods of time and a quick return to Earth in case of an emergency will not be possible. We therefore need to have a detailed understanding of basic biological processes in a microgravity environment, how to combat detrimental effects of microgravity on human health, an understanding of illness and disease in microgravity, and an understanding of appropriate medical treatment. To a great extent, this understanding will come from studies at the cellular level.

More generally, investigating how cell biology in microgravity differs from that on the surface of Earth may provide us with a better understanding of Earth-bound biology. By removing the effect of gravity from cellular behavior, other, subtler, effects may become observable.

2.3. Fish and Other Aquatic Life

For current human spaceflight missions, which take place between Earth's surface and low Earth orbit, food and air are supplied from Earth. For long-duration spaceflight, it may not be possible to bring sufficient supplies. An important question that needs to be answered to plan for long-duration spaceflight is whether suitable food sources such as fish and other aquatic life could be raised in flight.

In addition, 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 spaceflight 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. Species that produce eggs that can be dried and later reactivated with water (such as brine shrimp) are especially suitable for microgravity experiments, since this means that the eggs can be sent into space and reactivated as needed to conduct the microgravity experiment.

Another aspect of the study of aquatic life in a microgravity environment is the investigation 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 spaceflight, but also may 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 (*e.g.,* 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 (large-scale), as opposed to microscopic (small-scale), 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. As a result, fluid diffusion experiments in microgravity provide great insight into subtle effects of fluid physics that are often not easily observable on Earth due to gravity-driven convection. Investigating these microscopic effects in detail helps us better understand the behavior of fluids in general.

2.5. Food Products

For current human spaceflight missions, which take place 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 spaceflight, since there may not be chances of replenishing food supplies after the launch, except for what can be grown within the vehicle.

Some of the questions that can be addressed by experiments studying the effect of microgravity on food products include: Do the ways 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. Many polymers and glasses are amorphous solids, while metals, ceramics, and semiconductors are examples of crystalline solids. It is even possible to grow crystals from organic compounds like proteins (see Section 2.8).

As an example of crystallization, consider how liquid water changes into ice. When water cools, small ice crystals start to form, and they grow and fuse together until all of the liquid water has turned into solid ice. The kind of crystal structure formed when a fluid turns into a crystalline solid depends on the chemistry of the fluid, and the conditions under which it solidifies. 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 the fluid to the bottom of a container), and hydrostatic pressure (the pressure exerted by the fluid on itself due to gravity) 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. Comparing the crystals grown in space and on the ground also may help us develop methods to make better crystals on Earth.

Understanding the crystal growth of solid materials is important for many fields of materials science. For example, creating high-quality crystals can lead to greatly improved crystal performance in devices using semiconductor crystals, which is are an essential aspect of our electronics-oriented world.

2.7. Microencapsulation

In microencapsulation, tiny particles or droplets are surrounded by a coating, creating a great number of individually packaged microcapsules. These microcapsules can have a number of useful properties, such as isolating the central 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 also are called microspheres. While microcapsules have numerous applications, from pesticides to textiles, one of their most promising uses is to deliver drugs to the human body in a more efficient way. For example, a drug in a microcapsule can be kept safe from the its surroundings until it is absorbed in the body, or the capsulation may aid in the release of a drug in a more controlled way, 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 (the turbulent rising of low-density materials on top of high-density materials) can cause eddies that make it more difficult to make uniform, strong microcapsules. In microgravity, these effects are eliminated. 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. It also appears that the interactions 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 and with a higher purity. As a result, microcapsules developed in microgravity appear to be 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, we 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 is rock candy (though it is not a protein crystal). 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 the fluid to the bottom of a container), and hydrostatic pressure (the pressure exerted by the fluid on itself due to gravity) 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, they 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 the function of the protein 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, water, and light into oxygen, leaves, stems, seeds, and food – food for animals to eat, and food for the plant's own life functions. For current human spaceflight missions, which take place between Earth's surface and low Earth orbit, food and air are supplied from Earth. For long-duration human spaceflight, it may not be possible to bring enough supplies and to process air by chemical means sufficiently well to preserve a safe air supply. Agriculture – plant farming – may be necessary for these missions to provide food for astronauts and to recycle the chemical constituents within a closed ecosystem using light energy supplied by power sources in the spacecraft or from collected sunlight.

All the plants humans regularly consume have a stem and grow upward, with an orientation defined by gravity. (The exception is seaweed, which does not grow upward.) But under microgravity conditions, there will be no preferred orientation, and plants will not have a sense of up versus down. Can plants grow in space? Can seeds germinate and develop properly? Will plants grown in space yield the same stored energy and nutritional content as when grown on Earth? Will we have to grow a different variety of plants in a microgravity environment as compared to what we are used to farming on Earth? 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 answer a host of questions crucial to future long-duration spaceflight.

Finally, exploring germination and the early phases of plant growth in microgravity can provide insight into how these processes are affected by gravity, and in this way increase our general understanding of these processes at a fundamental level. This may even provide valuable insight for Earth-bound agriculture, such as farming plants in harsh environments here on Earth.