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Didactic Resources

Microgravity indoor

Microgravidade em recintos fechados

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Some experimental activities of low cost and easy accomplishment are proposed to reproduce the microgravity environment that exists in space ships, free fall towers and parabolic flights. The objective is to provide didactical material to aid teachers in terms of assembling instructions, besides the implementation of these experiments and explanation of the results. The experiments were based on the free fall concept and were recorded in several stages of their falls, making it possible the observation of curious phenomena in this environment.

Keywords: Gravity, Microgravity, Experimental Activity, Free Fall.

São propostas algumas atividades experimentais de baixo custo e fácil realização, para reproduzir o ambiente de microgravidade presente nas naves espaciais, torres de queda livre e vôos parabólicos de aeronaves. O objetivo é proporcionar material didático de apoio ao professor em termos de instruções para a montagem e para a execução destes experimentos, além das devidas explicações acerca dos resultados. Os experimentos são baseados no conceito de queda livre e são registrados em imagem em vários momentos da queda, o que torna possível a observação de fenômenos curiosos neste ambiente.

Palavras-chave: Gravidade, Microgravidade, Atividade Experimental, Queda Livre.

1. Introduction

In movies about space travel or real images inside space ships everything and everybody appear floating. It leads many people to think that gravity does not exist in outer space, what is contrary to Isaac Newton's Universal Gravitation Law. For example, in our solar system, the sun gravity maintains the planets in their orbits.

What happens is the phenomenon called microgravity, where most of a body weight does not exist for a frame of reference. It can be better understood by the elevator example.

1.1. The elevator example

Suppose a person in an elevator on a weighing scale. If the elevator is not moving or it is in linear motion, the normal force (N) will have the same magnitude of a person weight (W), but the opposite direction, see Figure 1.

Figure 1: A person in an elevator at rest or in linear motion, the normal force (N) will have the same magnitude of person weight (W) but the opposite direction (adapted from Rogers et al, 1997[2]).

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Applying the 2^{nd} Newton's law:

$$N - W = m.a \tag{1}$$

Where: N= normal force; W = person weigh; a = elevator acceleration; m = person's mass

Equation 1 could be rewrite as:

$$N - m.g = m.a \tag{2}$$

Or

$$N = m.(g + a) \tag{3}$$

Where: g = gravitational acceleration

When the elevator is not moving or it is in linear motion, the elevator and the person will have zero acceleration and the normal force will be:

$$N = m.g \tag{4}$$

And the weighing scale will mark the person's weight (mg).

If the elevator is in accelerated moving [1]:

- Going up the normal force will be larger than the person's weight (Figure 2a).
- Going down the normal force will be lesser than the person's weight (Figure 2b).
- Going down with acceleration equal to "g", the normal force will be zero and the person inside will float (Figure 2c).
- Going down with acceleration larger than "g", the normal force will be "negative" (the same direction of weight force) and the person will float up to the elevator ceiling (Figure 2d) and, eventually, can walk on it.

In other words, the normal force will be the apparent weight in a frame of reference fixed inside the elevator

Note that, in all situations, the person weight in a frame of reference fixed on earth was the same: m.g

The situation where "a" is equal to "g" and, therefore, normal force is zero is that we are interested in, because it will simulate condition of no apparent weight inside the elevator.

1.2. Microgravity

The term "zero g" is not correct, because we should not forget the other bodies on Earth and in the outer space, as the Sun and the Moon, will attract the bodies in free fall. The prefix "micro" in this case means very low and not 10^{-6}, a microgravity environmental cause by which a free fall can reach about 1% of "g" ($a = g.10^{-2}$) [2]. What does this means? A stone in free fall, without air resistance, obey the equation

$$\mathrm{y(t)} = \mathrm{y_o} + \mathrm{v_o} + \frac{\mathrm{a}t^2}{2} \tag{5}$$

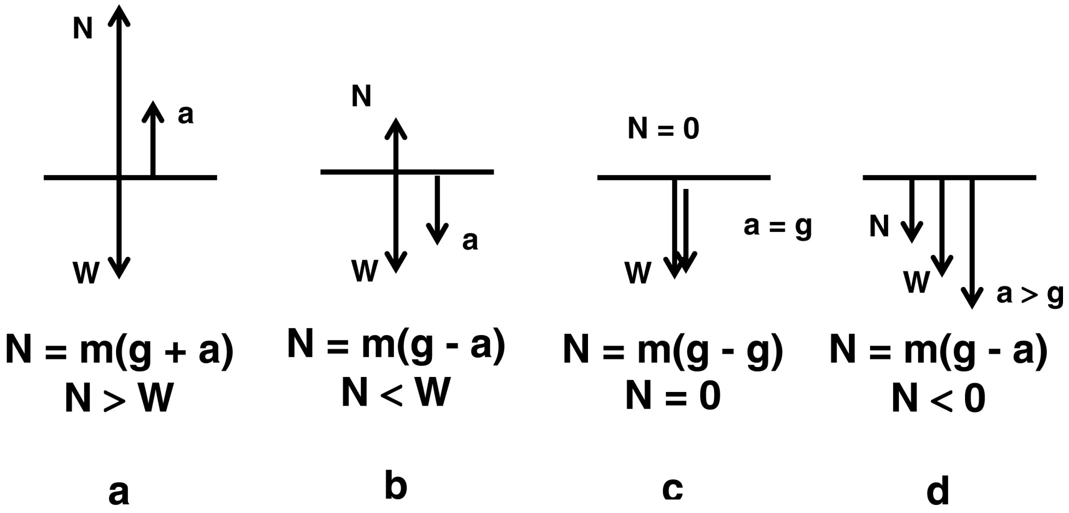

Figure 2: Elevator in accelerated moving: a) Going up, the normal force will be larger than the person's weight. b) Going down, the normal force will be lesser than the person's weight. c) Going down with acceleration equal to "g", the normal force will be zero. d) Going down with acceleration larger than "g", the normal force will be "negative" (the same direction of weight force).

Where: y(t) is the stone vertical position versus time; y_o is the initial position; v_o is the initial speed; “a” is the acceleration, in this case: gravitational acceleration (g); “t” is the time.

If the fall of stone starts from the rest: $v_o = 0$; and if the initial position is chosen as the zero point: $y_o = 0$, the equation will be:

$$\mathrm{y(t)} = \frac{\mathrm{g}t^2}{2} \tag{6}$$

Isolating the time:

$$\mathrm{t} = \sqrt{\frac{2y(t)}{g}} \tag{7}$$

Considering: $\mathrm{g} = 9.8\ \mathrm{m/s^2}$ and $\mathrm{y(t)} = 5\mathrm{m}$, by equation (7) is obtained:

$$\mathrm{t} = \sqrt{\frac{2\mathrm{x}5}{9.8}} \approx 1.01s$$

In a microgravity environment: a = 1% of g = $9.8 \times 10^{-2}\ \mathrm{m/s^2}$, therefore:

$$\mathrm{t} = \sqrt{\frac{10}{9,8\mathrm{x}10^{-2}}} \approx 10.10s$$

Where time is not tending to infinity, but it is low enough to consider the apparent weight, approximately, zero, allowing several studies in technological areas (such as Biotechnology, Medicine or Physics) or didactical and very interesting experiments.

1.3. Creating a microgravity environment

As illustrated in the elevator examples, the effects of gravity (apparent weight) may be removed quite easily by putting any of the following (a person, an object, an experiment) into a state of free fall.

1.3.1. Drop facilities

NASA Lewis Research Center has two drop facilities. One of them provides a 132 meter drop into a hole in the ground similar to a mineshaft. This drop creates a reduced gravity environment for 5.2 seconds. A tower at Lewis allows for 2.2 second drops down a 24 meter structure (Figure 3). NASA Marshall Space Flight Center has a different type of reduced gravity facility. This 100 meter tube allows for drops of 4.5 second duration. Other NASA Field Centers and other countries have additional drop facilities of varying sizes, to serve different purposes.

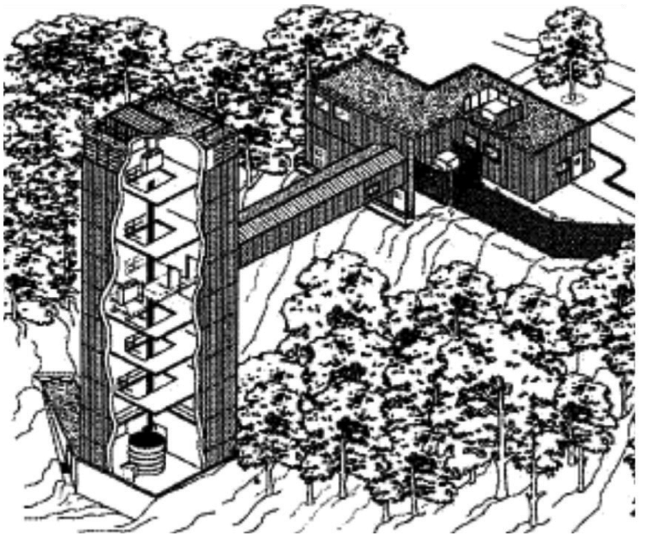

Figure 3: Scheme of NASA Lewis Research Center 2.2 Second Drop Tower [2].

The longest drop time currently available (about 10 seconds) is at a 490 meter deep vertical mineshaft in Japan and it has been converted to a drop facility. Sensations similar to those resulting from a drop in these reduced gravity facilities may be experienced on free fall rides, in amusement parks.

1.3.2. Aircraft

Airplanes are used to achieve reduced gravity conditions for periods of about 15 seconds. This environment is created as the plane flies on a parabolic path. A typical flight lasts two to three hours, allowing experiments and crew members to take advantage of about forty periods of microgravity. To accomplish this, the plane climbs rapidly at a 45 degree angle (this phase is called pull up), traces a parabola (pushover), and, then, descends at a 45 degree angle (pull out) (Figure 4). During the pull up and pull out segments, crew and experiments experience accelerations of about 2g. During the parabola, net accelerations drop as low as 1.5×10^{-2} g for about 15 seconds. Due to the experiences of many who have flown on parabolic aircraft, the planes are often referred to as “Vomit Comets.” Reduced gravity conditions created by the same type of parabolic motion, described above, may be experienced in the series of “floater” hills that are usually located at the end of roller coaster rides and, also, when driving over swells in the road.

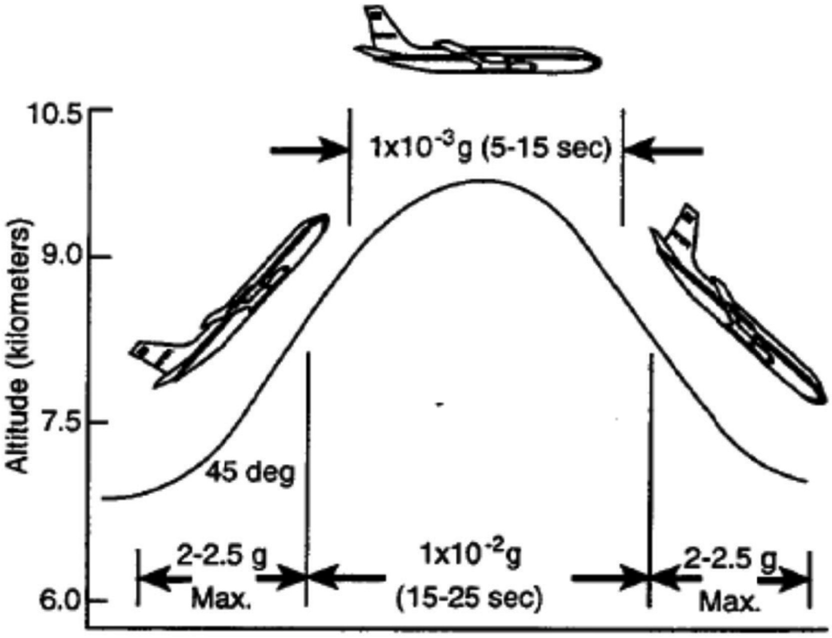

Figure 4: Parabolic Flight Characteristics Mathematics [2]

1.3.3. Orbiting Spacecraft

Although drop facilities, airplanes, and rockets can establish a reduced gravity environment, all these facilities share a common problem. After a few seconds or minutes, Earth gets in the way and free fall stops. To conduct longer scientific investigations, another type of freefall is needed. To see how it is possible to establish microgravity conditions for long periods of time, one must first understand what keeps a spacecraft in orbit. Ask any group of students or adults what keeps satellites, space-stations and spacecraft in orbit and you will probably get a variety of answers. Two common answers are “The rocket engines keep firing to hold it up,” and “There is no gravity in space.” Although the first answer is theoretically possible, the path followed by the spacecraft would technically not be an orbit. Other than the altitude involved and the specific means of exerting an upward force, little difference exists between a spacecraft with its engines constantly firing and an airplane flying around the world. A satellite could not carry enough fuel to maintain its altitude for more than a few minutes. The second answer is also wrong. At the altitude that a spacecraft typically orbits Earth, the gravitational pull on the spacecraft by Earth is about 90% of what it is at Earth’s surface. The altitude that a spacecraft typically orbits Earth is about 300 km above its surface, therefore:

$$F = MS.a = G\frac{ME.MS}{D^2}$$

$$\begin{aligned} a &= G\frac{ME}{D^2} = 6.67 \times 10^{-11}\frac{5.98 \times 10^{24}}{(6.671 \times 10^6)^2} \\ &= 8.96\frac{m}{s^2}(\approx 90\% of g) \end{aligned}$$

Where: a = Gravitational acceleration above 300 km; G = Universal gravitational constant = 6.67 x 10^{-11} N • m^2/kg^2; ME = Mass of the Earth = 5.98 x 10^{24} kg; MS = Mass of spacecraft; D = Earth’s mean radius + 300 km = 6.371 x 10^6 + 300 x 10^3 = 6.6 71 x 10^6 m.

In a previous section, we indicated that Isaac Newton reasoned that the closed orbits of the planets through space were due to gravity’s presence. Newton expanded on his conclusions about gravity and hypothesized how an artificial satellite could be made to orbit Earth. He envisioned a very tall mountain extending above Earth’s atmosphere so that friction with the air would not be a factor. He then imagined cannon at the top of that mountain firing cannon balls parallel to the ground. Two forces acted up on each cannonball as it was fired. One force, due to the explosion of the black powder, propelled the cannon ball straight outward. If no other force were to act on the cannonball, the shot would travel in a straight line and at a constant velocity.

But Newton knew that a second force would act on the cannonball: gravity would cause the path of the cannonball to bend into an arc ending at Earth's surface.

Newton considered how additional cannon balls would travel farther from the mountain each time the cannon fired using more black powder. With each shot, the path would lengthen and soon the cannonballs would disappear over the horizon. Eventually, if the cannon were fired with enough energy, the cannonball would fall entirely around Earth and come back to its starting point (Figure 5). The cannon ball would be in orbit around Earth. Provided no force other than gravity interfered with the cannonball's motion, it would continue circling Earth in that orbit. This is how a spacecraft stay in orbit. It launches on a path that makes an arc above Earth so that the Orbiter travels at the right speed to keep it falling while maintaining a constant altitude above the surface. For example, if a spacecraft climbs to a 320 kilometer high orbit, it must travel at a speed of about 27,740 kilometers per hour to achieve a stable orbit. At that speed and altitude, the spacecraft executes a falling path parallel to the curvature of Earth. Because the spacecraft is in a state of free fall around Earth and due to the extremely low friction of the upper atmosphere, the spacecraft or a space-station and its contents are in a high-quality microgravity environment [2].

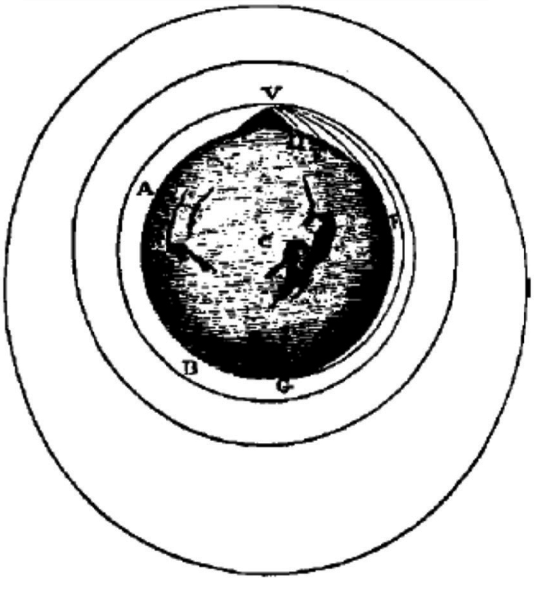

Figure 5: Illustration from Isaac Newton, Principia, VII,Book III, p. 551

Since we cannot go to outer space, we may use a few experiments to reproduce microgravity and its effects in our classroom, as it will be described next

2. Materials and methods

Three different experiments based on freefall towers were assembled to allow microgravity environment. The first experiment examines the behavior of a candle flame. The second examines the trickle of a liquid. The third is a reproduction of an experiment known as Einstein's elevator.

In the flame and liquid case, a digital photograph camera in record mode was utilized. The records were transferred to a computer for edition. The edition objective was to reduce the reproduction speed to 20% of the original and improve the observation of the results. The option frame to frame present in some video software was very useful too.

2.1. The candle flame

When a candle is lit, it produces an elongated flame because of the air convection currents. The mass of the air (included the oxygen) and the combustion products are heated, therefore increasing their volumes, becoming less dense and, then, rising because of the upward forces (Archimedes' principle). The space at the base of the flame is occupied by a colder, denser mass of air, which feeds the flame and is heated becoming less dense and rising due to the upward forces and so on (Figure 6). As the

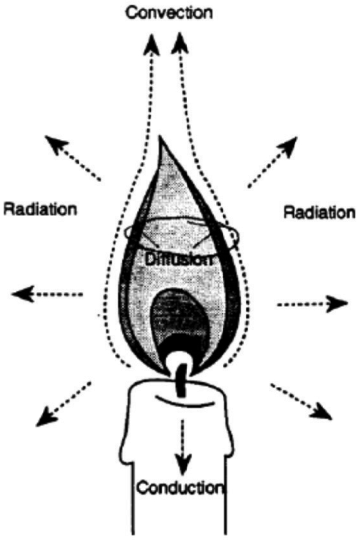

Figure 6: Elongated flame of a candle produced by air convection currents, generated by the flame itself [2].

strength of air convection currents depends on the gravity, if the gravity force is large, the flame became longer, in the contrary, it becomes shorter; and when there is no gravity or in the case of microgravity environment, the flame is short and spherical [1].

The candle flame experiment was based on Paula et al (2000) [3]. It consists of a cardboard box in free fall of about 1 meter, where a camera records the behavior of the flame (Figure 7). Figure 8 shows details of the experimental assembly.

2.2. The trickle of a liquid

It is one of the simplest ways to observe the microgravity effects. It was, also, based on Paula et al (2000) [3]. It utilizes:

- A plastic cup
- A basin
- Colored liquid (to facilitate visualization)
- A digital camera
- Floor cloths (to dry the floor or the equipment)

At the bottom center of the plastic cup, a little hole should be made; cover the hole (with your finger, for example), fill the cup with colored liquid, place it above the basin and uncover the hole. The liquid will begin to flow (Figure 9)

The cup should be released, it will be in free fall, and hold it again before it reaches the basin while the camera records the experiment.

2.3. Einstein's birthday gift

Einstein's birthday gift (called, also, Einstein's elevator) was a toy developed by the physicist Eric Rogers to demonstrate the equivalence principle. Rogers was a professor at Princeton in the 1950's and Einstein's colleague. From time to time, he and his wife liked to give a small puzzle involving physics to their neighbor Professor Einstein, often as birthday present.

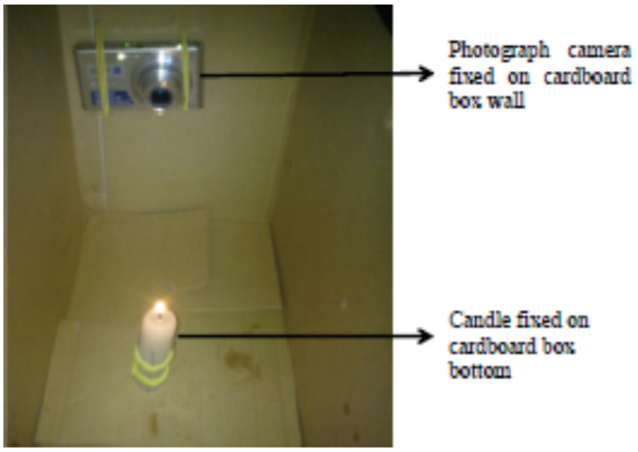

Figure 7: General vision of candle flame experimental assembly.

The last of these was a present on his seventy-sixth birthday, in 1955 (Einstein died about one month later). A metal ball attached to a smooth thread is enclosed in a transparent globe. There is a central, transparent, cup in which the ball could rest; but, initially, the ball hangs by the thread outside the cup (as shown in Figure 10). The thread runs from the ball up to the rim of the cup and down through a central pipe. Below the globe, the thread is tied to a long, weak, spiral spring protected by a transparent tube which ends in a long pole – a broom-handle.

Starting with the ball hanging down, get it into the cup by a 'sure-fire' method

The boundary conditions and information:

1) The globe and the transparent tube should not be opened.

2) The ball is made of solid brass.

3) The spring is already stretched, in a state of tension, even when the ball is in the cup; but, it is not strong enough to pull the heavy ball up into the cup.

4) The broomstick is long.

5) There is a method which will succeed every time – in contrast with occasional success by random shaking.

According to Rogers, Einstein enjoyed the puzzle and solved it at once. Grasping the gadget in the middle of the long pole, he thrusted it upward until the sphere touched the ceiling, let it drop in free fall and vertically, guiding it with his hand, until the bottom reached the floor. The transparent sphere at the top was now at eye level. Sure enough, the ball rested in the cup [4,5].

The apparatus proposed is an adaptation and a simplification of Einstein's elevator. In this work, the following items were utilized:

- A broomstick
- A nail
- A nut or a washer whose internal diameter is about the nail diameter
- Regular elastic
- A little plastic pot
- A marble

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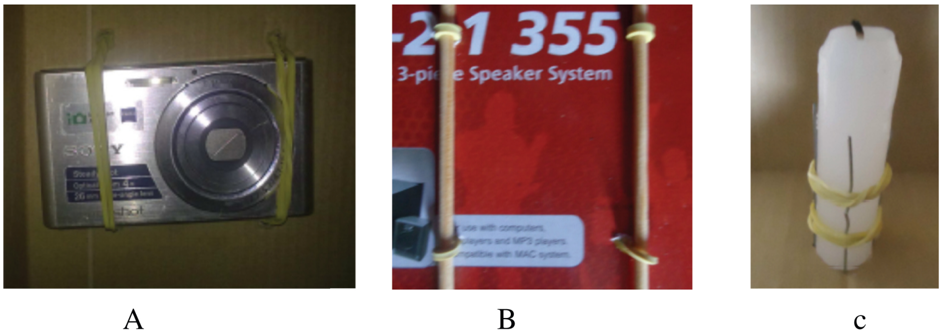


Figure 8: Details of candle flame experimental assembly: A) Photograph camera attached by elastic. B) View from behind of photograph camera, wooden sticks were used to attach the elastics. C) Candle fixed on cardboard box bottom.

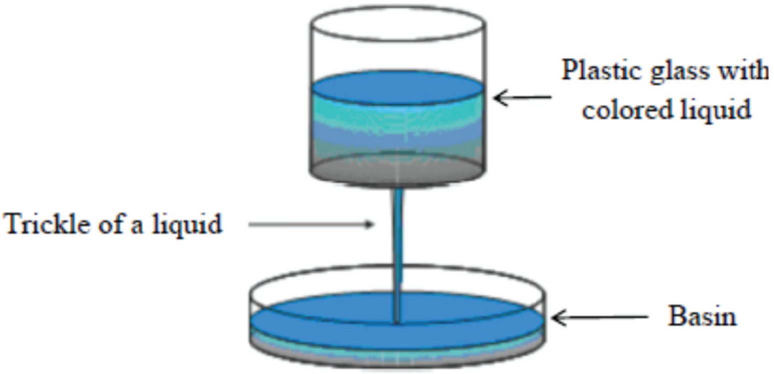


Figure 9: General vision of trickle of a liquid experimental assembly [3].

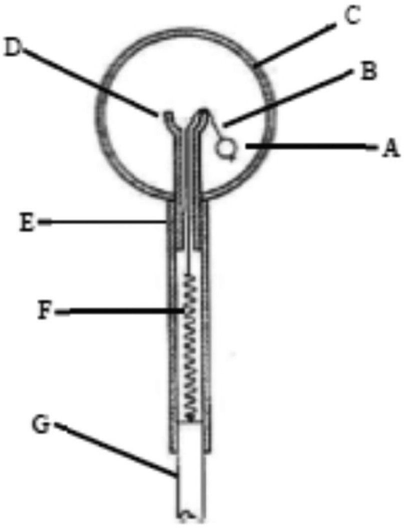


Figure 10: Einstein's birthday gift [4]. A: metal ball; B: Smooth thread; C: Transparent globe; D: Central, transparent, cup; E: Central pipe; F: long, weak, spiral spring; G: Long pole – a broomstick

- Clip
- Epoxy glue

The Figures 11 to 13 show the assembly sequence.

The execution of the experiment is very simple. Take the broomstick upright, lift it and drop it, guiding it by the hand and catching it again before it reaches the floor. After some number of executions, the elastic should be replaced.

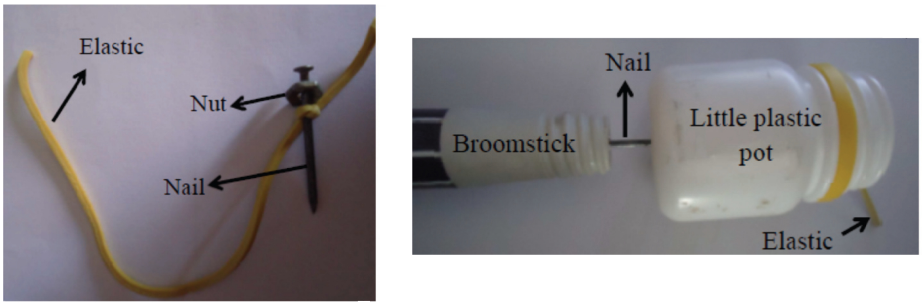
3. Results and discussion

3.1. The candle flame

In a static position the candle flame is elongated, Figure 14A. During the fall, it is possible to observe from the video, in 20% of the original speed, that the candle flame became smaller and spherical, because the air convection currents are almost absent [6], Figure 14B. When the carbon box hits the floor, the flame is extinguished by itself.

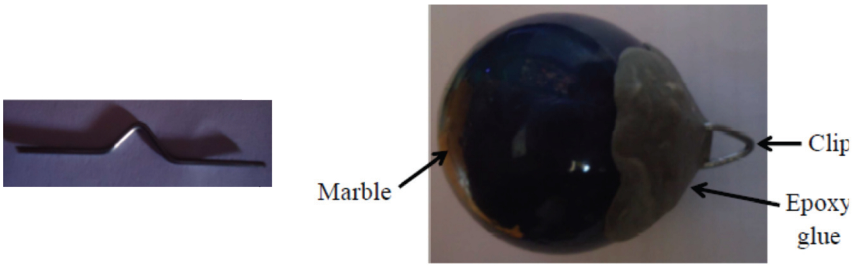
3.2. The trickle of a liquid

Before the fall the colored liquid flows through the hole at the bottom of the plastic cup (Figure 15A). During the fall, the liquid flow stops for the cup frame of reference (Figure 15B). When the cup is grabbed, the flow is restarted (Figure 15C). This



A B

Figure 11: A) Elastic tied to the nail inside the nut; B) Nail fixing the plastic pot to the broomstick.



A B

Figure 12: A) Clip cut and folded; B) Clip glued to marble

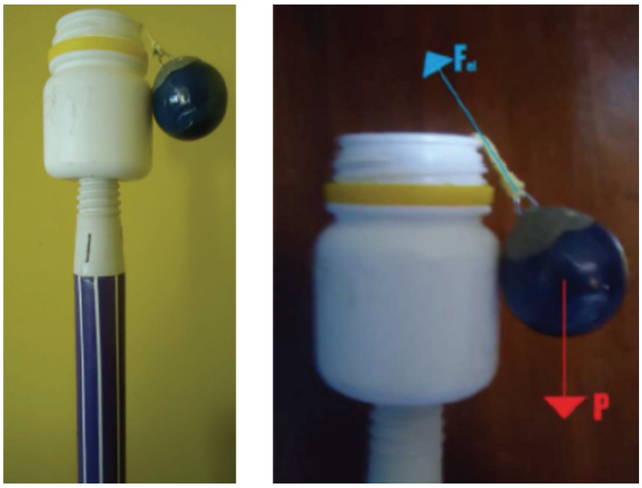


Figure 13: A) Final assembly of Einstein's elevator adapted; B) Diagram of forces: F = elastic force; P = weight of marble. The elastic force 'F' should not be strong enough to pull the marble.

experiment is very simple and the students can reproduce it easily during the class or in their homes. Recording it by a camera is, also, simple, but the film edition to show the experiment in slow motion is a bit more complicated and it is not essential to understand what is happening.

This experiment may be considered a variation of Einstein's elevator because it utilizes the equivalence principle [7].

3.3. Einstein's birthday gift

During the vertical fall, it is possible to observe that the marble goes inside the plastic pot everytime the experiment is performed. This may be explained by the forces diagram in the marble reference frame, before the fall: the vertical component of elastic force is equal to marble weight (Figure 16A) and the marble stays at rest. During the free fall: the marble weight is reduced and, then, the elastic force can pull the marble inside the cup (Figure 16B).

The great advantage of the Einstein's elevator is its practicality, it is ready to use. It does not need any edition of images or assemble a scenario (basin, plastic glass, colored liquid, etc.). It does not mean that one kind of experiment is superior to the other; all of them show different aspects of the microgravity.

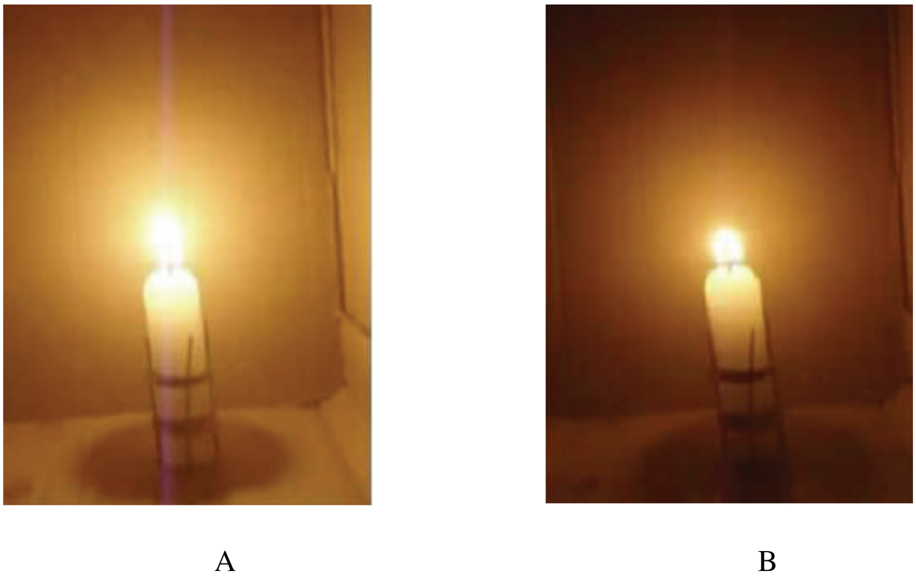


Figure 14: A) Flame before the free fall B) Flame during the free fall, note the spherical shape and the smaller size, because of the weakness of the air convection currents.

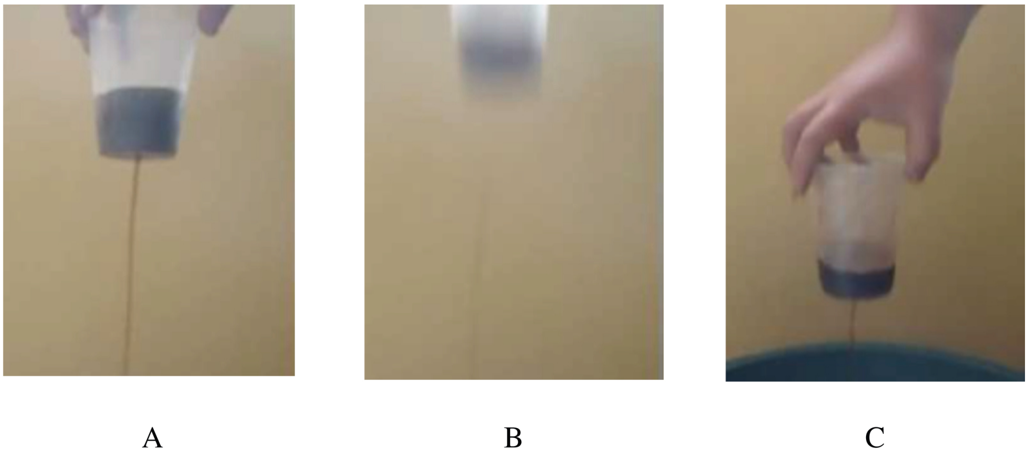


Figure 15: A) Liquid flows through the hole at the bottom of the plastic B) During the fall, the liquid flow stops C) When the cup is grabbed, the flow is restarted.

4. Conclusion

The microgravity is not explicitly part of the physics program for high school in Brazil, but as this phenomenon is present in several movies and documentaries about space travel, the subject arouses curiosity among students and can be studied as a particular case of gravitational force. The three experiments expose in this paper can help students understand it.

All experiments have positive and negative points. The candle flame experiment needs acquaintance about video edition and some time to do it beyond the time spend in assemble the experiment. But it is done only one time and the final video may be played numerous times. This experiment among the three is the only that allows the point of view as if the students were inside a spacecraft and incentive them to assemble their own candle experiment. Nowadays a lot of them have digital cameras and is ease to get free edition video programs from internet if it does not coming together with the camera.

The trickle of a liquid in free fall needs to carry a list of equipment (plastic cup, basin, colored liquid and floor cloths) and dry the floor and the utensils after the experiment. The advantage is that the students can reproduce it easily at their homes and they will.

Einstein's birthday gift or Einstein's Elevator needs some time to assemble it but is the easiest

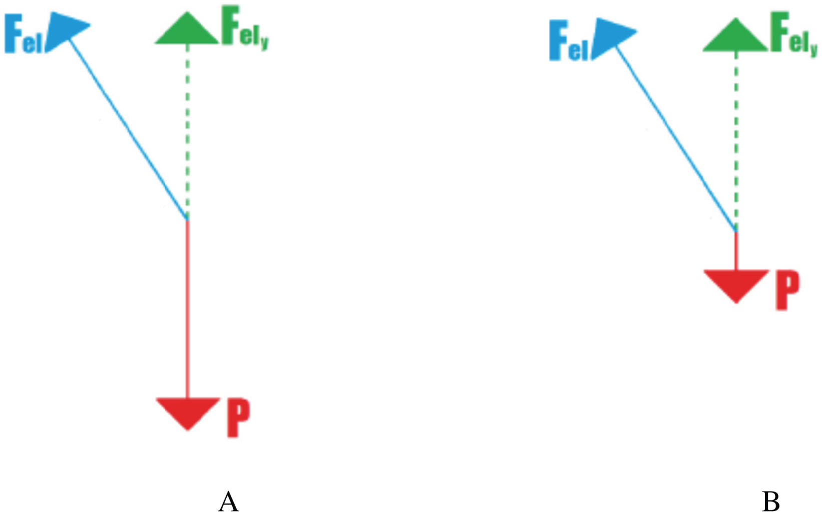


Figure 16: In the marble reference frame: A) Before the free fall: the vertical component of elastic force is equal to marble weight and the marble stays at rest B) During the free fall: the marble weight is reduced and now the elastic force can pull the marble inside the cup

to execute and very practical to carry and as it is related with a real episode of Einstein's life, so this experiment catches the students attention.

As these three experiments, there are several microgravity experiments of low budget available at Internet and most of them are apparently simple. But all of them needs a good assemble, tests before the presentation (some are difficult to visualize the microgravity phenomenon or difficult to reproduce, therefore they should not be regarded) and some practice before present them to the students or they are going to finish in failure. Finally, enjoy yourself and so do your students.

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