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Research into Students' Views About Basic Physics Principles in a Weightless Environment

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Abstract

In this research project, students are asked to explain what they think would occur if some everyday events were to take place in a weightless environment. The purpose of the study is to investigate: 1) whether students can understand the concept of "weightlessness"; and 2) how the level of understanding of such events develops as students progress from high school to college. We have investigated the nature of students' perceptions of the weightlessness concept by asking four open-ended questions and by conducting semi-structured interviews in the case of incomplete answers. The results show that most students lack a sense of "order of magnitude" when they imagine an experience different from what they are familiar with in daily life. We also describe the mental images that the students form, and the physical relations that the students infer from these images.

1. INTRODUCTION

Space and its mysteries have been an area of great curiosity for mankind since ancient times. Questions about this topic have played an important role in the development of science. Overcoming the force of gravity, reaching out to space, and discovering new stars and inhabitable planets have been some of the oldest dreams of mankind. Today, humans have acquired adequate information and technology for establishing and maintaining life outside Earth. Despite these developments, students still have some misconceptions about basic physics laws, and have difficulty applying them to the weightless environment.

When students encounter the terms "zero gravity" or "weightlessness," they often think "outside the Earth’s gravity." Students are therefore quite shocked to learn that during a typical shuttle orbit at an altitude of 250 miles, the force of Earth’s gravity on an astronaut is still 88 percent of what it is when he is standing on the ground. Students have the misconception that Earth’s gravity is negligibly small at these distances from Earth, and they do not recognize that it is the free-fall of the shuttle that creates the seemingly gravitation-free environment inside the spacecraft. Chandler (1991) and Morrison (1999) have addressed this misconception.

There have been discussions about what terminology should be used to prevent such misconceptions. One must distinguish between actual gravity (which refers to the attractive force that depends only on mass distribution) and effective or observed gravity in order to refer to the gravity that is measured in accelerated frames. Iona (1988), using geophysics literature terminology, prefers the term gravitation to refer to actual gravity, and the term gravity to refer to effective or observed gravity. NASA documents (Rogers, Vogt, & Wargo 1999; Rogers & Wargo 1999) use the term microgravity instead of weightlessness to refer to the situation in free-falling (orbiting) spacecraft. However, this term is meant to describe the fact that there are small tidal forces in free-falling spacecraft. The further one is from the center of mass of the spacecraft, the more the direction of acceleration deviates from the direction of the gravitational force. Thus the term microgravity alone does not address the problem of making a distinction between actual gravity and effective gravity; to the contrary, it is possible that use of the term microgravity could strengthen the misconception because the phrase "micro" could lead to the idea that the gravity is not zero, but very small because of the greater distance from Earth.

The meaning of the term weight (or weightlessness) would, of course, depend on whether we relate it to actual gravity or effective gravity. One might use terms like actual weight(lessness) or effective weight(lessness). However, it seems that students do not have much of a problem realizing that objects in a free-falling elevator appear to be weightless. Therefore, there is no problem in continuing to use the term weight in the sense of effective weight, and the term weightlessness in the sense of effective weightlessness, as Iona (1975; 1976) prefers. The problem seems to be that students have difficulty in realizing that a spacecraft orbiting the Earth is in a state of continuous free-fall.

The solution to this conceptual problem, however, is not a matter of terminology; rather, it is based around discussing the effect of an initial horizontal velocity in a free-fall, and addressing the transition from vertical fall to parabolic fall. Students could be asked a question such as, "What would happen if the initial horizontal velocity was so large, the vertical distance of the object from the initial point was greater than the size of the Earth?" This question makes it easier for students to conceptualize the transition from a parabolic orbit to an elliptical orbit. Thus, we will use the term weightless environment in our paper.

Science education has been structured around what is perceived to be the scientist’s concept of the natural world. We teach science to children to enable them to observe and draw logical conclusions about the events taking place around them. It is becoming clear that their framework is very successful in explaining everyday events as they see them, and these explanations are very hard to shake (Viennot 1979). In any type of teaching, the notion that the student’s mind is not a "tabula rasa" must be taken into account (Driver 1981; Stannard 2001). In this article, we investigated students’ pre-existing reasoning patterns about Earth’s gravity.

Research on this subject shows that students develop their own ideas about weight and gravitation. For example, Galili & Bar (1997) investigated ideas about gravity held by children aged five to sixteen. They found that children's views develop gradually from tactile experiences. Thus, such schemes as "weight is a pressing force," "weight is possessed exclusively by heavy objects," "suspended substances are weightless," and others are intuitively constructed at a young age. Osborne & Gilbert (1980) and Philips (1991) report that students think that gravity needs air to exist. Ruggiero et al. (1985) and Bar (1989) reported that children consider air to be the natural medium that can create the needed connection. They think that the existence of air is necessary for the action of gravity, as well as for magnetic attraction. Andersson (1990) comments that this idea prevails up to at least 15 years of age. Treagust & Smith (1989) interviewed 24 10th-grade students and, from their interviews, developed a questionnaire that was administered to 113 students. According to the questionnaire, students think that gravity is affected by temperature, that gravity is selective about what it affects and when, and that gravity is stronger at great distances. The question of whether children's theories are inconsistent and if they have fragmented knowledge is also the subject of the work of Brewer & Samarapungavan (1991), where the authors compare children's theories and the theories of the scientific establishment. Palmer (2001) investigated students' alternative conceptions of gravity and examined the nature of any possible relationship between students' conceptions and scientifically acceptable conceptions. The concept of weight in students' minds has been studied by many researchers (Gunstone & White 1981; Galili 1993; Galili 2001; Galili & Kaplan 1996).

Children's concepts about weight and free-fall also have been pointed out to science educators (Bar, Zinn, & Goldmuntz 1994). For example, researchers presented students with the examples of the space shuttle and the Moon. They told the students that these objects are held in orbit by gravity but that there is no air in space, and then asked the students how to apply this idea to Jupiter's moons. Some students who had previously believed that it was necessary to have air in order to have gravity said that gravity acts "only a little" in space, or "just near planets like Jupiter." The results indicated that even high school students' concepts about the matter of gravity and why things fall are not changed easily. These results were consistent with previous research that investigated schemes of common sense knowledge connecting the elements of weight, air, and gravity to the phenomenon of free-fall (Ruggiero et al. 1985; Noce, Torosantucci, & Vicentini 1988).

A number of studies have been conducted on children's conceptions about the shape of the Earth and weight. The first such research was done by Nussbaum & Novak (1976) and Nussbaum (1979), but other researchers have studied the same subject (Mali & Howe 1979; Sneider & Pulos 1983; Baxter 1989; Vosniadou & Brewer 1992; Sneider & Ohadi 1998). The general consensus from each study is that students' conceptions of gravity are closely tied to the conception of a spherical Earth. Roald & Mikalsen (2000) reported the results of an interview study of deaf and hearing children's conceptions about the Earth, its shape, and gravity. This study also reported on pupils' conceptions about the shape and composition of the Sun, Moon, and stars.

All of these studies indicate that students have certain intuitive ideas about a wide range of aspects of space and gravity. The purpose of our research is to investigate students' understanding of the concept of weightlessness, and to describe how they apply these concepts to questions about orbiting spacecraft. We find that the levels of understanding differ between high school students and college students.

2. METHODOLOGY

Students from one of two educational levels took part in the study concerning their understanding of the concept of weightlessness. The first group consisted of 85 16-year-old high school students. The other group consisted of 50 student teachers from the Physics Education Department in Istanbul, Turkey. The conceptual test consists of four open-ended questions on convection, the principle of action-reaction, and free-fall. At the time of the survey, the high school students had not been taught the action-reaction principle and free-falling within their standard curriculum. We compared the answers given by high school students, who reached their conclusions through spontaneous reasoning, and the answers given by college students, who used the knowledge acquired through university education. One of the four questions required solutions to a problem dealing with space life. This question assessed students' abilities to approach such topics as being in a weightless environment, a topic they had never encountered. The questions in the conceptual test are given below:

1. *What happens to a candle?* We know that when we light a candle on Earth, the flames go upward. If we were to light the candle in a microgravity environment where there is oxygen (e.g., a space station), what would be the shape of the flame? Why?

2. *Why is airflow needed?* In the compartments where the astronauts sleep, air is always circulated by fans. Why is this necessary?

3. *How might one remedy difficulties encountered when walking in empty space?* Astronauts walking in empty space always encounter problems when starting, stopping, and changing direction. What would you propose to eliminate such problems?

4. *What happens if the steel rope of an elevator is severed?* Imagine that a man is standing on a scale in an elevator on Earth and someone cuts the steel rope. While the elevator is in free-fall, what kind of change would the man notice in his weight if he looks at the scale?

The questions were prepared by researchers and applied in a pilot study that included eight graduate students from Marmara University's physics education department. These graduate students also taught physics in different high schools. (In this study, we refer to the graduate students as teachers to prevent confusion with high school students.)

In the pilot study, teachers' conceptions were assessed by giving them the test, and the test papers were modified to ask their opinions about the content of the test. After the necessary revisions were made, the final form of the test was determined, which included open-ended questions with drawings. The number of questions was reduced, and explanatory statements were added to help students visualize the situations. In the conceptual test paper, it was emphasized that the test was for diagnostic purposes only and would not influence grades in any way. Students were also asked to give their true thoughts on the physics involved in a very open way, and this input greatly helped us to design better instruction.

After examining the written answers, we gave a simple semi-structured interview to eight representative high school students. The topics covered in the interviews were based on students' answers written on their tests. We hoped to clarify some incomplete answers through verbal communication; the researcher played the role of the interviewer.

3. RESULTS

3.1 Data Analysis

Inductive analysis (Taylor & Bogdan 1984; Chang 1999) was used to evaluate the results of the open-ended written test and the information transcribed from the test. First, the researchers examined the information piece by piece, read the information repeatedly, and then wrote out the different kinds of conceptions that students reported. The analysis guidelines--specifically the conceptualization of the data, the coding of the data, and the development of categories--were determined in terms of students' answers. During this process, each researcher in this study independently read and coded students' sentences or phrases with simple descriptors. The researchers then met to discuss and label each sentence. Researchers assigned each sentence a code to represent the consensus. Throughout the labeling process, codes were revised and redefined. Classifications and their definitions are summarized in Tables 1 through 4. The results of this research were supported by the interviews, which included the following points:

1. Lack of a sense of "order of magnitude"
2. The relationship between school knowledge and everyday experience
3. Mental images and corresponding physical responses

3.2 Evaluation of the Answers Given to Question 1

Table 1. The answers given to the question "What happens to a candle?" and their percentages

ANSWER	REASON	High School (%)	College (%)	Total (%)
Spherical form	1.1--Due to lack of gravity, warmed air will not rise	4	32	15
	1.2--Due to lack of air pressure inside, flame does not rise	0	4	2
	1.3--No reason	3	12	7

Flames spread around	1.4--If there is no gravity, there would be no force to hold the flame together	13	2	9
	1.5--Because the concentration of oxygen gas differs alongside the room	0	2	1
	1.6--Like all other objects in space, flames also travel randomly	1	0	1
	1.7--No reason	20	12	16
Doesn’t change	1.8--The important factor is oxygen, which already exists in the medium	6	4	5
	1.9--Burning of the candle does not depend on gravity	3	2	3
	1.10--No matter which direction the candle is rotated, the flame remains upwards	0	2	1
	1.11--Electromagnetic wave is what makes the flames.	0	2	1
	1.12--No reason	17	8	12
Downward	1.13--Because buoyant force acting on the flame is eliminated	9	4	7
Rises more	1.14--Because the vertical downward force no longer exists	7	10	8
No flame	1.15--The candle does not burn	6	0	4
No answer		11	4	8

What happens to a candle? The burning of a candle is a phenomenon that every student can observe. When the students’ views are investigated, 32 percent of the college students and only 15 percent of the total students perceive the correct correlation (which is related to gravity and density differences) and recognize that neither buoyancy nor convection occurs in an environment in which the effective gravity is near zero. Answers 1.2 and 1.3 indicate the correct answer but incorrect reasoning. If this question were on a multiple-choice exam, it would not be possible to evaluate the students’ understanding. On the other hand, 17 percent of the students believe that Earth’s gravity is the force that holds the flame together (answers 1.4 and 1.14). Seven percent perceive it as a force that pulls the flame downward, as shown in answer 1.13. As the answers show, some students are not using the correct words to indicate directions in the weightless environment. For example, in answer 1.14, "rises" means outward from the candle. This topic is covered in both high school and college classes, yet differences can be observed between the two groups. The majority of high school students think that flames will spread. Below is a short interview with the student who gave answer 1.4:

> I: Why do you think the flames diffuse away into the environment?
> S: I thought it’s like burning of the Sun.
> I: What do we learn from the burning of the Sun?
> S: If the flames can escape from the gravitational force, they spread to space, but the core of the Sun holds the flames together because of the gravitational force.

This student has the following misconceptions:

1. Huge initial velocities occur in the bursts during solar activity. This is why flames rise thousands of kilometers off the surface of the Sun, and also why they can sometimes leave the Sun. There are no such high velocities involved with the burning of a candle. Although both processes can be called "flames," this covers immense qualitative (the nature of the process) and quantitative differences. We encountered misconceptions concerning order of magnitude at several occasions.
2. The gas molecules that are burned up at the tip of the candle actually diffuse into the environment, and new molecules come from the candle. Since the burning process takes place in the same region (at the tip of the candle), we perceive the flame as an "entity" that preserves its identity in time. In truth, the flame is not an "entity" but a process.

Meanwhile, six percent of the high school students believe that the candle will not burn.

3.3 Evaluation of Answers Given to Question 2

Table 2. Answers given to the question "Why is airflow needed?" and their percentages

STUDENTS' ANSWERS		**High School (%)**	**College (%)**	**Total (%)**
Correct answer	2.1--When no gravity exists, warmed air will not rise, so gases will not mix. Therefore, an astronaut might suffocate due to breathing CO_2.	6	40	19
Incorrect rationalization	2.2--In order to provide oxygen to the compartment	33	14	26
	2.3--In order for the gases in the compartment to spread homogeneously	19	4	13
	2.4--Acceleration of the air results in lessening the pressure on the astronaut	0	6	2
	2.5--The air circulation cools the environment	3	0	2
Confusion of Concept	2.6--Due to the structure of the respiratory system, air must be in circulation	25	8	18
	2.7--To exert pressure on the astronaut so that he will not become airborne	7	0	4
	2.8--If no gravity exists, air would rise, and the astronaut on the ground would suffocate	1	0	1
	2.9--Due to mass gravity, gases accumulate in one area	0	2	1
	2.10--Airflow acts as gravity	3	0	2
No answer		3	26	12

Why is airflow needed? Breathing is essential for humans, yet few realize that it is gravity that keeps humans from suffocating. In this case, it would be most beneficial to refer to the students' thoughts concerning the phenomena that take place in everyday life. Six percent of high school students and 40 percent of college students have explained this phenomenon accurately. Answers given by students also embody statements that are correct but that fall short of explaining the phenomenon. These have been grouped under the heading "incorrect rationalization." High school and college students have given quite different answers to this question. Some of the students tried to explain the phenomenon in terms of pressure. While high school students think of airflow as a factor that makes pressure, college students have been able to notice and distinguish the fact that when air is in motion, the pressure it exerts decreases. The answers to this question show that the conceptual errors of high school students differ from those of college students.

3.4 Evaluation of Answers Given to Question 3

Table 3. Answers given to the question about how to "walk in empty space" and their percentages

STUDENTS' ANSWERS		**High School (%)**	**College (%)**	**Total (%)**
Valid solution	3.1--I would have attached rockets to the astronaut's back and feet to provide pushing power	24	38	29
	3.2--I would tell him to throw an object in the opposite direction of his motion	3	4	4
	3.3--I would have him wear boots with magnets to attach to the metallic part of the spacecraft	1	0	1
Circumventing the question	3.4--I would put him on a vehicle that could travel in empty space	0	4	1
	3.5--I would construct a vehicle that could move the astronaut with remote control	0	2	1
	3.6--I would have suggested that he fly in empty space instead of walk	12	4	9
	3.7--I would have given him a starting push, and he would keep on moving	1	2	1

Unrealistic solution	3.8--I would have tried to create gravity in empty space	6	0	4
	3.9--I would have increased the weight on the astronaut so that it can be attracted by the spaceship	11	8	10
	3.10--I would tell him to tie himself with a rope and try to walk	12	4	9
Invalid solution	3.11--I would tell him to move forward by taking small steps	6	2	4
	3.12--I would have constructed a road in empty space	1	0	1
	3.13--I would have used rubber suction cup instruments to keep the astronaut's feet on the spacecraft	1	0	1
No solution	3.14--Nobody can walk in empty space	8	6	7
No answer		14	26	18

How might one remedy problems encountered when walking in empty space? Students must make use of their scientific knowledge so that they can make sense of material in a way that involves problem solving and questioning, and invokes scientific wonder. This question has been asked so that researchers can assess students' solutions to problems encountered in a space-like environment. During the assessment, it has been noted that high school students have been more successful with this question than with the other conceptual questions. Twenty-eight percent of high school students and 42 percent of college students have been able to find solutions to the problem. Answer 3.3 is not a complete solution for the whole of empty space, but it may be a solution inside or outside the spacecraft. Some answers do not address the problem, but circumvent it. Answer 3.12 is an invalid solution because, without a normal force, there would be no friction, making walking impossible.

Answers that do not constitute solutions include flying in empty space instead of walking, giving the astronaut initial momentum, pushing oneself forward, and tying a rope to the spacecraft and walking with its aid. Furthermore, six percent of high school students have declared that by creating gravity in empty space, one could walk. Some students suggested increasing the mass of the astronaut in order to increase the gravitational attraction between the spaceship and the astronaut so that the astronaut can walk on the outside of the spaceship. However, the gravitational force is too weak for this proposal to be realistic. A student who came up with the solution of tying a rope proposed that the rope be tied between the Earth and the spacecraft, and another student proposed that the rope be tied between the Moon and the Earth. Such answers show us the vastness of the students' imagination. Some students have perceived the problem as being about how to walk inside the spacecraft. A student who took the problem in such a way came up with the rubber suction cup for the walls, but rubber suction does not work without air, so this solution is not valid outside of the spacecraft.

Students could easily find a solution to this space walking problem if they correctly analyzed the phenomenon of walking on the Earth. The force of the friction between the surface and people's feet provides the action-reaction required for walking on the Earth. In a similar way, space walking with the help of rockets relies on exhaust gases from the rockets to provide the action-reaction pair. Incorrect answers of students indicate that both high school and college students are unable to put their knowledge into practice.

3.5 Evaluation of Answers Given to Question 4

Table 4. Answers given to the question, "What happens if the steel rope of an elevator breaks?" and their percentages

ANSWER	**REASON**	**High School (%)**	**College (%)**	**Total (%)**
Reduces	4.1--The acceleration of the elevator reduces the effect of the gravity	2	14	6
	4.2--The man becomes airborne and the pressure on the scale is reduced	17	0	10
	4.3--As the elevator is falling, upward pressure is applied to the man	2	0	2
	4.4--The air below reduces	2	0	2
	4.5--No reason	26	22	24
Becomes weightless	4.6--As the man is falling, he accelerates with a speed equal to the speed of gravity	0	2	1
	4.7--The man can't step onto the scale and will crash into the ceiling	9	2	6
	4.8--No reason	11	18	13

Increases	4.9--The acceleration of the elevator increases the acceleration of gravity	2	8	5
	4.10--As the elevator is falling, the pressure on the man increases	3	0	2
	4.11--All of the weight in the elevator falls on the scale	1	2	2
	4.12--No reason	7	8	7
Does not change	4.13--Since everything has the same motion, nothing changes	1	0	1
	4.14--Since it is the elevator that accelerates, the man's weight doesn't change	0	2	1
	4.15--No reason	2	2	1
Unstable	4.16--The man can't see a consistent weight; the scale moves continuously	5	0	3
No answer		10	20	13

What happens if the elevator's steel rope breaks? This question deals with an event that takes place on Earth. Free-falling is a topic very familiar to college students, although the answers show that the majority of these students are not able to make an assessment about what happens to weight during free-fall. Answers 4.1 and 4.2 indicate that 17 percent of high school students and 14 percent of college students express the same opinion in different words. This is a success for high school students, because this subject had not been taught to them yet. Answers 4.1 and 4.2 also reflect a qualitatively correct insight. The correct explanation came from two percent of college students with answer 4.6. During the interview, one high school student said that while the elevator is falling, it would get closer to the ground and therefore the Earth's gravity would increase. This is a typical misconception concerning order of magnitude. For a 1-km fall distance, the difference between gravitational forces at the beginning and at the end of the fall is only a small fraction (10-20) of the force. Although none of the situations in answers 4.7 and 4.16 actually takes place during free-fall, they are seen frequently in cartoons. Since cartoons and television programs clearly influence students, these resources might be effective in enhancing student learning. Teachers can take advantage of the entertaining nature of these informal sources of learning (Shaw 2000), and also encourage students to think critically about the information conveyed by these sources.

3.6 Result Evaluation Corresponding to the Topics

Input obtained through the questions has also been examined according to the topics shown in Table 5.

Table 5. Questions corresponding to topics

Question	**Topic**
1. What happens to the candle?	Convection
2. Why is airflow needed?	Convection
3. How might one remedy problems encountered when walking in empty space?	Action-reaction pairs
4. What happens if the steel rope of an elevator is severed?	Free-falling

All of the questions shown in Table 5 deal with phenomena that students have come across in popular media, science fiction, or cartoons. As Akridge (1990) points out, many students leave class with scripts in their minds of cartoons that they could write based on the violations of the laws of physics. Students also spend their time watching or reading the daily news about space exploration, and have increased access and exposure to quite sophisticated astronomical information (science fiction as well as science "fact") via television, computer, video, and other sources (Sharp 1996; Ziolkowski 2001).

In questions dealing with convection, five percent of high school students and thirty-six percent of college students have been successful. High school students have been less successful compared to college students in applying their in-class knowledge to explain events. On the other hand, walking in empty space is a question about devising solutions to a problem dealing with space life. High school students have been more successful in this problem-solving question than they have with the other questions. College students answered this question accurately about as successfully as the other questions.

For the free-falling elevator, the correct answer paired with the correct explanation came from only two percent of college students. The percentage of correct answers given by college students to this question seems to be lower than for the rest of the answered questions.

4. CONCLUSIONS

The results of our research show that students are not able to think of different topics like convection, gravitation, free-falling, and action-reaction together. These topics mainly are treated as independent subjects in their textbooks. The examples that integrate the different topics are often ignored. It is not surprising that students, even at advanced levels, do not fully realize the implication of basic physics principles if they do not compare different conditions such as extremely low effective gravity or hypergravity. Many students at all levels seem to lack a sense of "order of magnitude" when comparing size, scale, and dimensions (particularly about weakness of gravitation, as in answer 3.9). This is a general problem of verbal thinking. Statements such as "A causes B" cannot replace quantitative relationships like differential equations. On the other hand, equations are intuitively difficult to digest.

Concept maps are valuable tools that use the power of visual perception and overcome the linearity of verbal thinking. (One sentence follows another in linear fashion, so it is difficult to reflect complex cause-effect relationships using ordinary language.) However, concept maps cannot always provide the student with quantitative insight. Although no concept map can replace a differential equation, concept maps can be improved in a way that gives students a sense of quantitative properties. For example, if there is a cause-effect relationship between many concepts, the connection arrows between them can be drawn using arrows of different thickness to emphasize the quantitative differences. Or, one could use the thickness of the borders for a similar purpose. If A causes B and C causes B, but the effect of C on B is much stronger than the effect of A on B, one could draw the concept map shown in Figure 1.

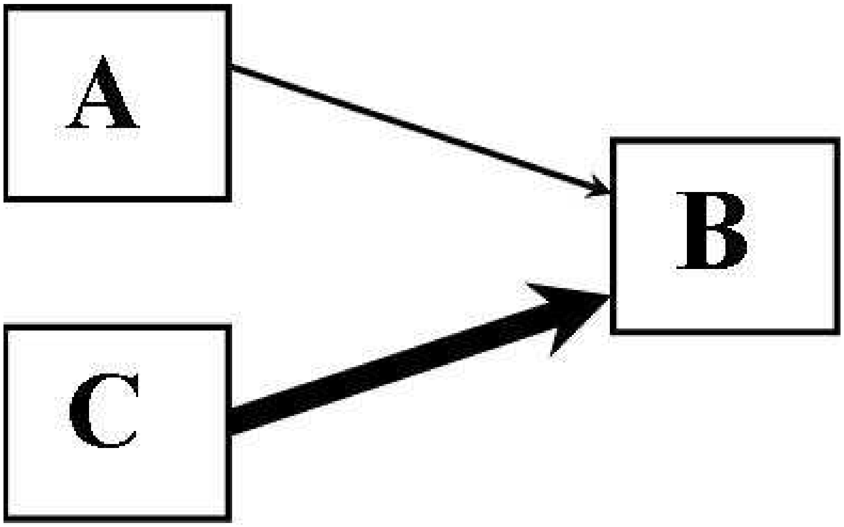

Figure 1. Example of a concept map

The results of this research show that high school students in particular give a lot of credit to cartoons (e.g., while the elevator is falling, the man crashes into the ceiling, as in answer 4.14, and the scale moves continuously, as in answer 4.16). Since cartoons are effective in enforcing misconceptions, they might also play an effective role in promoting students’ learning if the content makes use of correct physical principles.

Because we live in a 1-g gravity environment, it is difficult for us to imagine how much of what we experience in daily life would be different if there were no gravity, unless we think about these processes carefully. Good science fiction has the ability to separate the reader from his ordinary environment (rules, laws, ethics), and to demonstrate how all of its components are far from being self-evident; they depend on circumstances, evolutionary processes, and so on. In order to capture students’ interest and attention in the subject and to stimulate their imagination, teachers should make use of science fiction books and films, as well as the current developments in space technology and exploration.

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