EXPLORING ALTERNATIVE CONCEPTIONS OF FORCE

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Force is a fundamental concept in Newtonian mechanics that teachers and teacher educators are expected to understand well. However, students and teachers tend to hold several alternative conceptions around this concept. How do we draw out these alternative conceptions and challenge them?

Concepts of force and Newtonian mechanics are fundamental to elementary physics (see **Box 1**). However, studies suggest that students as well as teachers tend to hold many alternative conceptions about these concepts.[1-6] What forms do these alternative conceptions take? How do we challenge them? I explored these questions in a workshop with a group of teachers and teacher educators (see **Box 2**).

Motion and force

When presented with the first problem (see **Question I: Which exerts a force?**), twenty-two (81%) of the participants chose option B and five (19%) chose option E. The correct answer is option E. Why did most participants choose option B?

When the participants tried this experiment out, they observed that chair

Box 1. Newton's laws of motion[7]:

Newton's first law of motion (inertia)	In the absence of external forces, an object at rest remains at rest and an object in motion continues in motion with a constant velocity (that is, with a constant speed in a straight line).
Newton's second law of motion (force)	The acceleration of an object is directly proportional to the net force acting on it and inversely proportional to its mass.
Newton's third law of motion (action and reaction)	If two objects interact, the force exerted by object 1 on object 2 is equal in magnitude to and opposite in direction to the force exerted by object 2 on object 1.

Box 2. A brief overview of the workshop:

The participants: The workshop had 27 participants (19 science teachers and 8 teacher educators), all of whom worked in the same district of a state in North India. The teachers had undergraduate or postgraduate degrees in science. Each had at least 10 years of experience in teaching science and/or environmental studies (EVS) at the elementary or high school levels. All the teacher educators had postgraduate degrees in science and 0-15 years of combined experience in teaching and teacher education.

The format: The process cycle of the workshop was structured to draw out and challenge cognitive conflicts (see **Fig. 1**). It involved five stages. At each stage, I would introduce participants to a problem context, ask them a question, and invite them to choose their answer from a list of multiple options (the last question was open-ended). To protect their identity, each participant wrote out the option that they found accurate in a chit of paper. I collected these chits and made note of the relative frequency with which the different options had been selected. I followed this up with questions designed to provoke argumentation and help participants identify errors in their responses. In some cases, I would introduce new concepts to shed light on the original questions. We would move on from a question only after it had been thoroughly discussed and participants had arrived at a better understanding of the correct response.

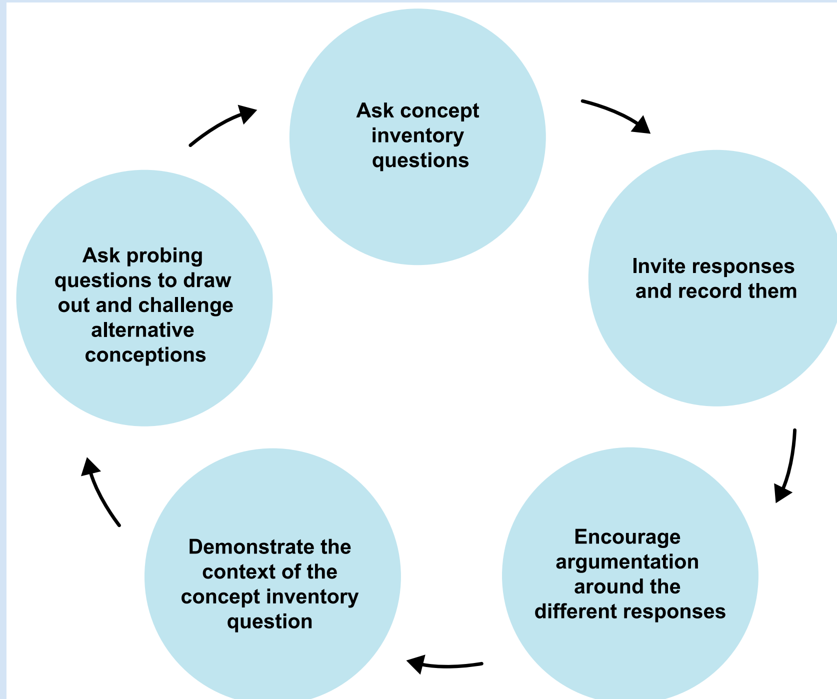

Fig. 1. The process cycle of the session.
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The questions: Questions II, IV, and V were adapted from the Force Concept Inventory (FCI).[8] Each question was presented in a problem context that participants were likely to encounter in their real worlds. The options for each question were shared orally and in writing (on the board). Both English and Hindi (the language that the participants were most familiar with) were used for discussion.

X hardly moved while chair Y moved quite a bit. Many of them associated the application of force with the motion of an object (in this case, the motion of chair Y). Citing Newton's first law of motion, these participants argued that as chair X had remained at rest, there was no force acting on it. This is incorrect because it ignores both Newton's third law of motion and the force of friction.

While all the participants were able to state Newton's third law of motion: *"Every action has an equal and opposite reaction"*, not all of them were able to apply it to this context (see **Fig. 2**). When the person sitting on chair X exerts a force on chair Y, chair Y also exerts an equal and opposite force on the person on chair X. Under the influence of these forces, both chairs move. As they move, the force of friction comes into play. This second force acts in a direction opposite to that of the force of push. Since friction depends on the mass of the object it acts on and chair X carries the additional weight of the person sitting on it, chair X experiences a greater force of friction than chair Y. This explains why the two chairs in this context move to different extents.

When presented with the second problem (see **Question II: How much force?**), fifteen (56%) of the participants chose option C, five (18%) chose option E, three (12%) chose option F, two (7%) chose option B, and one (4%) chose option A. The correct answer is option E. Why did so many participants choose the other options?

Those choosing option C or F had overlooked Newton's second law of motion. Based on the difference in acceleration they had observed in the two chairs, they had concluded that the forces acting on the two chairs were unequal. But to arrive at this conclusion, the relative masses of the two chairs also needed to be taken into consideration. The participants who chose option B made the erroneous assumption that only animated objects or objects having the intention to push can apply force.

Fig. 2. Do the pins and the ball exert an equal amount of force on each other?

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At this stage of discussion, the participants were invited to compare their responses to Questions I and II. The most common answers to both these questions stemmed from the same misconception—the amount of force acting on an object can be inferred by the amount of motion it causes. This led the participants to conclude that: (a) if an object did not move, then no force was acting on it, and (b) the more motion an object showed, the greater the force acting on it. The participants acknowledged that these responses were connected, but were unable to see how their responses ignored Newton's second and third laws of motion. I did not share the correct responses to the questions. But, to help them, I introduced Newton's law of gravitation and drew attention to its connection with Newton's three laws of motion—the force exerted by the Earth on any object is equal to that exerted by the object on the Earth.

Motion under gravity

The discussion on gravity led to the third problem (see **Question III: Which lands first?**). I invited the participants to predict which object in each of the three scenarios would land on the ground first.[9] Presented with the first scenario, the participants predicted that the two bottles would reach the ground at the same time. To confirm this, two bottles were dropped from increasing heights. In every case, as predicted, the two bottles reached the ground at almost the same time. In response to the second scenario, the participants predicted that the purse would fall faster than the sheet of paper. When asked to justify their response, the participants reasoned that the sheet of paper would face greater air resistance due to its larger surface area. A demonstration confirmed this prediction. To demonstrate the third scenario, I used a notebook and its thick front cover page. This ensured that both objects had the same surface area. The two objects were dropped from the same height. When they were held and dropped so that their faces were horizontal to the ground, the paper reached the ground after the notebook. The participants hypothesized that because the cover page was lighter, it did not overcome air resistance as easily as the heavier notebook. To test this, the two objects were dropped in such a way that their faces were vertical to the ground. In this case, both objects reached the ground at about the same time. By the end of this series of demonstrations, the participants were agreed that irrespective of their mass, any two objects released from the same height would reach the ground at the same time.

When presented with the fourth problem (see **Question IV: Which travels farthest?**), seventeen (65%) of the participants chose option A, eight (31%) chose option C, and one of them (4%) chose option B. The correct answer is option C.

To nudge them towards the correct option, I asked the participants to name all the forces that acted on the two balls at the edge of the table surface. Most participants named gravitational force. One of them expressed the belief that gravitational force acted on the balls even when they were rolling towards the edge of the table. Although most participants recognised the role of gravitational force in the problem context of Question IV and all of them had accurately applied Newton's law of gravitation to the three scenarios in Question III, many of them were unable to transfer that understanding to this context. On the one hand, the participants who had chosen option A compared this situation with their real-life experience of throwing lighter and heavier objects away from them. They argued that even when thrown with the same force, lighter objects would travel a greater distance (than heavier objects) before dropping to the ground. Why is this inaccurate? The two balls in this question rolled off the edge of a table under the influence of gravity. In this, they were like any of the two objects from each of the three scenarios in Question III—they would reach the ground at the same time. On the other hand, some of the participants who had chosen option C argued that the two balls would fall to the ground at the same time because they were acted on by the same amount of gravitational force. This is inaccurate because the gravitational force acting on an object is not independent of its mass. Objects of different masses fall to the ground at the same time not because they are acted on by the same amount of force, but because they experience equal acceleration (acceleration due to gravity).

When presented with the fifth problem (see **Question V: How long does the force of throw act?**), the responses offered by the participants were varied and interesting. All the participants agreed that at point A, two forces acted upon the ball—the force with which the ball was thrown and the force of gravity. Some of them rightly pointed out that the force of air friction also acted upon the ball. Sixteen (62%) participants expressed the view that the force of the throw would continue to act on the ball till it touched the ground, but would reduce in magnitude at every point in its trajectory. Thus, they reasoned, the force of the throw would be equal to the force of gravity at point B and would be much weaker than the force of gravity at point C. Ten (38%) participants expressed the view that the force of the throw would become zero at point B and gravity would be the only force acting on the ball at point C.

At this point in the discussion, I demonstrated the trajectory of a ball when hit with a bat and asked the participants to predict how long this force would continue to act on the ball (see **Fig. 3**). All the participants expressed the view that the force with which the ball was hit would continue acting on it till it reached the ground. If so, I countered, would the ball not continue to move rather than stopping as it did after having traveled a certain distance? To further clarify this point, I asked the participants to predict the trajectory of the ball in the absence of gravity. The participants were agreed that in a gravity-free environment, the ball would continue to move in a straight line. Referencing Newton's first law of motion, they argued that the ball's trajectory would be determined by the inertia of motion; not the force of hitting. I asked if it could be inferred that the curved path of the ball in Question V was due to gravity. After some discussion, most participants concurred with this inference. However, some of them expressed their dissatisfaction. One of them raised the question: *"How is it possible that the ball takes a curved path under the influence of gravity alone? Does this path not suggest a force that continues to act in the direction of motion?"* I steered the discussion back to Question III, reminding the participants that objects of different masses had fallen to the ground with the same acceleration. This led some participants to conclude that both balls in Question IV would reach the ground at the same time and travel the same distance from the table.

Fig. 3. How long does the force with which the ball is hit continue to act on it?

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Parting thoughts

Although the participants of the workshop were able to state Newton's laws of motion and the theory of gravitation, they showed an inadequate understanding of both. The workshop helped reveal some common alternative conceptions around these concepts. These conceptions stemmed from an inability to differentiate between: (a) mechanical force and gravitational force, (b) energy and force, and (c) velocity and acceleration. This is why, for example, the participants associated motion with force rather than with inertia. They also associated the curved path of a ball thrown into the distance with a motive- or impetus-like force rather than with gravity. Like many pre-Galilean and pre-Newtonian concepts of force, these alternative conceptions arise from interpretations of real-world experiences rather than individual errors or cognitive limitations.

Often, these alternative conceptions are so deeply ingrained in students and teachers that merely pointing out mistakes or sharing the correct response is unlikely to change their understanding. For example, even after I had reminded the participants that force was different from energy in being neither a conserved quantity nor the property of an object, they were unable to apply this understanding to Question V. Experiments to demonstrate the workings of force may also be insufficient in countering alternative conceptions. For example, despite elaborate demonstrations that all objects in free fall move towards the ground with equal rapidity, the participants stuck to their initial understanding that the mass of an object influences the horizontal distance traversed by it once it hits the ground.

Box 3. Outcomes of the workshop:

By the end of this session, many participants had started appreciating the fact that:

- Newton's third law means that forces exist in pairs.
- Free falling objects are acted upon only by the force of gravity.

Responses to these exercises brought to light three more aspects that are often difficult to appreciate:

- A force acting perpendicular to the direction of motion does not do any work.
- No force is required to sustain the motion of an object.
- Newton's laws of motion help predict the resolution of the different forces that act on an object at a given point of time.

This experience with teachers and teacher educators illustrates how questions around counterintuitive examples may be effective in exploring individual conceptual frameworks and challenging them (see **Box 3**). The questions I have shared here could be used in different ways. For example, the problem contexts of Questions I and II could be demonstrated using two people of more or less the same weight. Similarly, that of Question IV could be demonstrated by dropping the two balls (hollow and solid) to the ground from different heights. Or participants could be asked to measure and compare the distance traveled by the two chairs or two balls in these demonstrations. The sequence in which the problem contexts are presented could be adapted to align with the specific conceptual pitfalls that arise in discussion.

Try exploring these questions with your students or colleagues. What changes would you make to the problem contexts? What alternative conceptions would you discover?

Key takeaways

- While force and Newtonian mechanics are fundamental to elementary physics, many students and teachers develop alternative conceptions around these concepts.
- Many alternative conceptions bear similarities to pre-Galilean and pre-Newtonian concepts of force and arise from limited interpretations of real-world experiences rather than individual errors or cognitive limitations.
- These alternative conceptions can be so deeply ingrained that it may be difficult to counter them with accurate theory or experiments that demonstrate the workings of force.
- Presenting students or teachers with questions around counterintuitive real-world problem contexts can be effective in drawing out and challenging alternative conceptual frameworks.

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Notes:

1. This article was first published in i wonder…, January 2017, pp. 44-49. The original draft can be found here: https://publications.azimpremjiuniversity.edu.in/1279/. The version included in this issue has been reviewed and modified for school teachers. It includes five question sheets.
2. Credits for the image used in the background of the article title: Free fall. URL: https://www.rawpixel.com/image/5945830/free-public-domain-cc0-photo. License: CC0.

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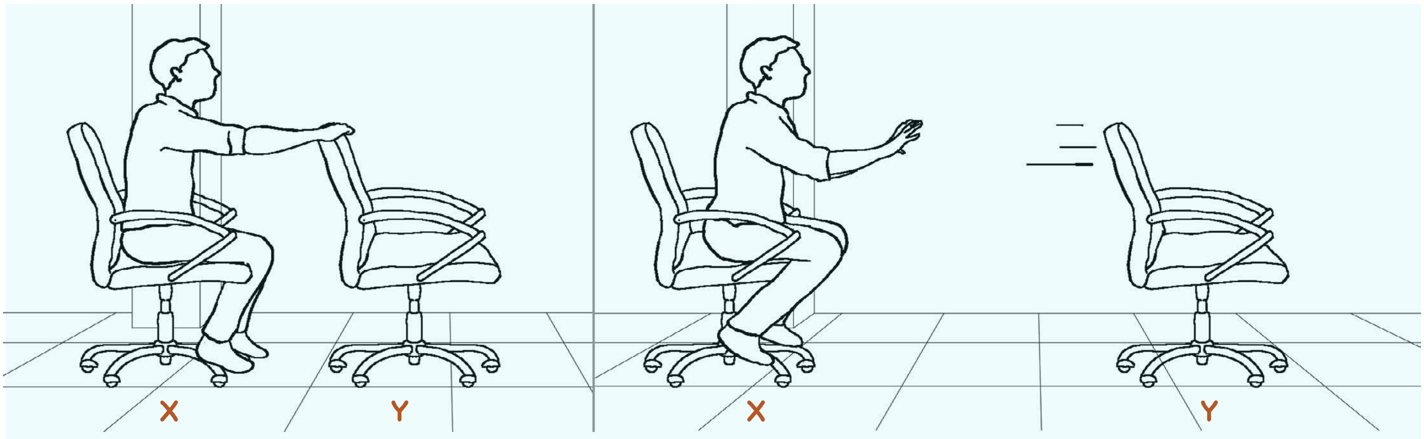
QUESTION I: WHICH EXERTS A FORCE?

Problem context:

Two identical chairs with wheels—X and Y—are placed one before the other and face the same direction. A person sits on chair X and places their hand on the back of chair Y. The person on chair X gives the chair Y a sudden push.

Do try this out and observe the result.



Question:

Which of the following statements are correct?

A) Neither the person nor chair Y exerts a force on the other.
B) The person exerts a force on chair Y, but the chair does not exert any force on the person.
C) Both the person and chair Y exert force on each other. The force exerted by chair Y on the person is greater than that exerted by the person on chair Y.
D) Both the person and chair Y exert force on the other. The force exerted by the person on chair Y is greater than that exerted by the chair Y on the person.
E) The person and chair Y exert the same amount of force on each other.

How would you justify your answer?

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QUESTION II: HOW MUCH FORCE?

Problem context:

Two identical chairs with wheels—X and Y—are placed one before the other and facing the same direction. A person sits on chair X and another person sits on chair Y. The mass of the man sitting on chair Y is about 1.5 times that of the person sitting on chair X. The person on chair X places their hand on the back of chair Y and gives it a sudden push.

Question:

Which of the following statements are correct?

A) Neither the person on chair X nor the chair Y exerts a force on the other.
B) The person on chair X exerts a force on chair Y, but chair Y does not exert a force on the person on chair X.
C) Chair Y and the person on chair X exert force on each other. The force exerted by chair Y is greater than that exerted by the person on chair X.
D) Chair Y and the person on chair X exert force on each other. The force exerted by the person on chair X is greater than that exerted by chair Y.
E) Chair Y and the person on chair X exert an equal amount of force on each other.
F) Chair Y exerts a force on the person on chair X, but the person on chair X does not exert a force on chair Y.

How would you justify your answer?

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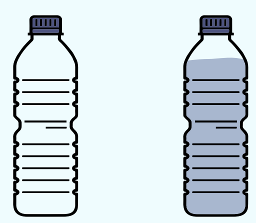
The Science Educator at Work

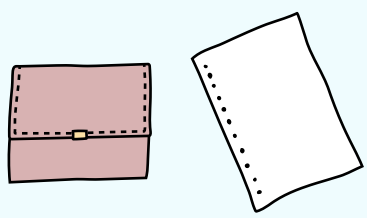
QUESTION III: WHICH LANDS FIRST?

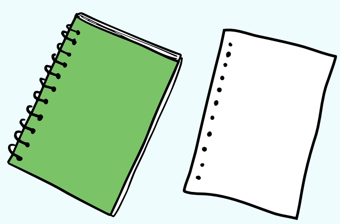
Problem context:

In each of the three scenarios given below, two objects are dropped from the same height.

- Scenario 1: An empty bottle versus a bottle filled with water.
- Scenario 2: A purse versus a sheet of paper.
- Scenario 3: A notebook versus a sheet of paper from it.







Question:

Can you guess which of the two objects in each scenario will reach the ground first? After you have shared your guesses with others, try these three scenarios out and observe the results!

How would you justify your answer?

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QUESTION IV: WHICH TRAVELS FARTHEST?

Problem context:

Imagine two iron balls of the same size rolling along a horizontal surface, like a table, with the same velocity. One of the balls is hollow, while the other is solid. The solid ball is 10 times heavier than the hollow ball.

Both balls roll off the edge of the surface at the same time. The hollow ball travels a horizontal distance of DH from the base of the table while the solid one travels a horizontal distance of DS from the base.

Question:

Which of the following statements best describes the relationship between DH and DS?
A) DH > DS
B) DH < DS
C) DH = DS

How would you justify your answer?

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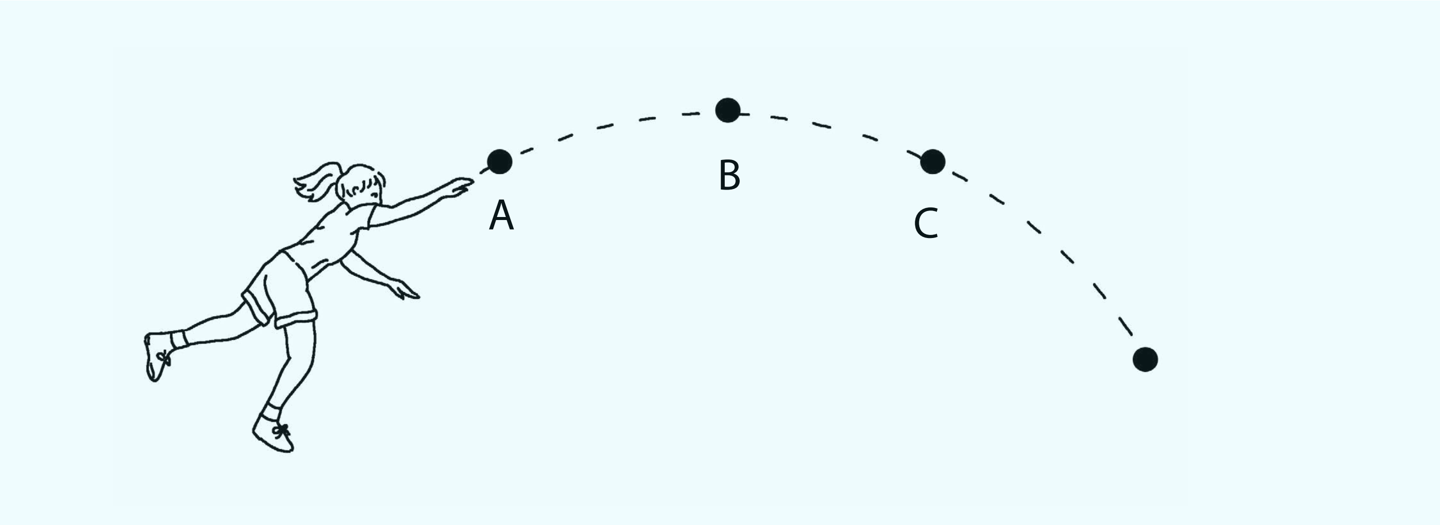
QUESTION V: HOW LONG DOES THE FORCE OF THROW ACT?

Problem context:

As shown below, a student throws a cricket ball.



Question:

Look at the points A, B, and C. What force(s) act on the ball at these points of its flight? Please ignore the effect of air resistance on the ball.

How would you justify your answer?

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