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Research Article

Students' Misconceptions are Falsely Measured by Concept Inventory Tests While Lack of Prior Knowledge is Ignored

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Abstract: Concept inventory (CI) tests are used to measure students' misconception. This article investigated and concludes that the current format of these tests is unable to measure students' misconceptions since the answers choices do not reflect student lack of prior knowledge, time lapse between when they learned the subject matter and when they try to recall it, and the conditions through which students construct their knowledge. CIs are better suited as tools to evaluate the effectiveness of pedagogical effectiveness and language in communicating the material to the students.

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0 Introduction

The failure to understand student language and access their prior knowledge has caused educators to label students' choices as misconceptions[1], assuming that students' incorrect responses are a result of pre-held beliefs[2,3]. However, a number of science curricula claim to measure students' misconceptions and level of understanding through concept inventory (CI) tests[4-6]. CIs are generally multiple-choice research-level instruments designed to test students' conceptual understanding[7], through a number of key concepts[8], but in other cases, it may be true/false or essay explanations or combinations of questions types[9,10] attempting to unmask students' misconceptions. Each question or item has one correct answer and a number of incorrect answers known as distractors. Physics education research (PER) proposes that these distractors are based on common students' misconceptions[6]. Hestenes, Wells, and Swackhamer[3] were the first to administer such a test, which they referred to as force concept inventory test (FCI), and have been met with little objection in the literature.

The following question is typical on the FCI tests, which is given to assess students' general conceptual understanding at the start of physics instructions[11], and claim to be measuring students' misconception:

Two metal balls are the same size but one weighs twice as much as the other. The balls are dropped from the roof of a single story building at the same instant of time. The time it takes the balls to reach the ground below will be:

A. About half as long for the heavier ball as for the lighter one.

B. About half as long for the lighter ball as for the heavier one.

C. About the same for both balls.

D. Considerably less for the heavier ball, but not necessarily half as long.

E. Considerably less for the lighter ball, but not necessarily half as long.

What concept is this question measuring? The expected correct answer for this question is "C," and any other answer is considered incorrect and labeled as misconceptions. PER and educators typically ignore other important, and possibly confounding variables such as students' potential lack of prior knowledge and language development levels which can lead to students guessing answers that make sense with their experience. We explore this question to understand students' thinking and answering patterns.

The success of FCIs in labeling students' misconceptions has caused it to be largely adopted as an adequate tool to uncover misconceptions. FCIs are widely accepted in science classrooms such as biology, chemistry, mathematics, and astronomy, for a number of reasons. For example, Briggs *et al*.[9] report their success in modeling CI for microbiology using true/false questions. This is falling short of such a claim since, through this design, there is a 50% chance of guessing the right answer, which results in students scoring high on true/false response but poorly when asked for a reason for their choice. This poor scoring is quickly deemed as a misconception; however, students are forced to guess, thus potentially revealing more of a Dunning-Kruger effect (DKE)[12] rather than misconceptions *per se*. Consequently, our major critique is that it is farfetched to claim that CI tests as currently built, can parse out if the students' responses are due to misconception, guessing, memory fading, or lack of knowledge. Looking at the following true/false question from Briggs *et al*.[9] Biology concept inventory (BCI) test, "if you cultured two bacteria together, where one is resistant to penicillin, is it possible for the other to acquire the resistance?"[9] I have no idea about the answer, although I have taken biology before, and thus I would be forced to guess. It is for me a question of memory or lack of prior knowledge, but CIs provide no formal way for me to communicate that. BCI results indicate that lack of understanding is more so related to randomness, for example, after students have taken courses in molecular, cell, and developmental biology.[10] The issue, in this case, is that randomness is not intuitively a rational concept for students, so much so that even the great Albert Einstein is quoted saying, "God doesn't play dice."

The question to contend with is: Are the students' experiences enough for them to reason and find the correct answer, or do these questions require rote memorization of prior knowledge? Thinking about my own learning experience and that of countless others, I do not believe that we are honest in representing the learning process because, for the most part, we too suffered from the same confusion that leads to our misunderstanding of the subject. It seems also apparent that language interactions between the learner, the pedagogy, and the instructor do play a part even when there is conceptual conflict in students' minds[1]. The real question is, does the learner have the necessary required tools in their toolbox to articulate a rational response? Students are still in continuous development and may be struggling to make sense of particular instances of reasoning, which only comes through repetition and familiarization with the material. Thus, this issue should cause instructors to reflect on pedagogy content in a reductionist way and focus more on imparting particular skills to students that will help to develop and explore content or even create new ones on their own.

Griffith's[13] concern in the following passage sets the tone for how we must interpret CIs results:

"The truth is, I did not really understand the point until much later. Does this mean that my freshman class was a waste? I don't think so. The learning process is mysterious and imponderably complicated. I personally learn by what Albert Baez used to call the 'spiral' approach, in which the same subject recurs again and again, and one's comprehension deepens with every pass. I don't think we should expect perfect understanding on the first encounter, and I do not believe a bad score on the FCI proves that the student has not - at some level - 'learned' the material.…. I am also skeptical about the reliability of multiple-choice tests. There are a thousand ways to get a problem wrong - not all of them bad - and many ways to get a problem right - not all of them good. … but I wonder if we are not reading a little too much into them. I'm sure they measure *something*, but I'm not convinced they measure what we would like to believe they do."[13]

However, the question that must be asked is: How do CIs measure students' misconception while controlling for their guessing, lack of prior knowledge, fading of memory, and how students constructed their knowledge in the first place? A student may have knowledge but may not yet develop the skills to apply it. Again, Griffith[13] adds to the discussion, "I knew how to get the right answer; why was he (a TA) being so fussy about my reasoning?"[13] However, after a number of repeats by taking more courses, Griffith[13] came to agree with the TA due to the reoccurrence of the concept that now made more sense. No one is born with knowledge in place.

It must be constructed through experience as Hume[14] contends. This occurs through cultural traditions in which the learners are formed, and also from self-exploration and prior instruction.

In a recent article, Crogman *et al*.[15] showed that the claims that CIs reveal misconceptions are a false positive since students consistently shifted their responses after instruction. Their analyses of pre- and post-CI tests scores resulted mainly from a lack of prior knowledge and misunderstanding of instructors' language. The authors argued that CIs fail to measure students' misconceptions and are used incorrectly by educators to access students' understanding. Huffman and Heller[16] questioned whether FCIs do actually measure students' misconceptions as what Hestenes *et al*.[3] (1992) claimed. They observed that items on the FCI are loosely related to each other and that students' understanding of concepts are vague and undifferentiated which is corroborated by Crogman *et al*.[15] The argument here is not that CIs are inadequate and should not be used, but that the information inferred from them are misleading. The most common use of CIs is to test the effectiveness of a particular pedagogical practice in altering misconception[17]. However, we are pushing back to suggest that CIs effectiveness is a measure of instructors' performance in getting through to the learner. CIs have an important use in the classroom to evaluate students' prior knowledge, help instructors in subject prep, facilitate the assessment of understanding on the subject and can be used to create groups that will enhance learning and collaboration in the classroom[18-20]. The following sections explore the effect of students' prior knowledge on their understanding of concepts.

1 Misconceptions versus misunderstanding

The main claim about CIs is that they allow educators and researchers to highlighting students' misconceptions. The basic dictionary definition is a view or opinion that is incorrect because it is based on faulty thinking or understanding. Researchers typically define misconceptions as explanations or descriptions of natural phenomena that make sense to students, even though the explanation may be scientifically incorrect[21-23]. This definition does not account for how students may have constructed their knowledge or the gaps in their knowledge, and fails to see that the notion of scientific correctness is not in the answers themselves but the inquiry that helps to confront, enlighten, or derive new knowledge. Moreover, the Committee on Undergraduate Science Education[24] has argued that misconceptions are conceptual misunderstandings (which is resulted from students being taught scientific information that does confront paradoxes and conflicts resulting from their preconceived notions and nonscientific beliefs)[24]. The conceptual misunderstanding's definition is misleading because it arises solely when instruction fails to challenge the learners' pre-held beliefs that are non-scientific. One myth propagated through educational research is that it suggests that the incorrect beliefs are not or cannot be gained through a scientific pathway. In other words, this definition victimizes the learner and misinterprets why misunderstanding occurs.

PER has argued that there is an incompatibility between their students' commonsense knowledge, and the Newtonian mechanics they tried to teach them. They did much work to undercover the differences existing between students' natural knowledge and Newtonian mechanics to improve their teaching. The focus of such incompatibility is somewhat disingenuous; it misrepresents the learning process and removes the educators as once being these same students themselves. Aristotle believes that no motion is possible without a force acting on the moving object, which seems to suggest that visual perception of motion does not always lead to the expected conclusions about dynamics[25-29]. All knowledge is constructed out of faulty thinking, and through repeats and new inquiry, thinking is refined. Is it really correct to say that one's thinking is faulty when one has lacks of prior knowledge? A direct 1-1 correspondence expectation between student's commonsense knowledge and Newtonian mechanics is thus somewhat unrealistic. Instruction participates in the process to create conflicts with students' constructed knowledge, which leads to a clarification in their thinking process[15].

A misconception may result from conceptual misunderstanding, but they are fundamentally different. Misunderstandings result rather from miscommunication between a hearer and a speaker. Therefore, before we can assess a misconception, we must first determine and have a real sense of learners' prior knowledge and scientific reasoning ability. Furthermore, wrong answers may not result from misconception but from the fact that there may be a gap in knowledge at some level, a misunderstanding of some sort[15]. We contend that a misconception can only arise after the instruction of certain basic principles is taught to the learner that is then tested. Many CI interpretations ignore this facet of prior knowledge. They actually assume that students have prior knowledge or are able to derive outcomes based on their scientific reasoning ability[15].

We formulate a definition of misconception because it is not clear from the above ones how the learner is to come to a scientific explanation when their first tools are their natural experiences:

Misconceptions are beliefs that were constructed through personal experience or cultural traditions and held in light of experiential scientific knowledge/conceptual conflict of the concept in question.

In other words, when instructors create conceptual conflicts in their students' minds, which are clearly understood by students, and they in turn still choose their pre-held beliefs in the face of evidence, misconceptions are born. For instance, in the case of FCIs, we contend that students who receive a formal scientific instruction with demonstrations and experimentations in class, and still choose the wrong concepts in their post-FCI test, they are showing true misconception[15].

PER has demonstrated a teacher-centered approach is not enough to overcome students' misconceptions. The above definition would suggest that a pedagogy that is only didactic will propagate misconceptions because in such situation learning is hardly ever multisensory. Instruction must add knowledge, confront knowledge, and provide tools to test and derive knowledge. Therefore, pedagogies that allow a teacher the freedom to move between didactic and active teaching will most certainly create conceptual conflicts through multisensory stimuli[15,30,31]. A misconception arises only after instruction and not before (it is just a lack of knowledge compared to what was previously experienced). Note also that instructors have reported that students mask their abilities pretending to know something that they have no idea of, which is an illusory response of students (DKE). This is often labeled as misconception (mistakenly). How do CIs determine misconceptions when students shift their answer to another incorrect answer, even after instruction as reported by Crogman *et al*.[15]? We explore later this issue further by addressing an "object fall" question above and looking more closely at CI tests in an unevenly skilled group of physics students.

Further, physics educators often consider that probably the biggest single students' misconception is their belief that when an object is pushed off or thrown, there continues to be a force in the direction of motion[2]. Why is this considered a misconception? From our definition, to assume that this typical answer is a misconception is to assume that the answer is easily derivable from experience. It is natural and commonsense (from natural experience) to assume that a driving force is needed to keep an object moving at a steady speed, that is, literally the perception from our everyday experience with gravity. When an object falls, we tell children that it is because of gravity, and to the eye, it looks like the object is falling at a constant speed, which might appear that way to the eye because the object reached terminal velocity. Thus, experience tells us that if gravity keeps the object falling by pulling on it, then when an object is pushed or pulled and released, it is reasonable to think that some force like gravity must be keeping it moving. Is this reasoning flawed (being that it is derivable knowledge and scientifically reason-based from the prior knowledge of the learner) when compared with everyday experience of gravity? The answer is clearly no. The argument would be that the learner is scientifically reasoning to come to a conclusion because their available prior knowledge is constructed from their cultural traditional experience and their self-exploration of the natural world. They may have not yet faced that particular conceptual conflict in their experience. In other words, there exists an information gap, especially if students never engaged with physics before, and the results are a misunderstanding of their experience and not a misconception. Surprisingly that distinction is never made in studies and use of CIs in the classroom.

We propose that students' perceived misconceptions could be so or a result of a misunderstanding of the subject, or a lapse in memory that leads to students guessing.

Let's then define misunderstanding:

"A misunderstanding is the communicatee's choice of an interpretation for utterance which is not the intended by the communicator"[32].

Humphreys-Jones[33] argued that misunderstanding occurs "when a hearer (H) fails to understand correctly the proposition which speaker (S) expresses in an utterance. This results in a conceptual misunderstanding in that learner fails to understand the concept or understood something else about the concept that an instructor intended to communicate. It is not that the instruction did provoke the learner to confront their paradoxes and conflicts that result from life experiences, but that something was understood that may not be based on preconceived notions or nonscientific beliefs; hence, this may show up in CIs as a shift in answers at posttest. All learners construct knowledge from their experience, which in itself is scientific, although they may arrive at faulty conclusions that cannot be changed until the conceptual conflict is generated through sensory stimuli. Misunderstanding, thus, involves how the communicatee "capturing of the content, structure, and sequencing of verbal messages, as well as the paralinguistic cues, gestures, facial expressions, body movements, and cues provided by the physical environment that accompany verbal messages"[34] are interpreted or comprehended.

Learning involves an interaction between what Crogman[1] terms L-Language (learners' language - which one should take into account cultural impacts) and the I-Language (teachers' language which is formal). When the teachers' language (I-language) fails to understand the learners' language (L-language), then misunderstanding occurs; learning is generated from the learner comprehending the instructor's language[1]. A misunderstanding is sometimes masked as a misconception but can be easily corrected when the instruction's language is clarified in the mind of the learner. That is, a misunderstanding can be cleared up in a single clarifying question/answer or targeted piece of feedback, but misconception requires undoing potentially layers on layers of misconceived ideas that have hold on the learners' thinking and language. Sayer[32] argued that "the multiplicity of tasks in the comprehension process casts heavy unconscious burden on the comprehender, which renders comprehension potentially risky and liable for interpretive errors. Such errors may preclude extracting the intended meaning behind a piece of discourse causing misunderstanding."

The point of this section was to make a distinction between misunderstanding and misconception, and for it to become clear for instructors and researchers, as we move forward to formulate our disagreement with what CI tests are claimed to measure.

Having clarified what we think misconceptions really are, Crogman *et al*.[15] have a detailed a strategy in a modified CI to parse out better what of students' answers constitute misconceptions and what does not; we address how instruction may unmask this difference through Socratic teaching strategy using sensory stimuli that bring about the conceptual conflict.

Figure 1. Pasco freefall system illustrating gravity laws in different scenarios.

2 Method

2.1 Experiment design probing student understanding

We designed the following experiment [Figure 1] to study students' experiential hypothesis with a physics concept. Students' concept about "falling" is typically that heavy objects fall faster than lighter ones. Our argument is based in part on addressing what FCIs measure in students. We observed the reaction of 24 students to the behavior of a falling object in various media (air, water, salt water, oil, and honey). Students were split in 6 groups of 4 but were instructed to make their prediction individually without talking about it to peers first.

We allowed the 24 students to explore in three ways (1) comparing various objects as they fall in air. (2) Set up an experiment using the Pasco freefall system [Figure 1], which models several objects of different masses and materials falling from the same height in various types of fluid media (air, water, salt water, oil, and honey). Students noted the density of each fluid, the time each type of objects took to fall, and their speeds. We also provided with insight to students' answers selections and the way forward for instruction. This gives insight into why students may have chosen answers that best reflected their experience. (3) Finally, the students watched a video of a feather falling with a metal ball in a vacuum and reflected on their conclusions.

3 Results and discussion

3.1 The implication of prior knowledge on student thinking

Among the 24 students observed, none knew the mathematical details behind the phenomena observed, but most students understood the basic role of air resistance. What most students do not generally know is that a falling object and the fluid in which it falls do not have a constant relation, but life experience does teach them that an object's motion is mass dependent (i.e. dropping a paper vs. a metal sphere from a certain height). This quickly becomes confusing when students observe that in dropping two papers of the same mass (one being crumpled), the crumpled paper hits the ground first. 83% of students predicted that both papers would hit the ground at the same time, whereas all of them predicted that the metal sphere would hit the ground first.

In a follow-up experiment, students folded a paper gradually, and with each fold noticed that the paper fell faster and faster to the point where it hit the ground at about the same time as the metal ball. <50% predicted that outcome correctly. This brings students to understand that surface area plays a key role in objects' behavior in space. The students were asked to draw the forces on the body diagram, but only 16% had context about what that meant and could produce a free body diagram (FBD) [Figure 2]. Do students know what a force is in this sense, since the word force is used in different ways in the students' everyday language: "She forced me to do it," "It was an act of force," "A force of nature, "The armed forces," and Star Wars: "May the force be with you"? Language is fundamental to the learning of concepts and cannot be ignored[1], and such may influence students' answer selection on the FCI test.

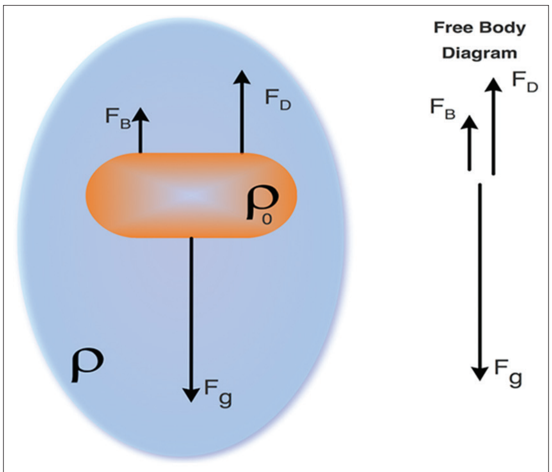

Figure 2. Free body diagram of an object falling in the fluid

Students were asked to drop a square paper along with a steel ball and followed by crumpling the paper in a sphere-like form. It was clearly differentiated that an un-crumpled paper fell much slower, while when crumpled, it hit the ground nearly at the same time. Most students had trouble determining if the steel ball would hit the ground before the paper ball, though the steel ball had a greater mass. Thus, the conclusion reached by the learners was that the area of the objects also played a key role. We argue that the level of "confusion" found in students is then resulting more from lack of knowledge in their experience than from misconception itself. The nature of the question of the FCI as is, without the modification proposed by Crogman *et al.*,[15] results in further confusion and can cause educators to conclude misconception in their students after instruction.

Although this model of no air resistance is easier to solve, it is more illusory and unintuitive to students' experience. There is no way for instructors to determine before instruction if the students' incorrect answers are a result of a misconception or some other factor. Choosing A in the prior question example would suggest that an understanding of the concept. Any other response than A, C, or D could be due to a lack of knowledge. All students in the survey chose A, C, or D as an answer to the question introduced earlier. Using Crogman *et al.*[15] findings, >60% of the students tested understood the concepts because they selected the right answer and the right concept, yet 16% of the students selected "I don't know" (IDK). Moreover, when the question was framed differently, more students understood or predicted that the air acts in opposition to the downward motion of falling objects. Crogman *et al.*[15] argued that the choice of IDK is a strong indication that the learners lacked prior knowledge, or might be the results of a memory lapse.

Now when we asked the same question but this time dropped the objects in a vacuum, the answers were mixed. For those students who had not taken physics prior, 71% stuck with the answer they gave previously. Is this a misconception or maybe just a misunderstanding or unfamiliarity to their experiences? Some educators and researchers are quick to conclude to a misconception.

I would argue the contrary, but rather students' choice was so because, based on what they experienced previously, they could not see any other possibilities beyond. Therefore, dropping the objects created conceptual conflicts, which becomes the essential point by which the instructor can influence students' thought process to clarify any misunderstandings or correct any misconception.

At this point, the subject of air resistance becomes real, and FCI questions are better understood with the expected answer from the educator as "C." No student predicted correctly in this case, "*if the surface area of the two objects were different*?" Here, only the instructor was aware that the area in question is the projected area or frontal area and not necessarily the surface area. This is why some prior knowledge would help students' choice. Thus, the lack of prior knowledge means that the likelihood of students choosing incorrect answers or guessing is increased. Therefore, their choice is not necessarily due to misconception, and the FCI in its original form cannot detect misconception. FCI is really measuring the instructors' performance or the effectiveness of the pedagogy. A student holding on to their choice as post-test means that the pedagogy used did not create conceptual conflict. In my experience as an educator and researcher, when pedagogy is able to create conceptual conflicts through sensory stimuli, the information is stored in long-term memory[18].

The FCI question above required the student to understand that the stated problem was based on $F_{Air} = 0$ since there is no medium (i.e., no drag coefficient); thus, giving $\sum F_y = -mg = -m\frac{dv_y}{dt}$. Do students at this stage understand what it means to have no air resistance? This means that the instructor expects students to understand t-hat all objects are falling with same acceleration, but what does that look like in relation to students' experience? Thus, one question that the instructor may ask students as a prediction to gauge their understanding is:

When an object falls does it speed up, slow down, or falls at a constant speed?

In our case, this was met with mixed results between speeding up and staying the same. Students, through experience, understood that it would not slow down. Looking at the questions, students' experiences would cause them not to choose B or C as an answer. Yet, if a student makes these choices, this may be a result of lack of knowledge or misunderstanding, based on experience constructed through primitive scientific inquiries.

In addition, students' understanding was probed by letting them explore the effects of objects falling in various fluids. Our 24 students dropped various spherical objects in fluids of different viscosities. All students reported that objects traveled more slowly in more viscous fluids. Since the small diameter did not vary too much, students' observations demonstrated that heavy objects fall faster than lighter ones. Students noted time differences between objects decreasing with the density of the fluid or the viscosity. From this observation, students were asked to predict what would happen when there was no density (meaning no fluid), and before submitting their answer, they were asked to discuss their conclusion with classmates from other groups. Again, all students concluded that in a vacuum, all objects would reach the ground at the same time. Thus, the students' cognitive conflicts between air, surface, and motion were now resolved.

This notion of heavier objects falling at the same rate as lighter ones disregards the nature of air resistance. No students' selection reflects anything otherwise than the heavier one "*falls considerably faster" or* "the heavier one *falls twice as fast" or "*about the same for both balls," which sums up students' state of understanding about *drag force, or viscous force, or* no *air resistance,* respectively. When students are asked to explain the reason for their choices:

1. Those choosing "about the same for both balls" explain that they had learned it before. These students have the tendency to disregard the effect of air resistance using the experience that their choice is the expected answer.
2. Students choosing A or D explain that the ball falls considerably faster than the paper, so they guess A or D since they did not know how to calculate the answers.

I fail to see where is the misconception and how CI would measure it in the current format of CI construction. It only seems that when CI is used in this fashion, it has the tendency to mislabel student choices as misconceptions. Yet, the FCI question discussed in this article requires "C" as the right choice and does not state that it is ignoring air resistance. Thus, the expected answer is based on rote memorization and not on scientific reasoning. I am led to conclude that the question is misleading, flawed, and ambiguous. I would be inclined to argue that the so-called distractors came through students' reasoning scientifically based on their constructed understanding of their experiences and the assumptions that are being made. Scientific reasoning does not mean that one comes to the correct or the accepted conclusion but instead is that their reason from assumption to a conclusion has taken a rational path.

Fadaei and Mora[35] reported that some misconceptions that had not existed before occurred after instruction, such as obstacles exerting no force, air pressure-assisted gravity, and gravity intrinsic to mass. But again, are these misconceptions or just misunderstandings. When do misunderstandings become misconceptions? Through this analysis, we uncovered that it is a very complicated situation to deal with the exact effects of the way instructor's present concepts to learners in their teaching. Misunderstandings are easily cleared up through better communication tools[32], but misconceptions require conceptual conflict since they are formulated based on the learners' cultural, traditional experiences.

3.2 The importance of student's prior knowledge in test questions about falling objects

Let's consider two objects falling and hitting the floor from some h height above the floor as described the FCI multi-choice question above. An object falling to the earth must experience air resistance. Air resistance is a concept for students to understand before they can even address the problem. There are three factors that are important for fluid resistance: The fluid's nature, the speed of the object, and the shape of the object. In this case, we may tell our students that it is a resistive force like friction, in that it tries to oppose the motion of the object falling to the earth, but that it is quite unlike the kinetic force of friction, which is independent of speed. From experience, most students are familiar with what friction does. In the case of our 24 students, all understood the basic of friction in the context of objects sliding across the floor with no force in the direction of motion. When asked what brings the object to rest, students opt for *friction*. From their language, friction means to be in opposition.

Experience teaches them that an object falling will also experience a resistive force. An object is falling in a fluid experiences three types of resistive forces. Unbeknownst to most introductory students, the some of the resistive forces vary with velocity: For small objects or very viscous fluid - i.e., the object experiences low speed, and the resistive force (viscosity force: F_{vis}) varies as v, and for very massive objects or not very viscous fluids such as air, the resistive force (drag force F_D) varies as v^2 since the object is experiencing high speed. Therefore, the drag force becomes more dominant at high speeds, but at low speeds, the viscosity force is more pronounced. How do we determine which of these forces will be more dominant? Computing the Reynolds number (Re) accomplished that $Re = \frac{\rho v d}{\mu}$ where, ρ is the fluid's density, v is the characteristic velocity, d is the characteristic flow length, and μ is the fluid's viscosity.

3.2.1 Drag force

F_D is the drag force that comes about as the object pushes the fluid out of the way. D (kg⁄m) depends on the shape and size of the body and the density of the air. This is the dominant resistive at high speed: $F_D = \frac{1}{2}C_d\rho Av^2 = Dv^2$ (C_d describes the drag coefficient, ρ is the density of the object, A is the projected area of the object, and v is the velocity of the object).

3.2.2 Viscous force

F_{vis} is the viscous force that comes from Stoke's law, which has to do with the small velocity of spherical objects. When velocity is slow, the flow of the fluid about the object is laminar. Thus, Reynolds number, on this case, is small. For the above experiment, we only used spherical objects. For non-spherical objects, the equation is somewhat more complex. Leith[36] has modified Stoke's law to predict the shape factor for spheres, cylinders, prisms, spheroids, and double conical. A car moving at slow speed down a road has a very low air resistance and experiences a resistive force F_{vis}=6πμRv = (μ describes the fluid's viscosity, R is the radius of the object, and is the velocity of the object).

3.2.3 Buoyancy force

F_B = ρVg is the buoyancy which is the weight of the displaced fluid. The buoyancy is resulting from the pressure difference between the pressures above and below the object. From Archimedes' principle, the object fully submerged in a fluid will displace its volume.

A body falling experiences all three of these forces [Table 1]. As the object falls, the air beneath it pushes on it and slows down its fall. The faster the object is moving, the harder the air pushes. Figure 3 is a FBD illustrating what happens as a body falls through the air. An experienced student can use Newton's second law to write the equation below:

$$\sum F_y = -F_{Air} + mg = ma_y = m\frac{dv_y}{dt} \quad (1)$$

Table 1. Essential mathematical formulae that should be understood by students to grasp the falling motion concept in air versus vacuum contexts

Concept	**No air resistance**	**Air resistance**		
	Freefall	**Slow speeds/Small objects**	**Fast speeds/Massive objects**	**Complete description**
Resistive force	0	$F_{vis}=\rho Vg+bv$	$F_D=\rho Vg+Dv^2$	$F_a=Dv^2+\rho Vg+bv$
Terminal velocity	N/A	$v_t=\frac{(\rho_o-\rho)Vg}{b}$	$v_t=\sqrt{\frac{(\rho_o-\rho)Vg}{D}}$	$v_t=\frac{b\pm\sqrt{b^2+4\rho_v gD}}{2D}$
Equation of motion	$\frac{dv}{dt}=-g$	$\frac{dv}{dt}=\rho_v g-\frac{b}{m}v$	$\frac{dv}{dt}=\rho_v g-\frac{D}{m}v^2$	$\frac{dv}{dt}=\rho_v g-\frac{b}{m}v-\frac{D}{m}v^2$
Velocity	$v=v_0-g$	$v=-\frac{mg}{b}+\left(v_0+\frac{mg}{b}\right)e^{-pt}$	$v=-v_t\tanh\left(\frac{\rho_v g}{v_t}t\right)$	$v=\frac{b}{2D}+\alpha\tanh\left(\frac{\alpha D}{m}t\right)$
Position	$y=y_0+v_0t-\frac{1}{2}gt^2$	$y=y_0+v_0t-\frac{1}{2}gt^2$	$y=y_0+v_0t-\frac{1}{2}gt^2$	$y=y_0+v_0t-\frac{1}{2}gt^2$
Time	$y=y_0+v_0t-\frac{1}{2}gt^2$	Transcendental equation in time	$y=y_0+v_0t-\frac{1}{2}gt^2$	Transcendental equation in time

Students must grasp these formulae to truly understand the dynamics between air and vacuum falling objects' behaviors. When an object is moving slowly, the viscous force dominates. For fast moving objects, the drag force is much greater than that of viscous force, therefore, the terminal velocity. m=ρ_o V_o

$m=\rho_o V_o$ is the mass of the object, and V_o is the object's volume, while ρo is the object's density. Vo =V for an object submerged in a fluid. $\rho_V=\left(1-\frac{\rho}{\rho_0}\right)$ and $\alpha=\sqrt{\frac{b^2}{4D^2}+\frac{m\rho_V g}{D}}$ are constants. The apparent mass $m_V=\left(1-\frac{\tilde{n}}{\tilde{n}_0}\right)V_o$

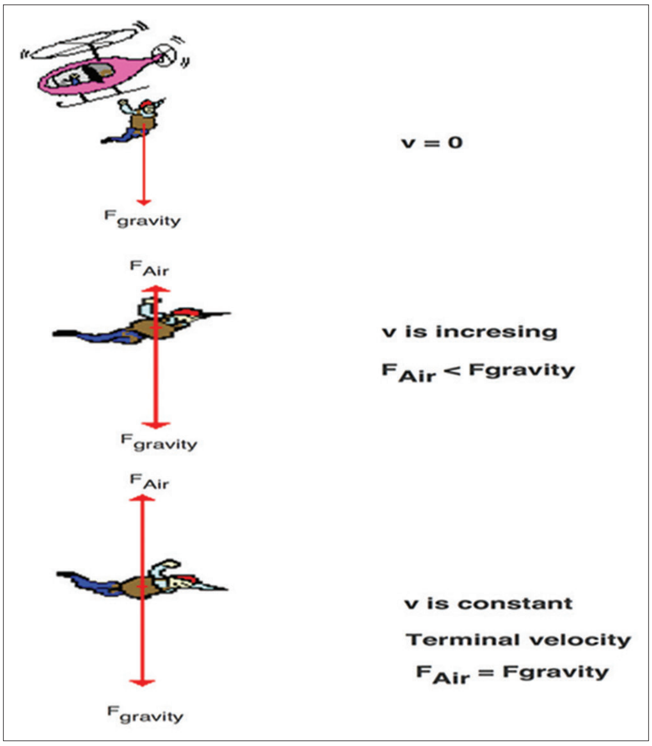

Figure 3. The free-body diagram of a falling object

Table 1 illustrates the possible solutions for this equation. The question is, how does an educator distill this into a class of freshmen who have not yet acquired the skill set to solve equation (1) and get results as in Table 1? Using the experiment design that we described above, we would create conceptual conflict to engage the students' thinking and foster conceptual understanding.

Considering the situation when $a_y=0$, the instructor can introduce the concept of v_y reaching constant velocity that we termed as terminal speed. Figure 3 shows the stages as the object goes toward its terminal speed. The idea of terminal speed matches the learner's intuition of heavier objects falling faster (*falls twice as fast in case of the question in the beginning*) in their environment as shown in Table 1. At this point, the learner has no notion for other environments because they lack knowledge and experience with change in the medium; asking the student to predict what they think would happens engages the student thought process to bring about understanding through inquiry.

$$mg-F_{Air}=0 \tag{2}$$

The equation above shows that students' intuition is correct and is not a misconception. What instructors know is that the objects will accelerate at different rates due resistive forces of the air; the larger mass will accelerate longer causing objects to reach a greater terminal velocity provided their projected area is smaller. In a more viscous fluid where $F_{vis}>F_D$ then $v_{t,heavier}=2v_{t,ligher}$ (choice A) and in case that $F_{vis}<F_D$ then $v_{t,heavier}=\sqrt{2}v_{t,ligher}$ (choice D).

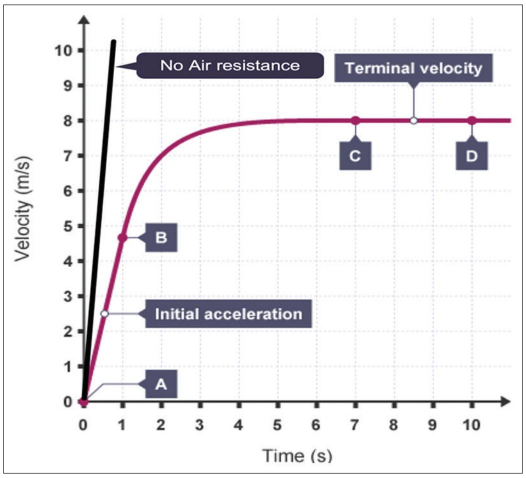

Figure 4. An object falling in air. Between A and B the object begins to accelerate and as it speeds up the resistive force increases. Between B and C, the acceleration is decreasing due to the increases of the resistive force until, between C and D, the object is not accelerating anymore due the resistive force being equal to the weight of the object. The object at this point is said to have reached its terminal velocity[37]

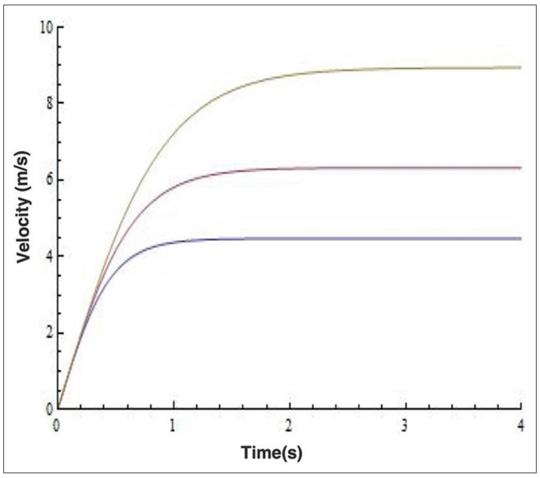

Figure 5. The graph shows the velocity with for three different objects. The lowest blue curve corresponds to the smaller mass, and each successive curve above it corresponds to a mass twice as large as for the last curve

The concepts described above are expected to be familiar and understood in STEM education settings, but most of the students in introductory physics classes do lack prior knowledge of basic forces laws. Thus, the students tend to rely on their experience, and when in uncertainty, they compensate for lack of knowledge by guessing or may misrepresent their understanding of the subject matter to please the instructor (DKE). This behavior is often erroneously labeled as a misconception. Looking at Figure 4 one could see why a number of student thinks the speed is constant because the object quickly gets up to its terminal speed as compare to an object falling with no air resistance. In this case, the choice reflects that the terminal velocity of the bigger mass will have a faster velocity than a smaller mass. This is seen in Figure 5, which suggests that students' thinking that a heavy object fall faster better reflecting their experience about how objects fall. Why such attempts are made by the instruction to introduce the learner to the subject in ways that is unnatural to their experience? Instruction would benefit greatly if we go from their natural experience to cases that are unfamiliar in a very derivative way. It is understandable why students misunderstand concepts in the class, not only do they have to overcome the technical language but the approach is not intuitive for them, which means that they are unable to see the connection that the instructor is trying to make. Although we discuss this in the context of falling objects, it is true for so many other concepts in science.

Asking the students: "*if you have two objects of similar area and you drop them from the top of some building which of them will hit the ground first*?" How would they answer the question? Does this lesson create conceptual conflict to change students' prior beliefs? In our discussion, few students if any at all would have this prior knowledge, what they have is what they might observe visually in a very limited way. For this reason, CIs cannot be a tool to gauge out students' misconception, but help to determine the class level for better instruction prep. It is, for this reason, Crogman and TrebeauCrogman[18] argued for sensory learning that recreates student real-life experience in the classroom and uses question asking as an exploratory tool to create conflict and effectively tackle misconceptions.

4 Conclusion

The question we started within this article must be deemed ambiguous, and our expectation that all object falls at same rates are unrealistic, not according to our experience. Thus stated, it assumes that students understand what it means to have no or negligible air resistance. Further, the question does not even explain what air resistance is, and how it works, thus asking students to know an object's behavior inside of a vacuum has no connection to their experience and cannot be labeled a missed concept. A student taking the FCI test and answering C for this question should be considered as a misconception because their answer defies experience. Until further knowledge comes to first create a conceptual conflict, it is irrational for instructors to suggest that the students' experience is not correct. Students choosing A or D seem to have a better understanding of how things work in obvious to most students what role the object's projected area plays. Further, because this effect is nonlinear, then all the other FCI chosen answers are to be seen as correct. The conclusion is that students' lack of knowledge must be taken into account to better understand what FCI does measure.

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