

**Teaching Undergraduate Physics through a Research-based
Clicker Methodology**

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Abstract

Student personal response systems, also known as clickers, have been widely used in undergraduate science classrooms to engage students in active learning. In physics, a number of clicker resources that target students' conceptual understanding are available. These materials typically are individual questions that are discretely designed and used, with each addressing a distinct concept. Differing from the traditional materials, a new clicker methodology is developed and tested in our studies based on the theory of contextualized learning. Specifically, we have created coherent sequences of clicker questions; within each sequence 3-4 seemingly disparate questions are systematically crafted to address the same underlying key concept but are embedded in different contexts. Through consistent exposure to these sequences, students are trained to flexibly seek and apply learned core concepts across diverse situations; thus effectively reducing their difficulties associated with context-dependent learning. Following this sequence-based clicker methodology, we have created, validated, and implemented ~150 question sequences, sufficient in number to cover the entire introductory physics. Empirical results from real classroom implementation and testing show our clicker materials have significantly increased students' conceptual understanding—measured by concept inventories—as well as enhanced their learning interest.

Teaching Undergraduate Physics through a Research-based Clicker Methodology

Introduction

Clickers, also known as student personal response systems, have been widely used in undergraduate introductory physics classes for promoting student active engagement and learning outcomes. An instructor can use clickers to conduct in-class formative assessments and receive instant feedback on student understanding of course materials. Based on the results, the instructor can make a decision to either move on to the next topic or provide more discussion on the same topic, a technique often referred to as contingent teaching (Wood & Wood, 1996). Clickers also afford students a great opportunity to reveal their answers in a way that is anonymous to their peers, therefore alleviating the pressure of feeling embarrassed in front of the class if they provide wrong answers (Draper, Cargill, & Cutts, 2002; Lee, Ding, Reay, & Bao, 2011). Perhaps most importantly, when combined with carefully crafted teaching materials and strategies clickers can stimulate an interactive learning environment in which students deeply engage in classroom discourse with the instructor as well as with their peers so as to facilitate deliberate learning (Duncan, 2005; Knight & Wood, 2005; Mazur, 1997).

Previous studies on this research topic was largely devoted to measuring emergent characteristics and advantages of the clicker technology in the teaching and learning of science, but relatively less work was focused directly on the programmatic construction of clicker materials as part of curriculum development to bring about students' best learning outcomes. In the physics education field, a few research-based clicker resources are recognized that contain substantive reports emphasizing the importance of design and implementation, such as Mazur's Peer Instruction (Mazur, 1997), Dufresne et al. and Beatty et al.'s response system teaching (Beatty, Gerace, Leonard, & Dufresne, 2006; Dufresne, Gerace, Leonard, Mestre, & Wenk, 1996), and Duncan's classroom clickers (Duncan, 2005, 2006). Questions in these clicker

materials are single items that are created and used individually to address discrete concepts. Differing from this traditional approach, we developed an innovative clicker methodology that emphasizes systemic construction and implementation of question sequences to enhance student flexible application of core physics ideas across diverse situations (Ding & Reay, 2012; Lee et al., 2011). In this new methodology, clicker questions are systemically crafted into sequences. Each sequence is a cohesive unit that consists of 3-4 individual questions sharing the same underlying concept but containing distinct contextual features. The contextual features are at the surface level, involving various entities, properties thereof, storylines, scenarios, or representations, and therefore are separate from the core ideas needed to answer the questions (Ding & Reay, 2012; Lee et al., 2011). This clicker methodology draws on the theoretical basis that learning is context dependent; in other words, students who have learned a concept in a specific situation may not be able to use it in a seemingly different situation that requires application of the same concept (Anderson, Reder, & Simon, 1996; Bransford, Brown, & Cocking, 2000; Broudy, 1977; Clement, 1982; Ding & Reay, 2012; Koedinger & Nathan, 2004). This phenomenon is frequently observed in physics education and, if not properly handled, can pose a serious problem for student conceptual understanding and application.

Following this new clicker methodology framework, we have developed, validated, implemented and evaluated 167 clicker questions sequences, approximately 500 individual questions. These sequences are extensive enough in number to populate a typical year of college-level introductory physics. Our goal is to most effectively promote student conceptual understanding and application of physics core concepts through the use of our clicker question sequences.

In what follows, we report using the new sequence-based clicker methodology framework to promote student conceptual learning in undergraduate introductory physics. Specifically, we discuss four stages of creation, validation, implementation, and evaluation of clicker question sequences. Interested readers can find more details regarding the cognitive foundations on contextualized learning and related theoretical models elsewhere in Ding & Reay (2012).

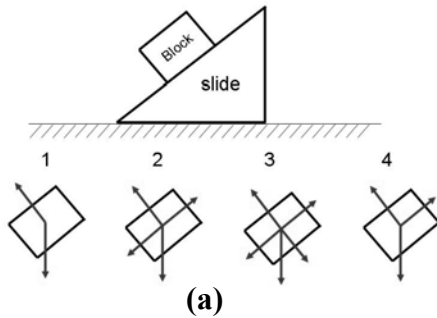
Clicker Question Sequence Framework and Theoretical Foundation

We intended to create a repository of multiple-choice clicker question sequences with an extensive content coverage for a typical first-year college-level introductory physics. We used popular textbooks (Halliday, Resnick, & Walker, 2008; Knight, 2008) as a guide to identify important physics concepts for inclusion into the clicker materials and consulted a number of physics faculty members at four different institutions to ensure that these concepts are valued by the physics education community.

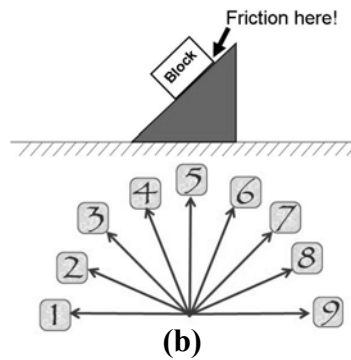
For each concept, we created a sequence of 3-4 individual questions that address the same core idea but contain differing contextual features. It should be noted that creation of a clicker sequence is not a simple assembly of individual questions. Instead we systemically designed each sequence with careful considerations of the cognitive features in the questions that are required of students. In all cases we deliberately avoided items that are aimed at low level of cognition, such as recall, recognition, or routine use of formulas. More importantly, we strived to diversify the cognitive emphasis of the individual questions within each sequence. By doing so, not only the contextual features vary, but also the level of mental effort invoked in answering each question is different within a sequence. It is through this exterior contextual and interior

cognitive variety together with the invariant underlying core idea in the question of each sequence that students experience flexible application of physics fundamentals. In what follows, we present two sample sequences and the primary basis of their design.

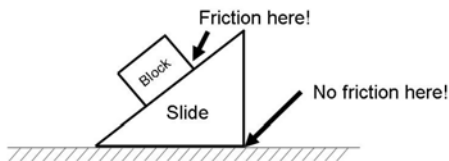
A block sits at rest and stays at rest on a slide with frictional surfaces. Which of the following sketches most closely resembles the correct freebody diagram for all forces **acting on the block**? Each red arrow represents a force. Observe their number and direction, but ignore their lengths.



The block sits **at rest and stays at rest** on the slide. What is the direction of the sum of all forces, (*i.e. the resultant force*), that the **slide exerts on the block**?



The block still sits at rest on the slide, held by friction, but now there is no friction between the slide and the ground. The slide



1. Moves to the right
2. Moves to the left
3. Doesn't move
4. Can move either way.

(c)

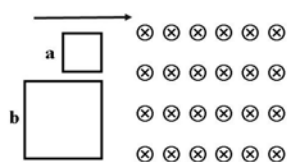
Figure 1 A mechanics sequence connecting force diagrams to the concept of net force.

Figure 1 illustrates a mechanics sequence. It requires students to connect force diagrams with net force in analyzing a system. It contains three questions with different perspectives. The first question asks students to focus on the individual forces exerted on a block sitting at rest on a slide by using diagrams. The second question then changes the perspective from the individual forces to the net force on the block. Students need to consider both the net effect of all forces on

the block and the net effect due to the slide. The third question further shifts the focus from the block to the slide, yet another perspective to look at the same event. It asks students to decide how the interaction between the block and the slide causally affects the motion of the slide.

Collectively, these three questions form a coherent sequence, motivating students to consider the same topic from multiple viewpoints.

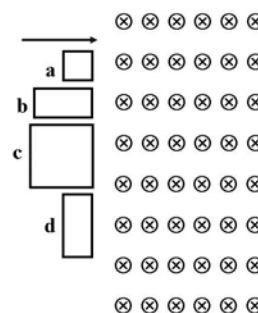
The figure shows two wire loops, with edge lengths of L and $2L$, respectively. Both loops will move through a region of uniform magnetic field B at the same constant velocity. Rank them according to the emf induced **just as their front edges enter the B field region**.



1. $a > b$
2. $a = b$
3. $a < b$
4. Depends on the magnitude of their common velocity
5. Depends on the magnitude of the B field

(a)

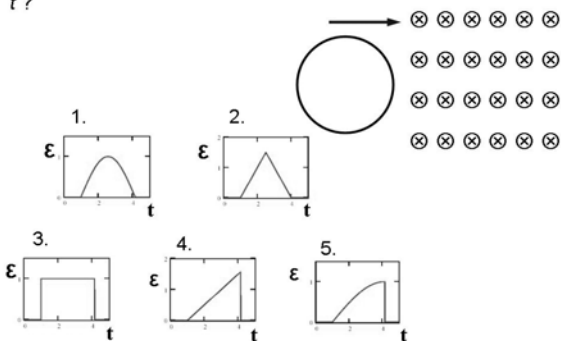
The figure shows four wire loops, with edge lengths of either L or $2L$. All four loops will move through a region of uniform magnetic field B at the same constant velocity. Rank them according to the emf induced **just as they enter the B field region**.



1. $a < b < d < c$
2. $a < b = d < c$
3. $a < b < c < d$
4. $a = b < c = d$
5. $a = b < d < c$

(b)

A circular wire loop moving at constant velocity enters a long region of uniform magnetic field B . Which one of the graphs describes the emf ϵ in the loop as a function of time t ?



(c)

Figure 2 An electricity and magnetism sequence concerned with induced EMFs.

Figure 2 shows a sequence on electricity and magnetism. Questions in this sequence contain different entities and representations but address the same key concept on induced

electromotive force (EMF). The first question asks students to make a comparison in the induced EMF between two loops of different sizes when they enter a uniform magnetic field. Because both loops are square, the larger one generates a greater EMF. When answering this question, students may use “larger means more”, a phenomenological primitive, to get a correct answer. The second question involves four loops of different dimensions. It is designed to test knowledge differentiation between magnetic flux and the rate of change in magnetic flux. Students who choose a correct answer by using the “large means more” p-prim in the first question will likely choose a wrong answer to the second one. The third question further asks students to apply the EMF concept to a circular loop, a situation that is not typically discussed in textbooks. This question also requires students to translate between diagrammatic and graphical representations. Overall, this sequence utilizes contrasting cases to highlight the flexible application of the EMF concept.

Validation of Clicker Question Sequences

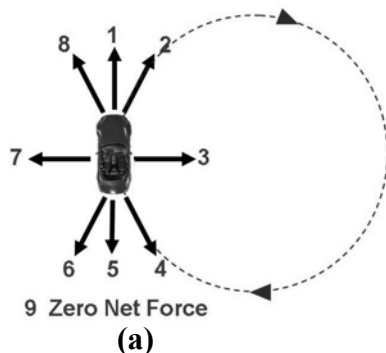
All question sequences were validated through expert review and student interviews. The experts comprised of 6 physics faculty members, 2 postdoctoral fellows and 45 graduate teaching instructors from four universities and colleges. We invited these experts to review our clicker question sequences and examine if these materials were technically correct, covered important key concepts, contained clear language and addressed student common misconceptions in alternative choices. We also asked them to rate each question on a 5-point scale with 5 being a good question and 1 being a poor question. All ratings were above 4, and experts' written comments were mostly minor, pertaining to the refinement of language and representations.

Based on the expert feedback, we made revisions, which were then cross-examined by a team of researchers to ascertain that the revisions resolved the issues raised by the experts.

Using these expert-validated question sequences, we then conducted private one-on-one student interviews to further examine our clicker materials. Traditional approach to student interviews is to uncover learners' common misconceptions. In our studies, we viewed students as consultants who would be able to provide a new perspective to construe the questions that would result in a different but not necessarily an incorrect way to answer them. By doing so, we would be able to identify and rectify potential validity issues in our clicker materials (Ding, Reay, Lee, & Bao, 2009).

During the interviews, students were asked to rephrase each question without answering it, provide free comments on the quality of the question, and then choose an answer with reasoning. We first conducted extensive interviews with dozens of student volunteers, from which we then selected 16 who were verbal and detail-oriented for repeated weekly interviews. These 16 students reviewed the entire repository of the 167 clicker question sequences, with each sequence examined by at least three different students. Since all question sequences used in student interviews were already validated by experts, our initial intention was to establish statistical evidence on the validity of the clicker materials through a large-scale interview study. However, to our surprise, student interviews uncovered various validity issues that were not previously expected, and as a result a significant portion of the expert-validated question sequences (38% of the total 167 sequences) was further revised. Among them, 11% of the question sequences underwent major changes. Figure 3 is an example.

A car rounds a curve while maintaining a constant speed. Which arrow represents the direction of the net force on the car as it rounds the curve?



A car rounds a curve while maintaining a constant speed. Which arrow represents the direction of the net force on the car as it rounds the curve at the instant shown below?

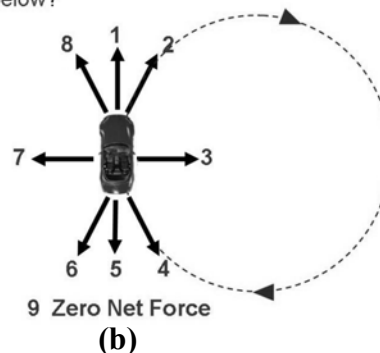


Figure 3 Question (a) is affirmed by experts, and question (b) is modified based on student interviews.

This question asked students to identify the direction of a net force on a car moving around a circle (Figure 3). One student interviewee selected “zero net force” as an answer, although he correctly drew inward arrows to represent the net force on the car at a series of locations along the circle. As revealed in our interview, this student did not choose the incorrect answer because he did not know what the net force was at each instant along the circle; but instead he thought the question asked for the time average of the net force on the car. To avoid this alternative (not incorrect) interpretation, we added a specific statement in the question, asking students to determine the net force on the car “at the instant shown” in the graph.

Implementation of Clicker Question Sequences

We implemented all question sequences in real classrooms. Each sequence was used as a cohesive micro-system to highlight a single concept across differing contexts. In a typical class of 48 minutes, 2-4 clicker question sequences were used, interspersed with mini-lectures or

demonstrations. Each sequence usually took 7-9 minutes to complete and was enacted in variations of the following procedure.

Students individually answer each question and are shown a response histogram. Without revealing the correct answer, the instructor then initiates small-group discussion among students or a whole-class dialogue. Next students either re-vote on the same question or move on to the next one. The first question is often straightforward and is used as a warm-up exercise. The majority of a class can answer it correctly. So transitioning from the first question to the second often requires a brief discussion or no discussion at all. However, the second question oftentimes is challenging, and student answers split between two or three alternative choices. Students are encouraged to talk with their neighbors to articulate their own responses and evaluate each other's ideas, a technique similar to peer instruction (Mazur, 1997). At the same time, the instructor circulates the classroom, listening to student discussion and asking clarifying questions, if needed, to better understand student thoughts. Then a revote on the same question is carried out, and student responses tend to converge to the correct choice. At this point, the majority of the students have gained a fairly good mastery of the key concept that underlies differing surface features. So, student performance on the last question, which is often more challenging than the second, is rather high.

In real classroom instruction we deliberately use our clicker materials to stimulate an interactive learning environment, in which peer discussion and whole-class dialogues are an integral component. Students are encouraged to work collaboratively in small groups, articulating their own thoughts and critically evaluating each other's responses. In doing so, not only do we bring out student discussions between the two polls of the same question, as typically practiced in peer instruction, we also use them as a mediating transition between isomorphic

questions. As such, student attention is directed to the individual questions locally as well as to the overarching key concept globally. With some added comments from the instructor during the final round of discussion, the idea of using the same concept across different contexts is reinforced and extended to other possible cases not shown in the sequence.

Evaluation of the Effectiveness of Clicker Question Sequences

To evaluate the effectiveness of our clicker question sequences, we examined student conceptual learning gains and their affective outcomes. Student conceptual learning gains were measured by administering pre and post concept tests on the key topics covered in class. These concept tests contained questions that were selected from standardized assessments published in literature, such as the Force Concept Inventory (Hestenes, Wells, & Swackhamer, 1992), Mechanics Baseline Test (Hestenes & Wells, 1992), and Conceptual Survey of Electricity and Magnetism (Maloney, O'Kuma, Hieggelke, & Van Heuvelen, 2001). If necessary, we also added into the tests additional questions designed by our research team to ensure a sufficient content coverage that would allow us to make an overall evaluation of student conceptual gains in the three major domains of physics: mechanics, electricity and magnetism, and modern physics (waves, optics, relativity, and quantum physics). We adopted Hake's normalized gains (Hake, 1998) to gauge changes in student conceptual learning and compared the results between two parallel classes of the same course in each academic term: one used our clicker materials and the other did not. For convenience, we name them clicker and non-clicker classes thereafter. Student affective outcomes were measured using a survey on clicker usage that was developed by our research team.

In years of efforts for conducting effective measurement of student learning gains, we found that test timing and incentives play a crucial role in measurement results (Ding, Reay, Lee, & Bao, 2008). Typically, a pretest is given on or near the first day of class. However, our research shows that instruction as little as what is covered in one or two classes can have a significant influence on the pretest results. Similarly, timing and incentives of a posttest also can exert a considerable impact on the test scores and the student participation rate—two potentially correlated outcomes. We found the most stable situation for evaluating student conceptual gains is to administer the pretest on the first day of class before students receive any instruction, and give the posttest as part of final examination. More details on the effect of timing and incentives on test results can be found in (Ding et al., 2008).

Informed by these results, we therefore consistently administered all pretests on the first day of class and gave posttests as part of final examination. The comparison results between the clicker and non-clicker classes are shown in Table I. It is worth noting that in the E&M term we only exposed students to our clicker materials once in class and did not afford them an opportunity to review the materials after class. Retrospectively we do not consider this is an optimal approach. As Bransford & Schwartz (1999) mentioned, one-time exposure to instructional materials can only yield limited effect even in the best learning environment. Therefore, in the mechanics and modern physics terms, we uploaded to a secure website the clicker materials used in class (without answer) to allow students to review the questions sequences after class. As a result, students in the clicker class demonstrated a statistically higher normalized gain than those in the non-clicker class.

Table 1 Clicker and non-clicker comparisons. The differences in normalized gains are significant at the level of $\alpha < 5\%$ for mechanics and modern physics, but not for E&M. In the E&M term, students did not have the opportunity to review the clicker materials after class. However, in the mechanics and modern physics terms, students were allowed to review the clicker materials (without answer) after class.

Term	Assessment	Normalized Gains
Mechanics	MBT with selected items from FCI and research-team developed items on rotation & angular momentum	28.5% (clicker, N = 185) 22.7% (non-clicker, N = 198)
E&M*	CSEM	51.6% (clicker, N = 106) 48.4% (non-clicker, N = 122)
Modern Physics	17-item concept test developed by a research team	60.1% (clicker, N = 156) 44.4% (non-clicker, N = 140)

We also conducted a survey at end of each term to investigate student affective opinions about using clickers. Students were given 17 statements and were asked to express their endorsement for each statement by using a 5-point Likert scale, ranging from +2 strongly agree to -2 strongly disagree. Some examples of the statements include: “I liked using clickers”; “Clickers made me feel involved in the course”; and “I would recommend using clickers in all future introductory physics courses.” Student responses were highly positive, in favor of clicker usage. To ensure that our positively phrased statements did not bias the results, we occasionally inverted the statements such as “I would not recommend using clickers in the future introductory physics course.” In this case, student highly negative responses confirmed that our results were not preferential biased.

Discussion and Summary

We developed an innovative sequence-based clicker methodology framework to enhance student conceptual understanding and flexible application of core ideas in physics. In this clicker methodology framework, questions are no longer created and used as individual pieces. Instead, sequences of 3-4 questions are systemically crafted to address the same underlying concept but contain differing surface-level contextual features. Each sequence is implemented as a cohesive unit in class to facilitate student abstraction of the underlying core concept, as well as to enrich the application of the concept across multiple situations.

Following this clicker methodology framework, we created, validated, implemented and evaluated 167 clicker sequences, approximately 500 individual questions. These sequences are extensive enough in number to populate a typical year of undergraduate introductory physics. Studies show that after using our clicker materials students exhibited a statistically better learning gain, measured by concept maps, than those who did not use our clicker materials. Students' affective outcomes also suggested that students enjoyed using clickers in physics classes.

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