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Improved Learning in a Large-Enrollment Physics Class

Louis Deslauriers,[1,2] Ellen Schelew,[2] Carl Wieman*†‡

We compared the amounts of learning achieved using two different instructional approaches under controlled conditions. We measured the learning of a specific set of topics and objectives when taught by 3 hours of traditional lecture given by an experienced highly rated instructor and 3 hours of instruction given by a trained but inexperienced instructor using instruction based on research in cognitive psychology and physics education. The comparison was made between two large sections (N = 267 and N = 271) of an introductory undergraduate physics course. We found increased student attendance, higher engagement, and more than twice the learning in the section taught using research-based instruction.

The traditional lecture approach remains the prevailing method for teaching science at the postsecondary level, although there are a growing number of studies indicating that other instructional approaches are more effective (*1*–*8*). A typical study in the domain of physics demonstrates how student learning is improved from one year to the next when an instructor changes his or her approach, as measured by standard concept-based tests such as the Force Concept Inventory (*9*) or the instructor's own exams. In our studies of two full sessions of an advanced quantum mechanics class taught either by traditional or by interactive learning style, students in the interactive section showed improved learning, but both sections, interactive and traditional, showed similar retention of learning 6 to 18 months later (*10*). Here, we compare learning produced by two contrasting instructional methods in a large-enrollment science course. The control group was lectured by a motivated faculty member with high student evaluations and many years of experience teaching this course. The experimental group was taught by a postdoctoral fellow using instruction based on research on learning. The same selected learning objectives were covered by both instructors in a 1-week period.

The instructional design for the experimental section was based on the concept of "deliberate practice" (*11*) for the development of expertise. The deliberate practice concept encompasses the educational ideas of constructivism and formative assessment. In our case, the deliberate practice takes the form of a series of challenging questions and tasks that require the students to practice physicist-like reasoning and problem solving during class time while provided with frequent feedback.

The design goal was to have the students spend all their time in class engaged in deliberate practice at "thinking scientifically" in the form of making and testing predictions and arguments about the relevant topics, solving problems, and critiquing their own reasoning and that of others. All of the activities are designed to fit together to support this goal, including moving the simple transfer of factual knowledge outside of class as much as possible and creating tasks and feedback that motivate students to become fully engaged. As the students work through these tasks, they receive feedback from fellow students (*12*) and from the instructor. We incorporate multiple "best instructional practices," but we believe the educational benefit does not come primarily from any particular practice but rather from the integration into the overall deliberate practice framework.

This study was carried out in the second term of the first-year physics sequence taken by all undergraduate engineering students at the University of British Columbia. This calculus-based course covers various standard topics in electricity and magnetism. The course enrollment was 850 students, who were divided among three sections. Each section had 3 hours of lecture per week. The lectures were held in a large theater-style lecture hall with fixed chairs behind benches grouping up to five students. The students also had weekly homework assignments, instructional laboratories, and tutorials and recitations where they solved problems; this work was graded. There were two midterm exams and a final exam. All course components were common across all three sections, except for the lectures, which were prepared and given independently by three different instructors.

During week 12, we studied two sections whose instructors agreed to participate. For the 11 weeks preceding the study, both sections were taught in a similar manner by two instructors (A and B), both with above average student teaching evaluations and many years experience teaching this course and many others. Both instructors lectured using PowerPoint slides to present content and example problems and also showed demonstrations. Meanwhile, the students took notes. "Clicker" (or "personal response system") questions (average 1.5 per class, range 0 to 5) were used for summative evaluation (which was characterized by individual testing without discussion or follow-up other than a summary of the correct answers). Students were given participation credit for submitting answers.

Before the experiment, a variety of data were collected on the students in the two sections

Table 1. Measures of student perceptions, behaviors, and knowledge.

	Control section	Experimental section
Number of students enrolled	267	271
Mean BEMA score (*13*) (week 11)	47 ± 1%	47 ± 1%
Mean CLASS score (*14*) (start of term) (agreement with physicist)	63 ± 1%	65 ± 1%
Mean midterm 1 score	59 ± 1%	59 ± 1%
Mean midterm 2 score	51 ± 1%	53 ± 1%
Attendance before experiment*	55 ± 3%	57 ± 2%
Attendance during experiment	53 ± 3%	75 ± 5%
Engagement before experiment*	45 ± 5%	45 ± 5%
Engagement during experiment	45 ± 5%	85 ± 5%

*Average value of multiple measurements carried out in a 2-week interval before the experiment. Engagement also varies over location in the classroom; numbers given are spatial and temporal averages.

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‡This work does not necessarily represent the views of the Office of Science and Technology Policy or the United States government.

(Table 1). Students took two midterm exams (identical across all sections). In week 11, students took the Brief Electricity and Magnetism Assessment (BEMA), which measures conceptual knowledge (*13*). At the start of the term, students took the Colorado Learning Attitudes about Science Survey (CLASS) (*14*), which measures a student's perceptions of physics. During weeks 10 and 11, we measured student attendance and engagement in both sections. Attendance was measured by counting the number of students present, and engagement was measured by four trained observers in each class using the protocol discussed in the supporting online material (SOM) (*15*). The results show that the two sections were indistinguishable (Table 1). This in itself is interesting, because the personalities of the two instructors are rather different, with instructor A (control section) being more animated and intense.

The experimental intervention took place during the 3 hours of lecture in the 12th week. Those classes covered the unit on electromagnetic waves. This unit included standard topics such as plane waves and energy of electromagnetic waves and photons. The control section was taught by instructor A using the same instructional approach as in the previous weeks, except they added instructions to read the relevant chapter in the textbook before class. The experimental section was taught by two instructors who had not previously taught these students. The instructors were the first author of this paper, L.D., assisted by the second author, E.S. Instructor A and L.D. had agreed to make this a learning competition. L.D. and instructor A agreed beforehand what topics and learning objectives would be covered. A multiple-choice test (see SOM) was developed by L.D. and instructor A that they and instructor B agreed was a good measure of the learning objectives and physics content. The test was prepared at the end of week 12. Most of the test questions were clicker questions previously used at another university, often slightly modified. Both sections were told that they would receive a bonus of 3% of the course grade for the combination of participating in clicker questions, taking the test, and (only in the experimental section) turning in group task solutions, with the apportionment of credit across these tasks left unspecified.

In contrast to instructor A, the teaching experience of L.D. and E.S. had been limited to serving as teaching assistants. L.D. was a postdoctoral researcher working in the Carl Wieman (third author of this paper) Science Education Initiative (CWSEI) and had received training in physics education and learning research and methods of effective pedagogy while assisting with the teaching of six courses. E.S. had a typical physics graduate student background except for having taken a seminar course in physics education.

The instructional approach used in the experimental section included elements promoted by CWSEI and its partner initiative at the University of Colorado: preclass reading assignments, preclass reading quizzes, in-class clicker questions with student-student discussion (CQ), small-group active learning tasks (GT), and targeted in-class instructor feedback (IF). Before each of the three 50-min classes, students were assigned a three- or four-page reading, and they completed a short true-false online quiz on the reading. To avoid student resistance, at the beginning of the first class, several minutes were used to explain to students why the material was being taught this way and how research showed that this approach would increase their learning.

A typical schedule for a class was the following: CQ1, 2 min; IF, 4 min; CQ2, 2 min; IF, 4 min; CQ2 (continued), 3 min; IF, 5 min; Revote CQ2, 1 min; CQ3, 3 min; IF, 6 min; GT1, 6 min; IF with a demonstration, 6 min; GT1 (continued), 4 min; and IF, 3 min. The time duration for a question or activity includes the amount of time the students spent discussing the problem and asking numerous questions. There was no formal lecturing; however, guidance and explanations were provided by the instructor throughout the class. The instructor responded to student-generated questions, to results from the clicker responses, and to what the instructor heard by listening in on the student-student discussions. Students' questions commonly expanded upon and extended the material covered by the clicker questions or small-group tasks. The material shown on the slides used in class is given in the SOM, along with some commentary about the design elements and preparation time required.

At the beginning of each class, the students were asked to form groups of two. After a clicker question was shown to the class, the students discussed the question within their groups (which often expanded to three or more students) and submitted their answer using clickers. When the voting was complete, the instructor showed the results and gave feedback. The small-group tasks were questions that required a written response. Students worked in the same groups but submitted individual answers at the end of each class for participation credit. Instructor A observed each of these classes before teaching his own class and chose to use most of the clicker questions developed for the experimental class. However, Instructor A used these only for summative evaluation, as described above.

L.D. and E.S. together designed the clicker questions and small-group tasks. L.D. and E.S. had not taught this class before and were not familiar with the students. Before the first class, they solicited two volunteers enrolled in the course to pilot-test the materials. The volunteers were asked to think aloud as they reasoned through the planned questions and tasks. Results from this testing were used to modify the clicker questions and tasks to reduce misinterpretations and adjust the level of difficulty. This process was repeated before the second class with one volunteer.

During the week of the experiment, engagement and attendance remained unchanged in the control section. In the experimental section, student engagement nearly doubled and attendance increased by 20% (Table 1). The reason for the attendance increase is not known. We hypothesize that of the many students who attended only part of a normal class, more of them were captured by the happenings in the experimental section and decided to stay and to return for the subsequent classes.

The test was administered in both sections in the first class after the completion of the 3-hour unit. The control section had covered the material related to all 12 of the questions on the test. The experimental section covered only 11 of the 12 questions in the allotted time. Two days before the test was given, the students in both sections were reminded of the test and given links to the postings of all the material used in the experimental section: the preclass reading assignments and quizzes; the clicker questions; and the group tasks, along with answers to all of these. The students were encouraged by e-mail and in class to try their best on the test and were told that it would be good practice for the final exam, but their performance on the test did not affect their course grade. Few students in either section finished in less than 15 min, with the average being about 20 min.

The test results are shown in Fig. 1. For the experimental section, 211 students attended class to take the test, whereas 171 did so in the control section. The average scores were 41 ± 1% in the control section and 74 ± 1% in the experimental section. Random guessing would produce a score of 23%, so the students in the experimental section did more than twice as well on this test as those in the control section.

The test score distributions are not normal (Fig. 1). A ceiling effect is apparent in the experi-

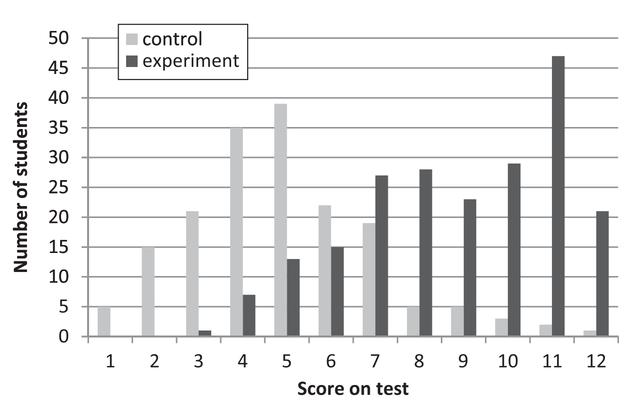

Fig. 1. Histogram of student scores for the two sections.

mental section. The two distributions have little overlap, demonstrating that the differences in learning between the two sections exist for essentially the entire student population. The standard deviation calculated for both sections was about 13%, giving an effect size for the difference between the two sections of 2.5 standard deviations. As reviewed in (*4*), other science and engineering classroom studies report effect sizes less than 1.0. An effect size of 2, obtained with trained personal tutors, is claimed to be the largest observed for any educational intervention (*16*).

This work may obtain larger effect sizes than in this previous work because of the design and implementation that maximized productive engagement. The clicker questions and group tasks were designed not only to require explicit expert reasoning but also to be sufficiently interesting and personally relevant to motivate students to fully engage. Another factor could be that previous work primarily used end-of-term tests, and the results on those tests reflect all the learning that students do inside and outside of class, for example, the learning that takes place while doing homework and studying for exams. In our intervention, the immediate low-stakes test more directly measured the learning achieved from preclass reading and class itself, in the absence of subsequent study.

We are often asked about the possible contributions of the Hawthorne effect, where any change in conditions is said to result in improved performance. As discussed in citations in the SOM, the original Hawthorne plant data actually show no such effect, nor do experiments in educational settings (*17*).

A concern frequently voiced by faculty as they consider adopting active learning approaches is that students might oppose the change (*18*). A week after the completion of the experiment and exam, we gave students in the experimental section an online survey (see SOM); 150 students completed the survey.

For the survey statement "I really enjoyed the interactive teaching technique during the three lectures on E&M waves," 90% of the respondents agreed (47% strongly agreed, 43% agreed) and only 1% disagreed. For the statement "I feel I would have learned more if the whole physics 153 course would have been taught in this highly interactive style." 77% agreed and only 7% disagreed. Thus, this form of instruction was well received by students.

In conclusion, we show that use of deliberate practice teaching strategies can improve both learning and engagement in a large introductory physics course as compared with what was obtained with the lecture method. Our study compares similar students, and teachers with the same learning objectives and the same instructional time and tests. This result is likely to generalize to a variety of postsecondary courses.

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SOM Text
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Supporting Online Material for

Improved Learning in a Large-Enrollment Physics Class

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This PDF file includes:

Supporting Online Material for

Improved learning in a large enrollment physics class

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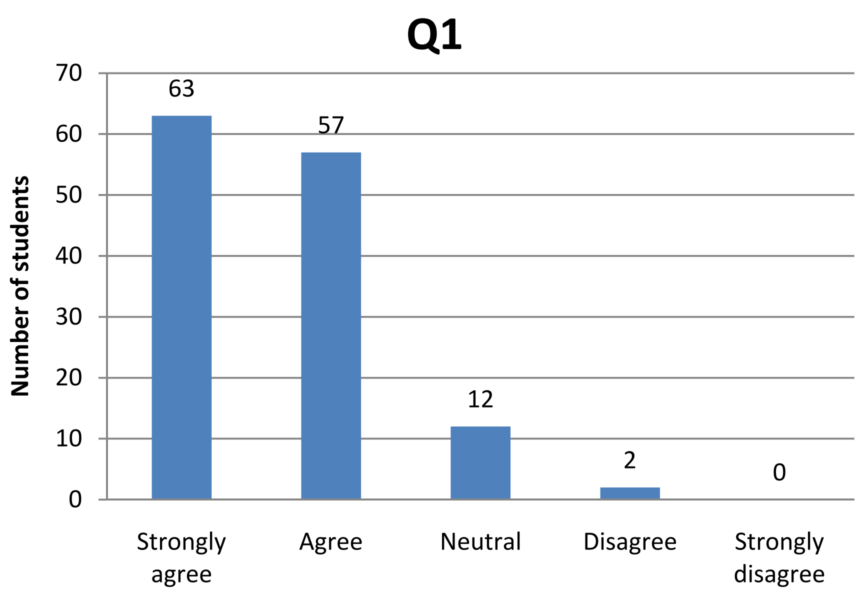
1. Engagement measurements discussion.
2. Experimental section opinion survey and responses.
3. Test given to both sections on the material taught.
4. Slides shown in the three days of class in the experimental section. There is typically one question or task per slide, with about six slides per 50 minute class. Commentary on the design and preparation is inserted (in italics).
5. Learning objectives agreed upon by the two instructors.
6. Hawthorne effect comment, and discussion of engagement and attendance in courses with similar design over a full semester.
7. List of proven teaching practices used, with references.

1. Engagement measurements

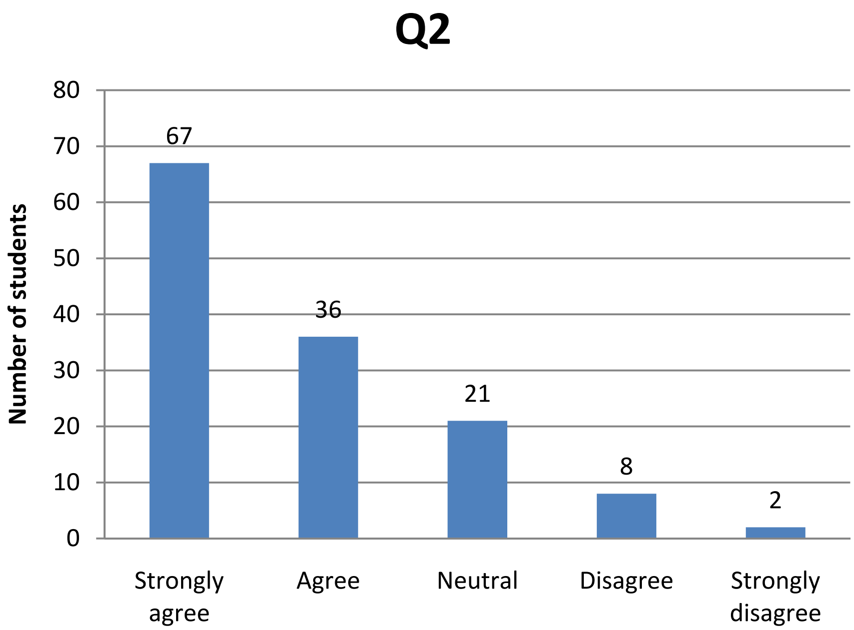
The engagement measurement is as follows. Sitting in pairs in the front and back sections of the lecture theatre, the trained observers would randomly select groups of 10-15 students that could be suitably observed. At five minute intervals, the observers would classify each student's behavior according to a list of engaged or disengaged behaviors (e.g. gesturing related to material, nodding in response to comment by instructor, text messaging, surfing web, reading unrelated book). If a student's behavior did not match one of the criteria, they were not counted, but this was a small fraction of the time. Measurements were not taken when students were voting on clicker questions because for some students this engagement could be too superficial to be meaningful as they were simply voting to get credit for responding to the question. Measurements were taken while students worked on the clicker questions when voting wasn't underway. This protocol has been shown by E. Lane and coworkers to have a high degree of inter-rater reliability after the brief training session of the observers.

2. Opinion survey and responses given in the experimental section

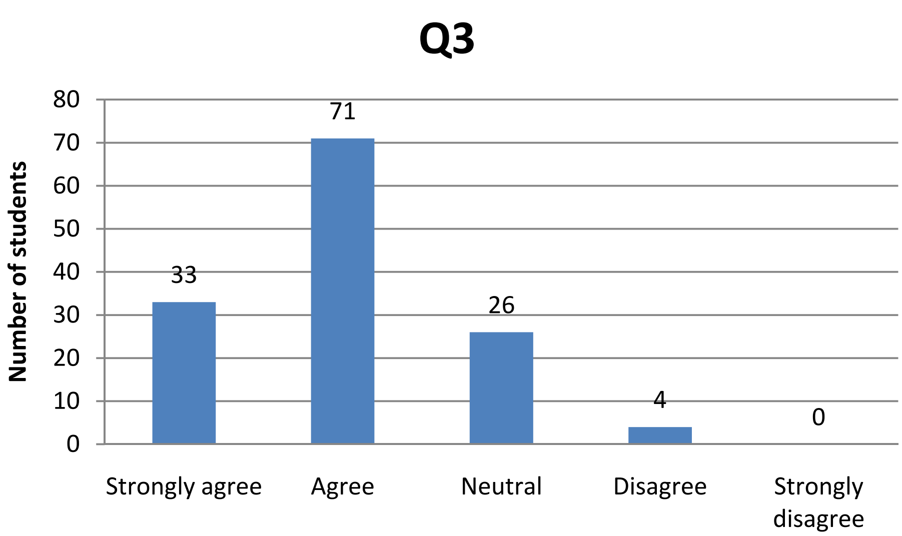
Q1 I really enjoyed the interactive teaching technique during the three lectures on E&M waves (Ch32):



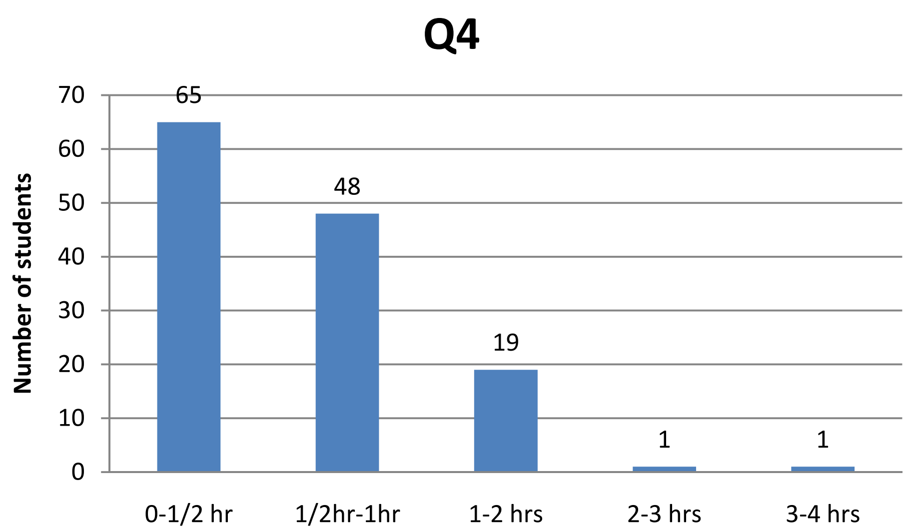
Q2 I feel I would have learned more if the whole course (Phys153) would have been taught in this highly interactive style:



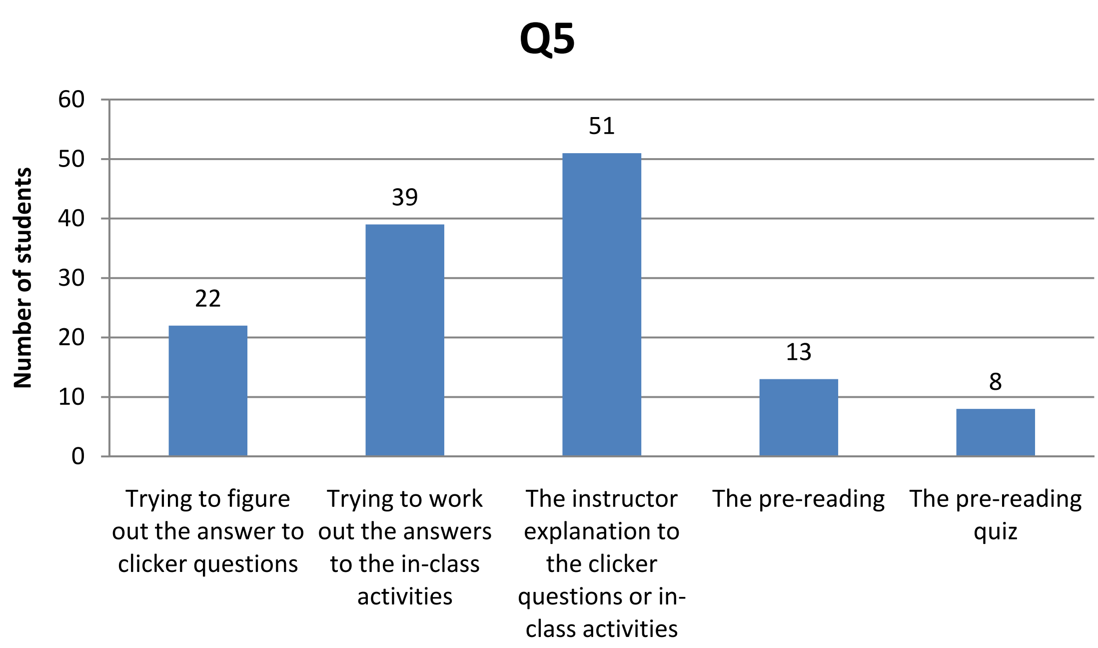
Q3 I thought the 30 min exam on E&M waves did a very good job at measuring how much I know about E&M waves and photons:



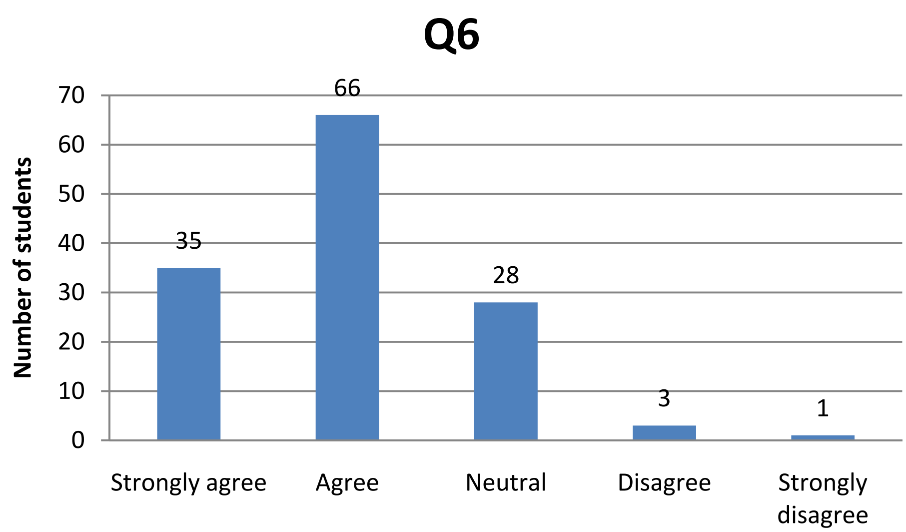
Q4 I studied for the E&M test/quiz for:



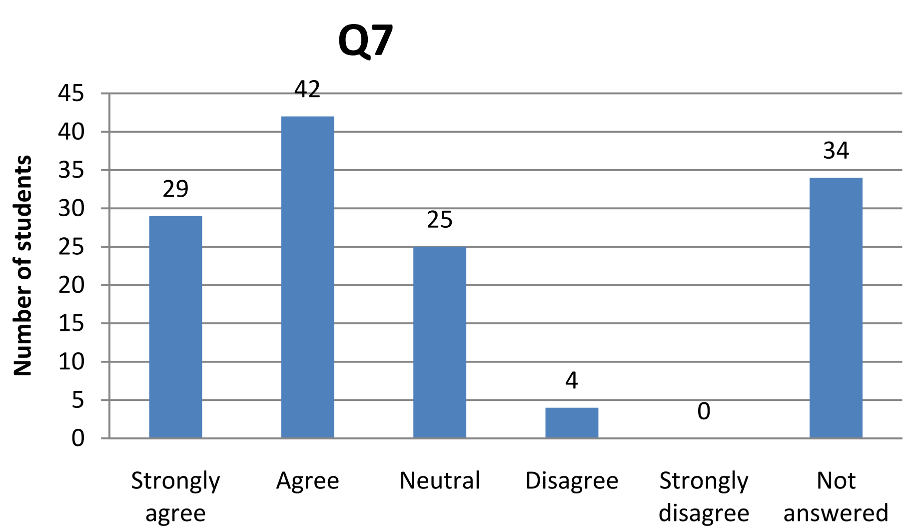
Q5 What contributed most to my learning during these three lecture on E&M waves:



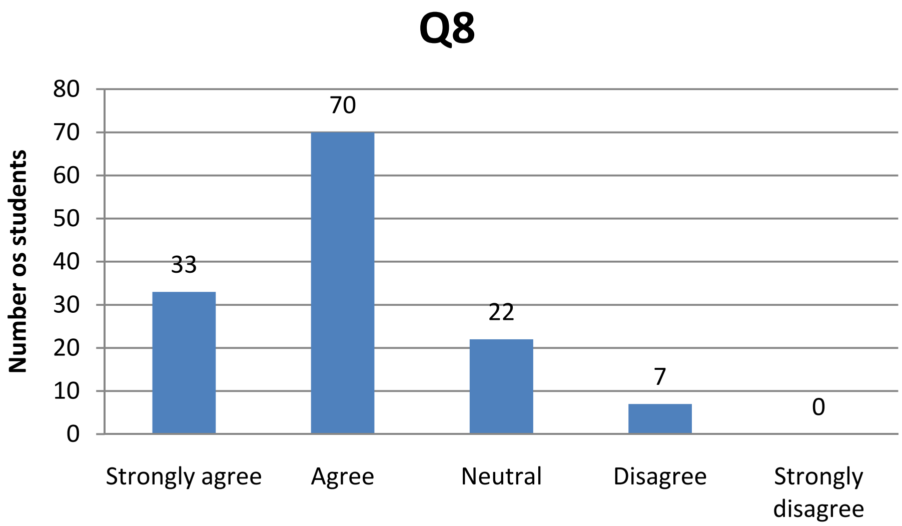
Q6 I found the pre-reading to be very helpful to my learning:



Q7 I found the pre-reading quiz to be very helpful to my learning:



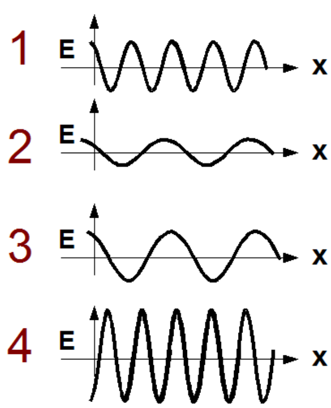
Q8 In class, the group discussions with my neighbors were very helpful to my learning:



3. <u>Test given to both sections on the material taught</u>

Question 1

The amplitude and frequency of 4 E&M waves are shown below. The waves are representative of one instant in time and are all travelling in vacuum. Which wave travels the fastest?



a) 1 c) 3
b) 2 d) 4 e) All 4 waves travel at same speed

Question 2

An Electromagnetic wave is traveling along the negative x-direction.
What is the direction of the Electric field vector E at a point where the Magnetic field vector B is in the positive y-direction?

(a) The E field points along the positive x-direction
(b) The E field points along the negative x-direction
(c) The E field points along the positive z-direction
(d) The E field points along the negative z-direction
(e) The E field points along the negative y-direction

Question 3

An electromagnetic wave is propagating along the positive x-direction with a magnetic field pointing along the z-direction:

$$B_z(x,t) = 3 \cdot 10^{-4} \sin(2\pi \cdot 10^6 x - \omega t)\ Tesla$$

What is the wavelength of this EM wave?
(*Note: 1 nanometer= 10^{-9} meter*)?

a) 10^4 nanometers
b) 10^3 nanometers
c) 100 nanometers
d) 10 nanometers
e) 1 nanometers

Question 4

An electromagnetic wave is propagating along the positive x-direction with a magnetic field pointing along the z-direction:

$$B_z(x,t) = 3 \cdot 10^{-4} \sin(2\pi \cdot 10^6 x - \omega t)\ Tesla$$

What is the strength of the Electric field ***E***?

a) 3×10^{-4} V/m
b) 9×10^{-8} V/m
c) 3 V/m
d) 9×10^{4} V/m
e) Not enough information is given

Question 5

An electromagnetic wave is propagating along the positive
x-direction with a magnetic field pointing along the z-direction:

$$B_z(x,t) = 3 \cdot 10^{-4} \sin(2\pi \cdot 10^6 x - \omega t)\ Tesla$$

How will the intensity of the EM wave change if you increase the strength of the Magnetic field B_z by a factor of 4?

a) The intensity will increase by a factor of 16
b) The intensity will increase by a factor of 8
c) The intensity will increase by a factor of 4
d) The intensity will remain the same
e) Not enough information is given

Question 6

An electromagnetic wave is propagating along the positive x-direction with a magnetic field pointing along the z-direction:

$$B_z(x,t) = 3 \cdot 10^{-4} \sin(2\pi \cdot 10^6 x - \omega t)\ Tesla$$

How will the intensity of the EM wave change if you decrease the *wavelength of the EM wave by a factor of 4*?

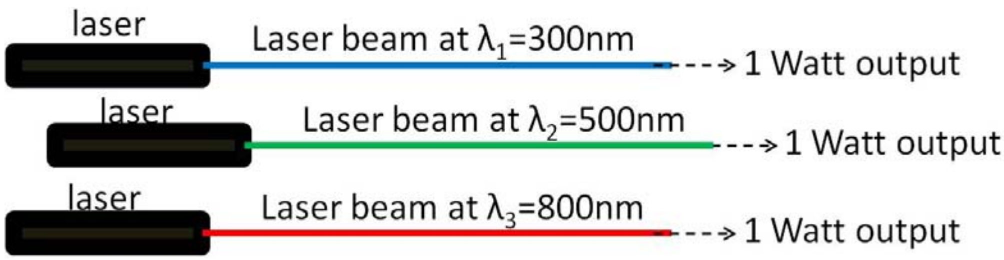
a) The intensity will decrease by a factor of 16
b) The intensity will increase by a factor of 16

c) The intensity will decrease by a factor of 4

d) The intensity will increase by a factor of 4

e) The intensity will remain the same

Question 7



Three laser beams have wavelengths λ_1=300nm, λ_2=500nm, and λ_3=800nm. The output power of all three lasers is **precisely 1Watt**.
Which laser emits the most energetic photons?

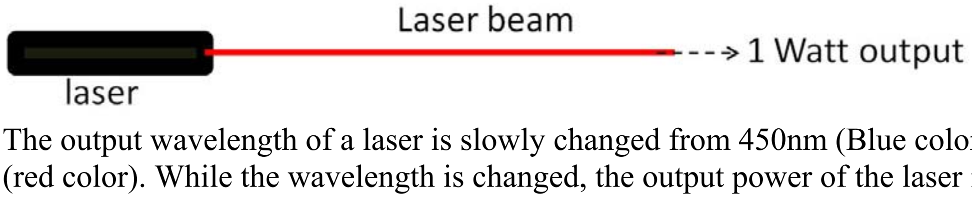
a) The Laser at λ_3=800nm

b) The Laser at λ_2=500nm

c) The Laser at λ_1=300nm

d) All three lasers emit photons with the same energy

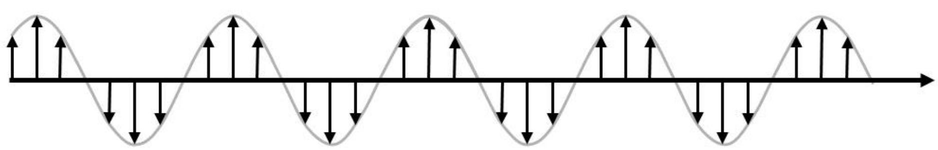
Question 8



The output wavelength of a laser is slowly changed from 450nm (Blue color) to 750nm (red color). While the wavelength is changed, the output power of the laser is kept precisely to 1Watt.
What can we say about the number of photons that are emitted by the laser every second?

a) Number of photons leaving the laser each second *decreases* as we increase λ
b) Number of photons leaving the laser each second *stays the same* as we increase λ
c) Number of photons leaving the laser each second *increases* as we increase λ
d) Not enough information is given

Question 9



$E(x,t) = E_{max}\sin(kx-wt)$ E_{max}=peak amplitude

What quantity best characterizes the energy/sec carried by the Electromagnetic wave?

a) frequency
b) wavelength (color)
c) E_{max}
d) $(E_{max})^2$
e) frequency^2

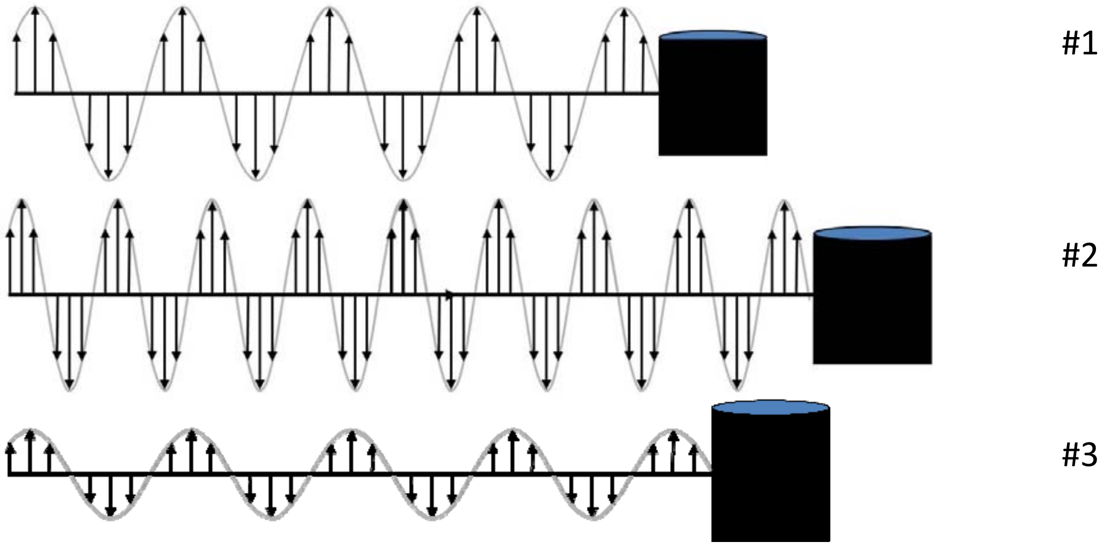
Question 10

True or False: In the absence of external forces, photons move along sinusoidal paths.

1) True
2) False

Question 11

3 Electromagnetic waves are absorbed by a dark object:



Which barrel will heat up the fastest?

a. 2>1>3 b. 1>2>3 c. 1=2>3

d. 1=3>2 e. 2>1=3

Where, E_{max}=peak

$E_{1max}=E_{2max}>E_{3max}$

Question 12

Light from the sun or from a light bulb appears to be constant (i.e. the rate at which the energy reaches your eyes doesn't appear to change in time). But we know that the strength of electromagnetic waves oscillates in time. So why do we see "steady" light? Pick the best answer.

a) The oscillations of the E and B fields cancel out so it looks like the rate of energy is constant
b) The oscillations in the rate of energy flow happen so quickly that we see an average energy which is steady
c) The maximum E and B fields are <u>constant</u>
d) You are looking over a large area so all the light combined will be constant

4. <u>In-class activities used in the experimental section for the three days</u>

The preparation of the in-class activities was based upon a "cognitive task analysis" of how physicists think about this material in terms of the mental models, multiple representations, related associations, and specific metacognitive processes they use with the different particular aspects of the material. The design of the activities also take into account known "naïve" student understandings or interpretations of particular aspects of this material that we were aware of from published literature or that LD and ES have observed in physics students. A full discussion of both these aspects is beyond the scope of this paper, but we have provided a brief annotation after each activity in italics to provide some guidance as to what expert-like thinking the activity is intended to stimulate the students to practice. This practice is primarily happening as the students formulate their answers and discuss the questions and answers with their fellow students and the instructor. As noted in the main text, the student questions and discussion often resulted in the coverage of material beyond what is shown in the activities presented here. There was also a few minute introduction to each class which is not reflected in the class notes shown here. We do not intend to imply that these activities are optimum. They were created by relatively inexperienced teachers as described in the main text, and with more experience with the course and the students these instructors could improve these activities.

The preparation of the experimental classes, which include class activities and reading quizzes, took roughly 20 person hours for the first class, dropping to 10 hours by the third class. Much of this preparation time was spent becoming familiar with the course material and, due to inexperience, designing activities for which there was not sufficient class time to utilize. The decrease in time required from the first to the third class is a reflection of increasing familiarity with the material and more experience with what these students could accomplish in a one hour class.

We estimate that under normal circumstances a moderately experienced instructor would require about 5hrs of preparation time per one hour class in this format. This includes: 3hrs to come up with clicker questions, activities, and reading quiz, 1hr of interview testing with one or two students, and 1hr to implement changes based on the student interview(s). Of course such material can be readily reused, in which case the preparation time would be far less.

Physics 153 Class Activities

CQ = Clicker Question
GT = Group Task

Day 1

CQ1

Which of the following is NOT one of Maxwell's Equations?

a) Gauss's Law for magnetism

b) $\frac{d^2E_y(x,t)}{dx^2} = \frac{1}{c^2}\frac{d^2E_y(x,t)}{dt^2}$

c) $\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$

d) Ampere's Law

Commentary: Largely factual review, but does practice expert distinction and relationship between Maxwell's equations and combination of Maxwell's equations that is the wave equation.

CQ2

Labelled 1-4 are Maxwell's equations in integral form. Labelled i-iv are the names of Maxwell's equations. Which of the following is the correct match?

1 $\oint \vec{E} \cdot d\vec{l} = -\frac{d\Phi_B}{dt}$

2 $\oiint \vec{E} \cdot d\vec{A} = \frac{Q_{enc}}{\epsilon_0}$

3 $\oint \vec{B} \cdot d\vec{l} = \mu_0 i_{enc} - \frac{1}{c^2}\frac{d\Phi_E}{dt}$

4 $\oiint \vec{B} \cdot d\vec{A} = 0$

i) Ampere's Law

ii) Gauss's Law

iii) Gauss's Law for magnetism

iv) Faraday's Law

a) 1i, 2ii, 3iv, 4iii
b) 1iv, 2ii, 3i, 4iii
c) 1ii, 2i, 3iii, 4iv
c) 1i, 2ii, 3iii, 4iv

Commentary: Factual memorization/review, not practicing expert thinking except small amount involved in translating between different mathematical representations.

CQ3

Which of the following best expresses what Gauss's Law describes?

a) The net electric flux through an enclosed surface is proportional to the net amount of charge inside the enclosed surface.
b) If you integrate over the electric field inside a box you get charge.
c) The net magnetic field along a closed path is proportional to the current flowing through the closed loop.
d) If you integrate the electric field over two parallel planar surfaces you get the charge enclosed between the two planar surfaces.

Commentary: Development of mental models of static electric and magnetic fields. Translation between representations, particularly between mathematical representation and physical models of electric and magnetic fields.

CQ4

Which of the following is true?

a) For EM waves to exist, they must propagate in a medium with atoms. With no atoms present, the field cannot have any effect on the system and therefore can't exist.
b) An EM wave can propagate through a vacuum.
c) An EM wave is like a wave travelling along a rope in that it needs atoms to move up and down.
d) An EM wave can *only* propagate in a vacuum since any medium would get in the way of its propagation.
e) More than one of the above is true.

Commentary: Develop and test mental model of EM wave. Practice metacognitive thinking in this context.

CQ5

Which of the following are forms of the wave equation for an EM wave propagating in vacuum along the x direction?

i) $$\frac{d^2 E_y(x,t)}{dx^2} = \epsilon_0 \mu_0 \frac{d^2 E_y(x,t)}{dt^2}$$

ii) $$\frac{dE_y(x,t)}{dx} = \epsilon_0 \mu_0 \frac{dE_y(x,t)}{dt}$$

iii) $$\frac{dB_z(x,t)}{dx} = \epsilon_0 \mu_0 \frac{dB_z(x,t)}{dt}$$

iv) $$\frac{d^2 B_z(x,t)}{dx^2} = \epsilon_0 \mu_0 \frac{d^2 B_z(x,t)}{dt^2}$$

a) i and iv
b) ii and iii
c) ii
d) i
e) None of the above

Commentary: Practicing translation between mathematical representations and physical phenomena.

GT

A friend of yours reminds you that en EM wave consists of both an E and B field.

She asks you if the following electric field
$E(x,t)=100x^2t$ Volts/m could be that of an EM wave.
Can you help? Be quantitative in your answer.

[*Hint*: Is there an equation that the electric field portion of an electromagnetic wave, E(x,t), must satisfy?]

Commentary: Recognize relationship between form of solution and its origin.

<u>Day 2</u>

CQ1

Which of the following are types of electromagnetic waves, just like the light coming from our sun?

a) FM radio (i.e. Signal picked up by your car)
b) Microwave (i.e. Popcorn)
c) Infrared (i.e. Night vision goggles)
d) X-rays (i.e. I just broke my leg)
e) all of the above

BONUS: 🟢 Can you see with your eyes all EM radiation?

Commentary: Links to prior knowledge and building expert associations among previously encountered phenomena. Connect class material to real world phenomena.

CQ2

Could the following E wave function describe the electric field portion of a propagating EM wave?

$$E_y = E_{max}\cos(kx)$$

a) Yes
b) No
c) Not enough information to determine this

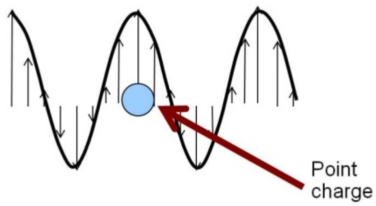
BONUS: 🟢 What about cos(kxt)?
🔵 What about cos[k(x-vt)]?

Commentary: Translating between representations. Explicitly testing mathematical representations of physical phenomena.

GT

PhET Simulation: Radio Waves and Electromagnetic Fields
http://phet.colorado.edu/en/simulation/radio-waves
Observe the simulation of an EM wave being generated.

1. What do the arrows show?
2. A classmate tells you, "If I place a charge right there (see picture), the wave will pass over it and it won't affect it or apply a force on it". Do you agree with your classmate? Explain.



Commentary: Developing mental model, understand and apply expert representations and models to make predictions. Develop metacognitive capabilities.

CQ3

What is a source of EM waves?

a) A static charge distribution
b) A static current distribution
c) Charges moving at a constant speed
d) Accelerating charges
e) none of the above

Commentary: Developing and testing mental model, make explicit and provide feedback on known naïve interpretation.

CQ4

Someone has told you the maximum electric field strength and the electric field polarization of an electromagnetic wave. What do you know about the magnetic field?

i. Its maximum strength
ii. Its polarization
iii. Its propagation direction

a) i
b) i and ii
c) i and iii
d) ii and iii
e) all of the above
f) none of the above

Commentary: Sophisticated development and refinement of mental model, likely calling on multiple representations and self-checking in the process.

CQ5
Which of the following electromagnetic wave functions can describe a wave travelling in the negative y *direction*?

i) $\vec{E} = \hat{\imath}E_{max}\sin(ky + \omega t)$
$\vec{B} = \hat{k}B_{max}\sin(ky + \omega t)$

ii) $\vec{E} = \hat{\imath}E_{max}\sin(ky + \omega t)$
$\vec{B} = -\hat{k}B_{max}\sin(ky + \omega t)$

iii) $\vec{E} = \hat{\jmath}E_{max}\sin(kx + \omega t)$
$\vec{B} = \hat{\jmath}B_{max}\sin(kx + \omega t)$

iv) $\vec{E} = \hat{\imath}E_{max}\sin(ky - \omega t)$
$\vec{B} = \hat{k}B_{max}\sin(ky - \omega t)$

a) i b) iii c) iv d) i,ii and iv e) i and iv

Commentary: Translating between representations, relating mathematical representation to physical phenomena.

Day 3
CQ1
The frequency *f* of a laser pointer is increased but the light's *intensity* is unchanged. As a result, which of the following (perhaps more than one) are true? Explain.

i) The output power is increased
ii) Each photon has more energy
iii) There are fewer photons per second
iv) There are more photons per second

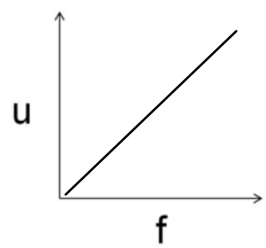
a) i
b) i and ii
c) ii and iii
d) ii and iv
e) iv

Commentary: Developing and testing mental models, building associations, confronting and providing targeted feedback on naïve understanding.

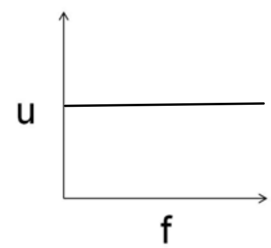
CQ2

Shown below are plots for the *energy density of an EM wave* vs. *frequency*. Think about how the energy density depends on the frequency of the wave. Which graph properly shows this relationship?

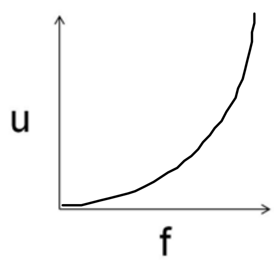
a)



b)



c)



d) Not enough information to tell

e) None of the above

Commentary: Translating between representations, and in the process developing associations and refining mental model. Practicing metacognitive skill utilizing multiple representations.

CQ3

Many of you have learned in chemistry that photons are *quanta* of light. Which of the following best describes how photons and EM waves are related.

a) An EM wave is essentially made up of a single photon with frequency f; the size of which depends on the energy of the EM wave.
b) An EM wave is the sum of many photons that are all in phase.
c) An EM wave is composed of many photons where the strength of the wave depends on the energy of each photon and how many it is composed of.
d) The photons are what is moving up and down in an EM wave.
e) More than one statement is true

Commentary: Developing mental model by addressing prior knowledge and known naïve models.

GT

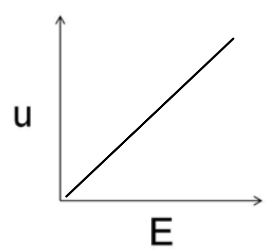
Three laser beams have wavelengths λ_1=400nm, λ_2=600nm and λ_3=800nm. The power (energy/sec) of each laser beam is the SAME at 1Watt. Rank in order, from largest to smallest:

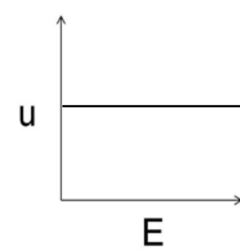
a) The photon energies $\mathbf{E}_1$, $\mathbf{E}_2$, $\mathbf{E}_3$ in these three laser beams. Explain your answer.
b) The maximum strength of the E fields, E_{max1}, E_{max2}, E_{max3}, in these three laser beams. Explain your answer.
c) The number of photons per second N_1,N_2,N_3 delivered by the three laser beams.

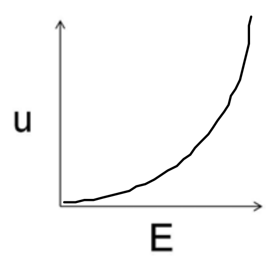
Commentary: A transfer task requiring recognition of relevant variables and use of mental model.

CQ4

Shown below are plots of energy density vs. electric field strength for an EM wave. Think about how the energy density depends on the electric field strength. Which graph properly shows this relationship?

a)


b)


c)


d) Not enough information to tell

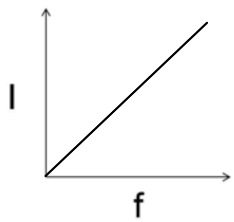
e) None of the above

Commentary: Similar to CQ2

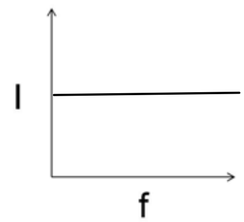
CQ5

Shown below are plots of intensity vs. frequency for a classical EM wave. Think about how the intensity depends on the frequency of the wave. Which graph properly shows this relationship?

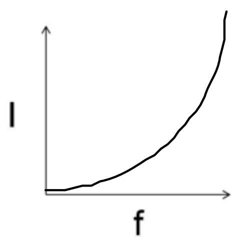
a)



b)



c)



d) Not enough information to tell

e) None of the above

Commentary: Similar to CQ2, and addressing and providing feedback to correct known naïve thinking.

5. <u>Learning objectives agreed upon by the two instructors</u>

The learning objectives were categorized into levels of importance with A being the most important to C being less important. The test primarily covered the category A objectives. Although we believe it would be educationally beneficial to provide the students with such objectives in class before the unit, in deference to the wishes of the instructor of the control section, the students were not given the learning objectives.

After completing this module on EM waves the students should:

A

1) Be able to write down the wave equation for electric and magnetic fields.
2) Be able to describe the characteristics of a plane wave.
    a) Direction of propagation
    b) Polarization
    c) Planes of constant phase (C)
3) Be able to write the relationships between wavespeed, wavelength, frequency,

angular frequency and wave vector.

4)
    a) Given an analytical expression for an EM wavefunction (E or B), be able to represent it graphically
    b) Be able to correctly interpret all of the features of the representation when plotted as a function of time or space, *i.e*. Amplitude corresponds to field strength, being able to identify wavelength, frequency etc (see 3)
5) Be able to write down the relationship between polarizations of the E and B fields of an EM wave and its direction of propagation.
6) Be able to identify the equation of energy density of an EM waves in terms of E and B and in terms of just E, *i.e*. know that it goes at E^2 and doesn't depend on frequency
7) Be able to contrast EM waves with mechanical waves
    a) Compare how energy depends on critical parameters such as amplitude and frequency
    b) Compare physical interpretation of their oscillating amplitude
    c) Appreciate the fact that EM waves propagate in a vacuum.
8) Be able to give a basic description of how EM waves are related to photons.
    a) Be able to contrast the energy dependence on critical parameters for EM waves and photons.
    b) For an EM wave with a given intensity, be able to identify how many photons of a given frequency it is composed of.
9)
    a) Be able to write the Poynting vector in terms of E and B.
    b) Be able to describe how the intensity is related to the Poynting vector
    c) Be able to give a basic description of what the Poynting vector represents.

B

1) Be able to identify Maxwell's Equations by name.
2) Be able to test whether **scalar** E and B wavefunctions for an electromagnetic wave satisfy the wave equation.
    a) Given an E and B equation plug it into the wave equation and check that the sides of the equation equate.
3) Be able to identify a set of **vector** E and B wave functions that properly describe an EM wave propagating in a given direction.
    a) Use right hand rule

C

1) Qualitatively be able to explain the meaning of Gauss' Laws, Faradays Law and Ampere's Law
2) Be able to identify the terms in Maxwell's Equations that lead to the wave equation (*i.e*. Plane wave light propagation)

3) Be able to give examples of transverse waves. Contrast transverse waves with longitudinal waves.
4) Give examples of how we experience the energy of EM waves in everyday life.
   a) Ex. From the sun get: heat, can power solar cells etc
   b) Ex. Need batteries to power flashlight
   c) Etc.
5) Be able to identify points of equal phase along on a wave.

6. Hawthorne effect discussion

It is not the intention of this paper to review the Hawthorne effect and its history, but we comment on it only because this is such a frequent question raised about this work. It is not plausible that it resulted in a significant impact on the results reported here. As discussed extensively in (*S1*-*S3*), analyses of the methodology and data used in the original Hawthorne plant studies reveal both serious flaws in the methodology, and an absence of statistically significant data supporting the existence of the claimed effect. Thus, the failure to replicate such an effect in an educational setting, as reported in (*S4*), is not surprising.

Even if the Hawthorne effect were true, namely that people engaged in routine tasks will improve performance when conditions are changed in any manner, it would not be very relevant to this experiment. If one examines the typical daily activities of these students, the differences introduced by this experiment are not a significant increase in the variety of their educational experiences. These students are going to a variety of classes every day. These classes incorporate both a wide variety of subjects and instructional styles. They have large and small lecture courses, seminar courses, instructional labs, recitation sections, and project lab courses, all with various types of individual and group assignments. So while this experiment is introducing change in the student experience in one particular course (3 total hours per week) it provides little incremental novelty to their overall daily educational experience.

Finally, there have been several other full length physics courses at UBC transformed following the same design as discussed here. Those courses had much higher attendance and engagement for the entire term than is typical for other UBC physics courses including previous offerings of those courses. The attendance was similar or higher than what was observed in the experimental section in this work, and the engagement appeared to be similar. There were no control groups for those courses that can be used for learning comparisons however. This indicates that the level of attendance and engagement reported here were due to the instructional design and not merely due to the one week novelty.

7. List of proven teaching practices used

The instruction in this experiment incorporates variants on many established active learning instructional techniques. These include Just In Time Teaching (*S5*), Peer Instruction (*S6)*, some elements of Scale Up (*S7*), use of clicker question practices to facilitate student thinking and effective feedback as discussed in (*S8*) and (*S9*), some elements of Interactive Lecture Demonstrations (*S10*), group work (*S11*) and numerous other references), and the use of interactive simulations (*S12*). See also (*S13*) for a more extensive set of references on these teaching practices.

Supplemental references

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