The Role of Research in Improving Science Education

David E. Meltzer

Department of Physics
University of Washington

Collaborators

- Mani Manivannan (Missouri State)
- Tom Greenbowe (Iowa State University, Chemistry)
- John Thompson (U. Maine Physics)

Students

- Tina Fanetti (ISU, M.S. 2001)
- Jack Dostal (ISU, M.S. 2005)
- Ngoc-Loan Nguyen (ISU, M.S. 2003)
- Warren Christensen (ISU Ph.D. student)

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- NSF Division of Undergraduate Education
- NSF Division of Research, Evaluation, and Communication
- NSF Division of Physics

Outline

1. Science Education as a Research Problem

    Example: Methods of physics education research

2. Research-Based Instructional Methods

    Principles and practices

3. Research-Based Curriculum Development

    A “model” problem: law of gravitation

4. Physics Course for Pre-Service Elementary Teachers

    Assessment and evaluation

5. Recent Work: Student Learning of Thermal Physics

    Research and curriculum development

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Science Education:
Crucial to Modern Society

- **National Research Council (2005):** top U.S. priority is to *“increase America’s talent pool by vastly improving K-12 science and mathematics education”*

- **National Science Board (2004):** quality education in math and science is a critical responsibility: *“The nation’s economic welfare and security are at stake”*

- **President Bush:** proposed large increase in numbers of high-school science and math teachers

Science and Technology *vs.* Science Education

- Vast improvements in science research and technology have occurred during the past century;

but:

- Science education in colleges and universities still bears strong resemblance to methods and practices of previous era.

➡ *Future K-12 science teachers learn science in colleges and universities!*

How has Science and Technology Progressed?

- Carefully designed and controlled studies with detailed documentation
- Peer review and archival publication, leading to broad dissemination
- Cumulative progress that builds on previous results

A Model for Improving Science Education?

Research in Science Education

- In recent decades, most science education research has focused on the K-12 level.
- Research on science education at the *undergraduate* level is a relatively new phenomenon.
- During the past 10 years, an increasing number of *university* science departments have initiated science education research.

Progress in Teacher Preparation

"Teachers teach as they have been taught"

- Advances in research-based science education have motivated changes in teacher preparation (and development) programs.
- There is an increasing focus on research-based instructional methods and curricula, emphasizing "active-engagement" learning.
- **Examples:** *Physics by Inquiry* curriculum (Univ. Washington); Modeling Workshops (Arizona State U.)

Research on Student Learning: Some Key Results

- Students' conceptual difficulties ("sticking points") and alternative conceptions play a significant role in impeding learning;
- Inadequate *organization* of students' knowledge is a key obstacle: need to improve linking and accessibility of ideas;
- Students' *beliefs and practices* regarding learning of science should be addressed.

Research-Based Instruction

- Recognize and address students' pre-instruction "knowledge state" and learning tendencies, including:
  - subject-specific learning difficulties
  - potentially productive ideas and intuitions
  - student learning behaviors
- Guide students to address learning difficulties through structured problem solving, discussion, and Socratic dialogue

Science Education Research Targeted at Undergraduate Students

In colleges and universities:

- **Physics Education Research (PER):**
  ≈ 80 departments, 15 Ph.D. programs
- **Chemical Education Research:**
  ≈ 50 departments, 25 graduate programs
- **Mathematics, Geosciences, Biological Sciences:** small but increasing number.

See: P. Heron and D. Meltzer, *CHED Newsletter*, Fall 2005, 35-37

Physics Education As a Research Problem

Within the past 25 years, physicists have begun to treat the teaching and learning of physics as a research problem

- Systematic observation and data collection; reproducible experiments
- Identification and control of variables
- In-depth probing and analysis of students' thinking

Physics Education Research ("PER")

Goals of PER

- Improve effectiveness and efficiency of physics instruction
  - guide students to learn concepts in greater depth
- Develop instructional methods and materials that address obstacles which impede learning
- Critically assess and refine instructional innovations

Methods of PER

- Develop and test diagnostic instruments that assess student understanding
- Probe students' thinking through analysis of written and verbal explanations of their reasoning, supplemented by multiple-choice diagnostics
- Assess learning through measures derived from pre- and post-instruction testing

What PER Can NOT Do

- Determine "philosophical" approach toward undergraduate education
  - e.g., focus on majority of students, or on subgroup?
- Specify the goals of instruction in particular learning environments
  - proper balance among "concepts," problem-solving, etc.

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Some Specific Issues

Many (if not most) students:

- develop weak ***qualitative*** understanding of concepts
  - don’t use qualitative analysis in problem solving
  - lacking quantitative problem solution, can’t reason “physically”
- lack a **“*functional*”** understanding of concepts (which would allow problem solving in unfamiliar contexts)

But … *some* students learn efficiently . . .

- Highly successful physics students are ***"active learners."***
  - they continuously probe their own understanding

    [*pose their own questions; scrutinize implicit assumptions; examine varied contexts; etc.]*
  - they are sensitive to areas of confusion, and have the confidence to confront them directly

- Majority of introductory students are unable to do efficient active learning on their own: they don't know "which questions they need to ask"
  - they require considerable assistance from instructors, aided by appropriate curricular materials

Research in physics education suggests that:

- Problem-solving activities with rapid feedback yield improved learning gains
- Eliciting and addressing common conceptual difficulties improves learning and retention

Active-Learning Pedagogy

(“*Interactive Engagement*”)

- problem-solving activities during class time
  - student group work
  - frequent question-and-answer exchanges

- “*guided-inquiry*” methodology: guide students with leading questions, through structured series of research-based problems

Goal: Guide students to “figure things out for themselves” as much as possible

Key Themes of Research-Based Instruction

- Emphasize qualitative, non-numerical questions to reduce unthoughtful “plug and chug.”
- Make extensive use of multiple representations to deepen understanding.

  (Graphs, diagrams, words, simulations, animations, etc.)

- Require students to *explain their reasoning* (verbally or in writing) to more clearly expose their thought processes.

Active Learning in Large Physics Classes

- **De-emphasis of lecturing**; Instead, ask students to respond to questions targeted at known difficulties.
- Use of classroom communication systems to obtain **instantaneous feedback** from entire class.
- Incorporate cooperative **group work** using both multiple-choice and free-response items

Goal: *Transform large-class learning environment into "office" learning environment (i.e., instructor + one or two students)*

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“Fully Interactive” Physics Lecture

DEM and K. Manivannan, Am. J. Phys. ***70,*** *639 (2002)*

- Use structured sequences of multiple-choice questions, focused on specific concept: small conceptual “step size”

- Use student response system to obtain instantaneous responses from all students simultaneously (e.g., “flash cards”)

[a variant of Mazur’s “Peer Instruction”]

Results of Assessment

- Learning gains on qualitative problems are well above national norms for students in traditional courses.
- Performance on quantitative problems is comparable to (or slightly better than) that of students in traditional courses.
- Typical of other research-based instructional methods

Interactive Question Sequence

- Set of closely related questions addressing diverse aspects of single concept
- Progression from easy to hard questions
- Use multiple representations (diagrams, words, equations, graphs, etc.)
- Emphasis on qualitative, not quantitative questions, to reduce “equation-matching” behavior and promote deeper thinking

Chapter 1 Electrical Forces

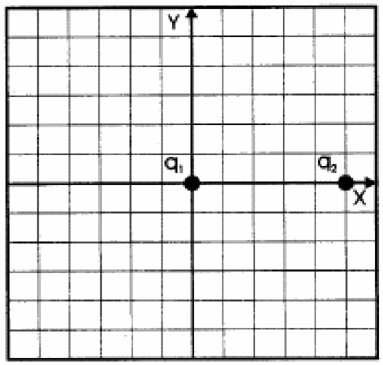
"Flash-Card" Questions

In-Class Questions

Prerequisite Concepts:

- **Positive and negative charges; Coulomb's law: $F = kq_1q_2/r^2$**
- **Protons (+) and electrons (–)**
- **Superposition principle: $F_{net}=F_1+F_2 + . . . + F_n$**
- **Vector addition: $F_{netx}=F_{1x} + F_{2x} + . . . F_{nx}$**
- **Newton's second law, a = F/m**

Questions #1–2 refer to the figure below. Charge q_1 is located at the origin, and charge q_2 is located on the positive x axis, five meters from the origin. There are no other charges anywhere nearby.



1. If q_1 is positive and q_2 is negative, what is the direction of the electrical force on q_1?

   A. in the positive x direction
   B. in the negative x direction
   C. in the positive y direction
   D. in the negative y direction
   E. the force is not directed precisely along any of the coordinate axes, but at some angle
   F. there is no force in this case

2. If q_1 is positive and q_2 is positive, what is the direction of the electrical force on q_1?

   A. in the positive x direction
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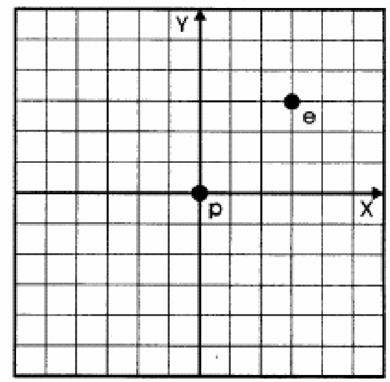
"Flash-Card" Questions

3. In this figure, a proton is located at the origin, and an electron is located at the point (3m, 3m). What is the direction of the electrical force on the proton?



A. 

B. 

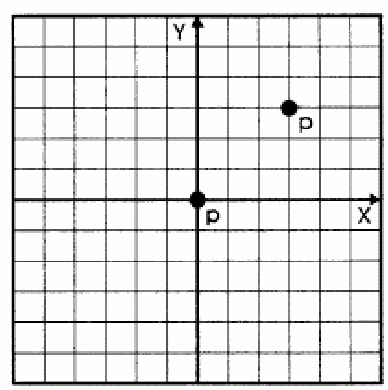
C. 

D. 

E. 

F. 

4. In this figure, a proton is located at the origin, and a proton is located at the point (3m, 3m). The vector representing the electrical force on the proton *at the origin* makes what angle with respect to the positive x axis?



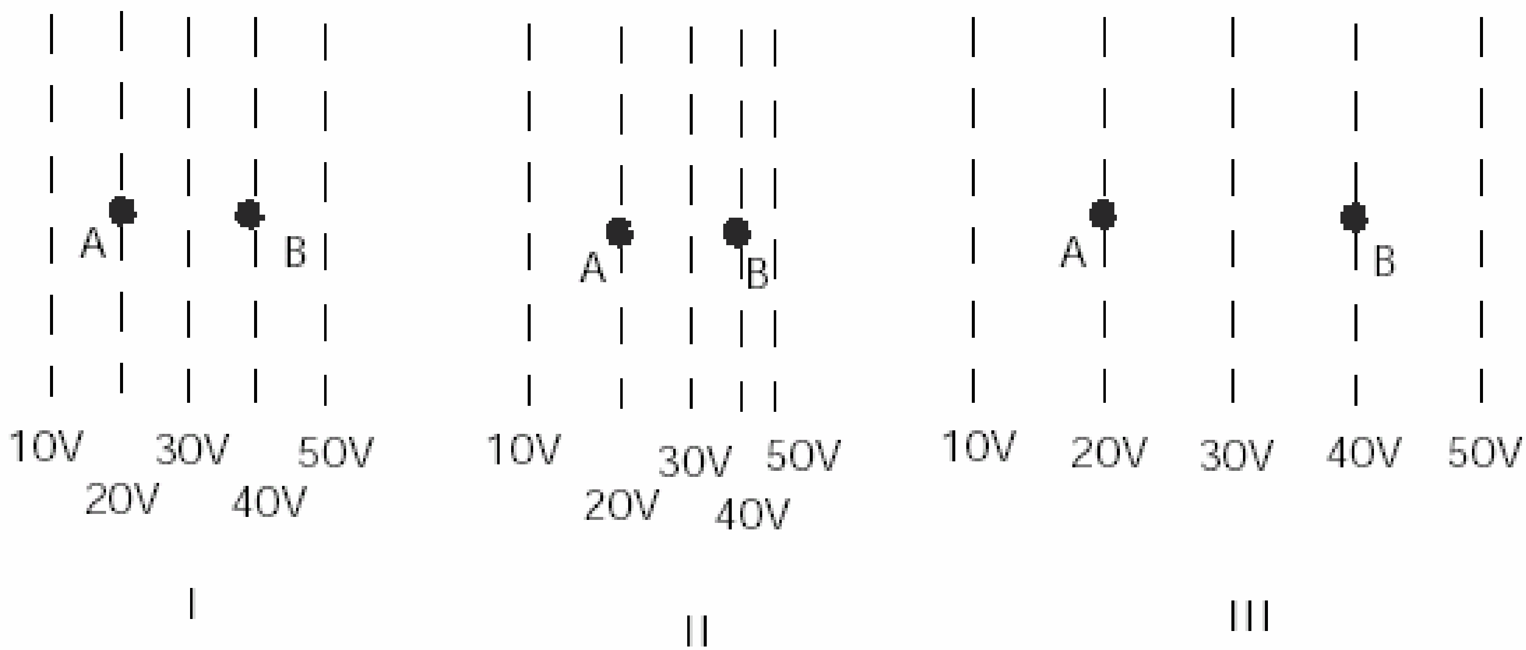
A. 0°
B. 45°
C. 90°
D. 135°
E. 225°
F. 270°

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	***N***
National sample (algebra-based)	402
National sample (calculus-based)	1496

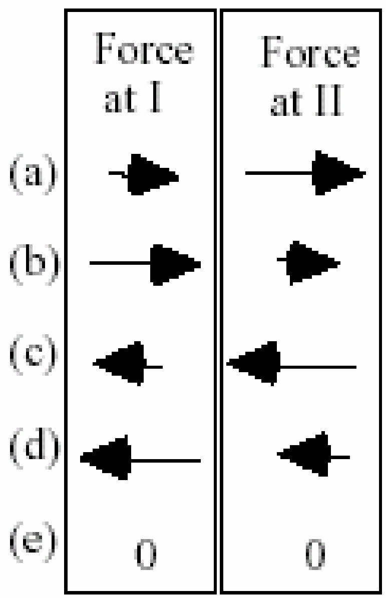
In the figures below, the dotted lines show the equipotential lines of electric fields. (A charge moving along a line of equal potential would have a constant electric potential energy.) A charged object is moved directly from point A to point B. The charge on the object is +1 μC.

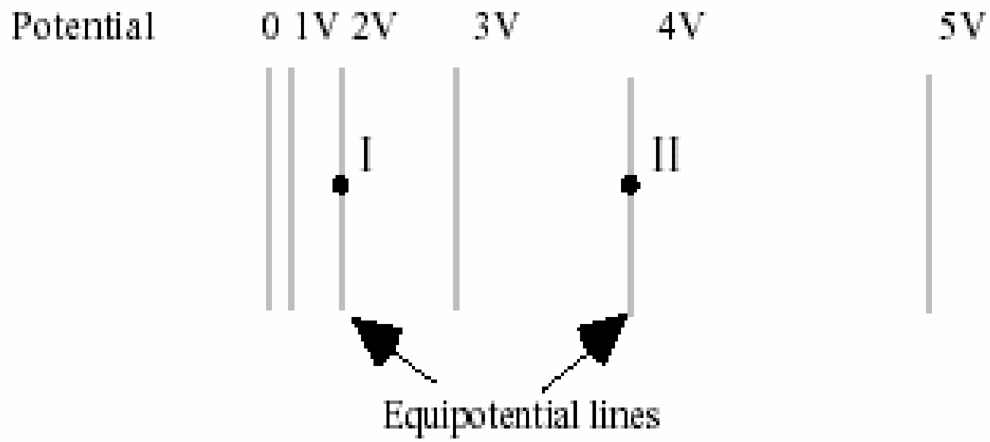


1. How does the magnitude of the electric field at B compare for these three cases?
   (a) I > III > II
   (b) I > II > III
   (c) III > I > II
   (d) II > I > III
   (e) I = II = III

D. Maloney, T. O'Kuma, C. Hieggelke, and A. Van Heuvelen, PERS of Am. J. Phys. ***69****, S12 (2001).*

2. A positively-charged proton is first placed at rest at position I and then later at position II in a region whose electric potential (voltage) is described by the equipotential lines. Which set of arrows on the left below best describes the relative magnitudes and directions of the electric force exerted on the proton when at position I or II?





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Sample	*N*	Mean pre-test score
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National sample (calculus-based)	1496	**37%**

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Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score	Mean post-test score
National sample (algebra-based)	402	**27%**	**43%**
National sample (calculus-based)	1496	**37%**	**51%**

Assessment Data

Scores on Conceptual Survey of Electricity and Magnetism, 14-item electricity subset

Sample	*N*	Mean pre-test score	Mean post-test score	<g>
National sample (algebra-based)	402	**27%**	**43%**	**0.22**
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ISU 1998	70	**30%**		
ISU 1999	87	**26%**		
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ISU 1999	87	**26%**	**79%**	**0.71**
ISU 2000	66	**29%**	**79%**	**0.70**

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	Mean Score
Physics 221: F97 & F98 ***Six final exam questions***	*320*	
Physics 221: F97 & F98 **Subset of three questions**	*372*	

Quantitative Problem Solving: Are skills being sacrificed?

ISU Physics 112 compared to ISU Physics 221 (calculus-based), numerical final exam questions on electricity

	N	**Mean Score**
Physics 221: F97 & F98 ***Six final exam questions***	*320*	56%
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%

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Physics 221: F97 & F98 ***Six final exam questions***	*320*	56%
Physics 112: F98 **Six final exam questions**	*76*	
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%
Physics 112: F98, F99, F00 **Subset of three questions**	*241*	

Quantitative Problem Solving: Are skills being sacrificed?

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Research-Based Curriculum Development

- Investigate student learning with standard instruction; probe learning difficulties
- Develop new materials based on research
- Test and modify materials
- Iterate as needed

Addressing Learning Difficulties: A Model Problem

Student Concepts of Gravitation

[Jack Dostal and DEM]

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- 10-item free-response diagnostic administered to over 2000 ISU students during 1999-2000.
  - *Newton's third law in context of gravity, inverse-square law, etc.*

Addressing Learning Difficulties: A Model Problem

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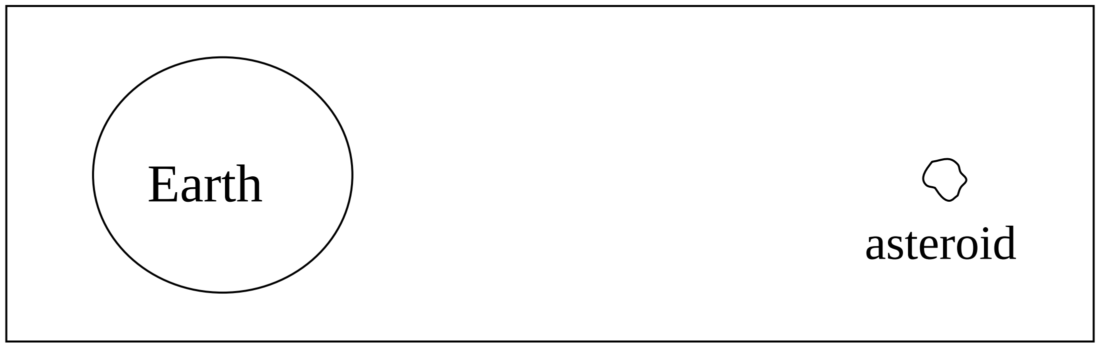
[Jack Dostal and DEM]

- 10-item free-response diagnostic administered to over 2000 ISU students during 1999-2000.
  - *Newton's third law in context of gravity, inverse-square law, etc.*

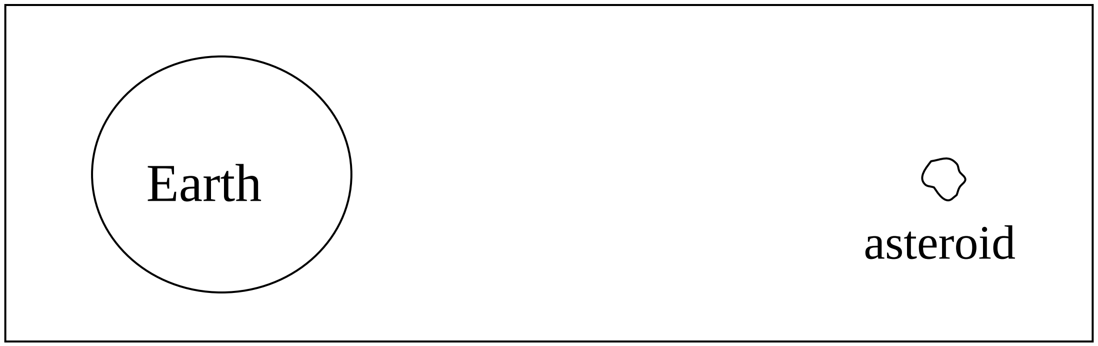
- Worksheets developed to address learning difficulties; tested in calculus-based physics course Fall 1999

Example: Newton's Third Law in the Context of Gravity



Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid?** *Explain the reasoning for your choice.*

Example: Newton's Third Law in the Context of Gravity



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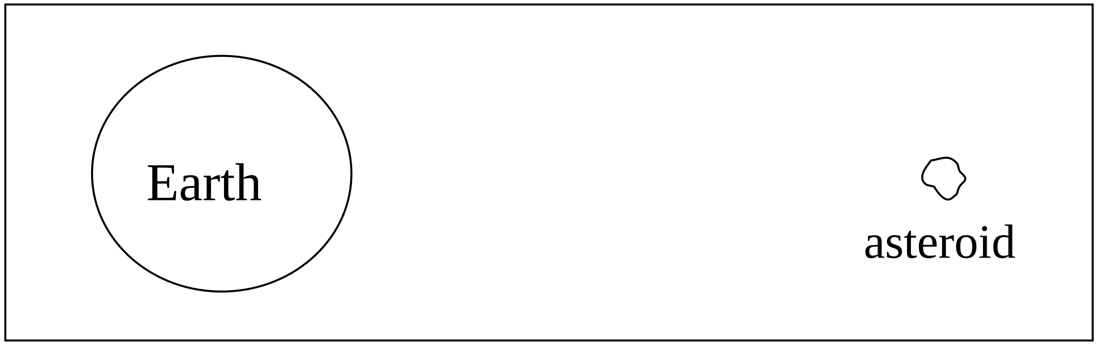

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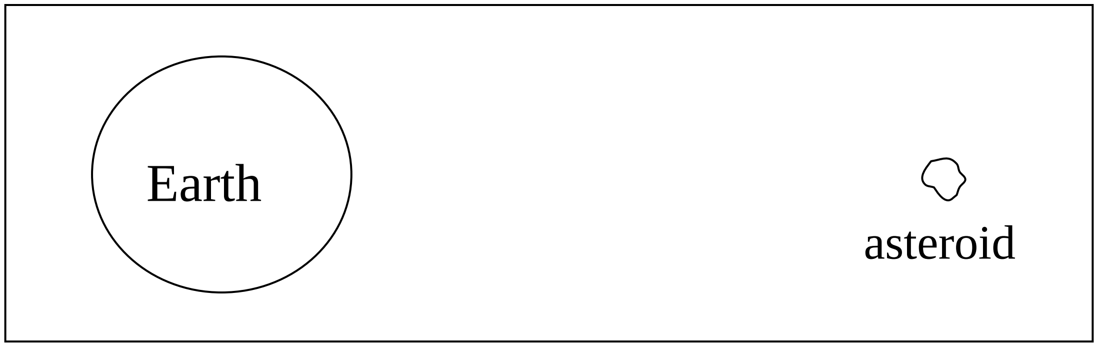

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First-semester Physics *(N = 546)*: ***15% correct responses***

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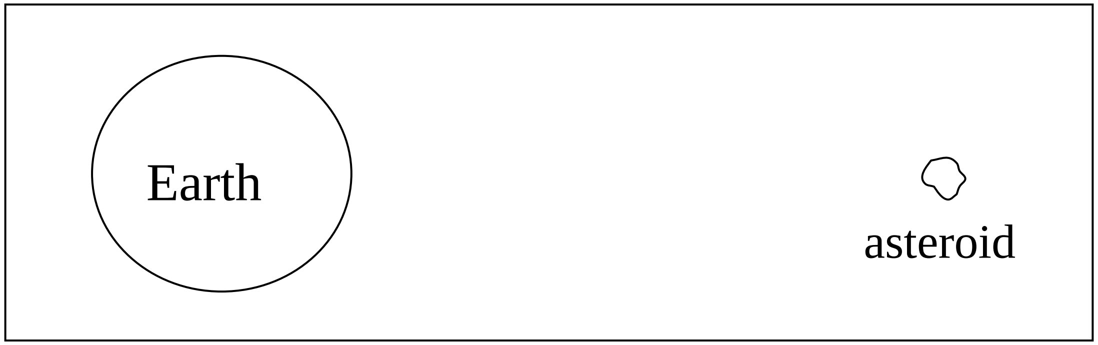

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Second-semester Physics *(N = 414)*: ***38% correct responses***

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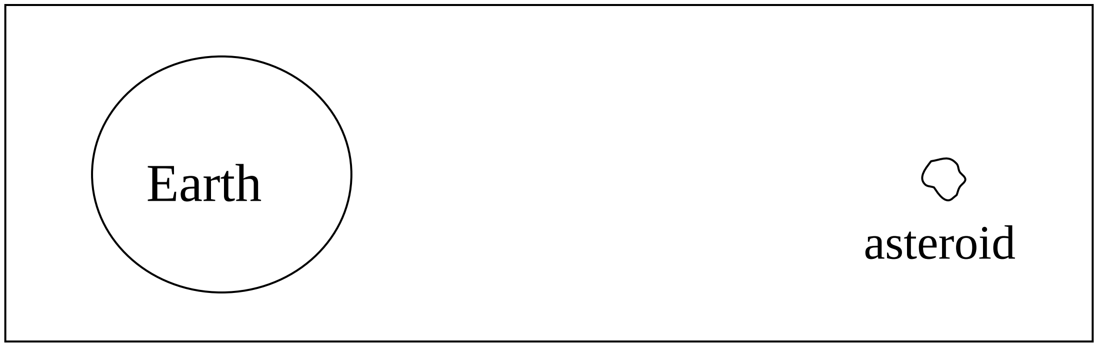

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Most students claim that Earth exerts greater force because it is larger

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

- Pose questions to students in which they tend to encounter common conceptual difficulties
- Allow students to commit themselves to a response that reflects conceptual difficulty
- Guide students along reasoning track that bears on same concept
- Direct students to compare responses and resolve any discrepancies

Implementation of Instructional Model

"Elicit, Confront, Resolve" (U. Washington)

→ *One of the central tasks in curriculum reform is development of "Guided Inquiry" worksheets*

- Worksheets consist of sequences of closely linked problems and questions
  - *focus on conceptual difficulties identified through research*
  - *emphasis on qualitative reasoning*
- Worksheets designed for use by students working together in small groups (3-4 students each)
- Instructors provide guidance through "Socratic" questioning

Example: Gravitation Worksheet

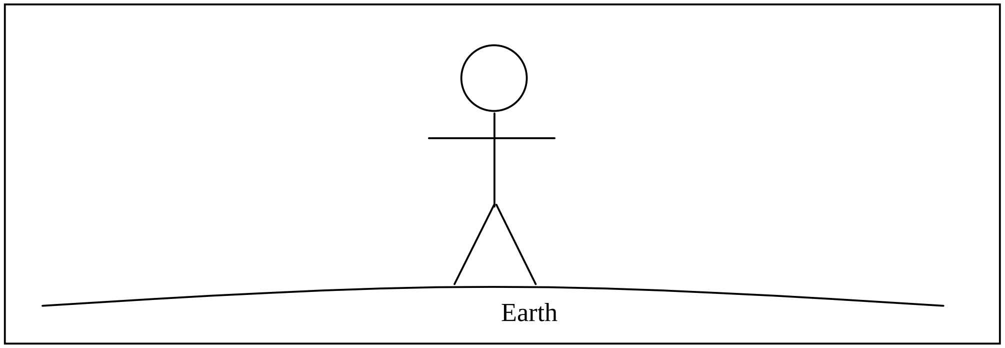
(Jack Dostal and DEM)

- Design based on research, as well as instructional experience
- Targeted at difficulties with Newton's third law, and with use of proportional reasoning in inverse-square force law

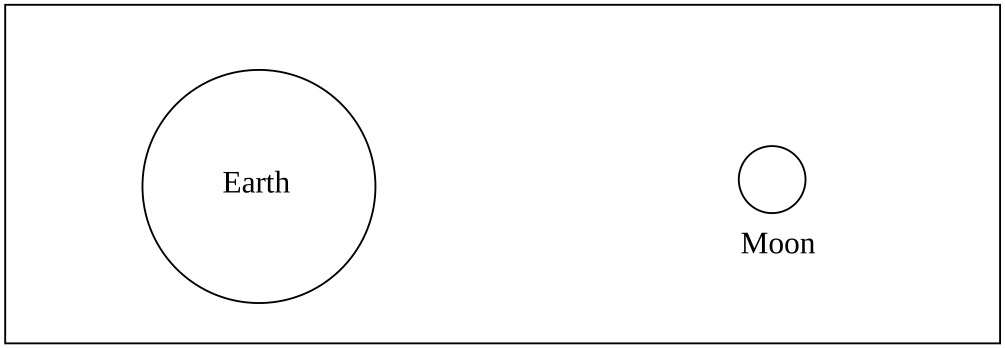
Name________________________

Gravitation Worksheet
Physics 221

a) In the picture below, a person is standing on the surface of the Earth. Draw an arrow (a vector) to represent the force exerted ***by*** the Earth ***on*** the person.



b) In the picture below, both the Earth and the Moon are shown. Draw an arrow to represent the force exerted ***by*** the Earth ***on*** the Moon. Label this arrow **(b)**.



c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

d) Are arrows **(b)** and **(c)** the same size? Explain why or why not.

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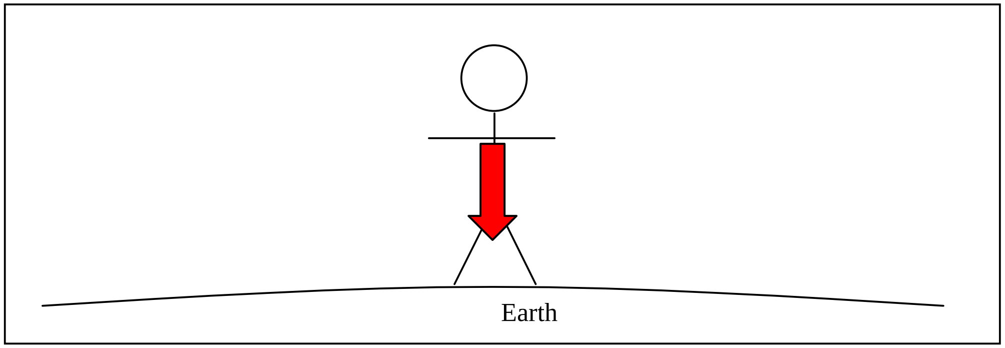

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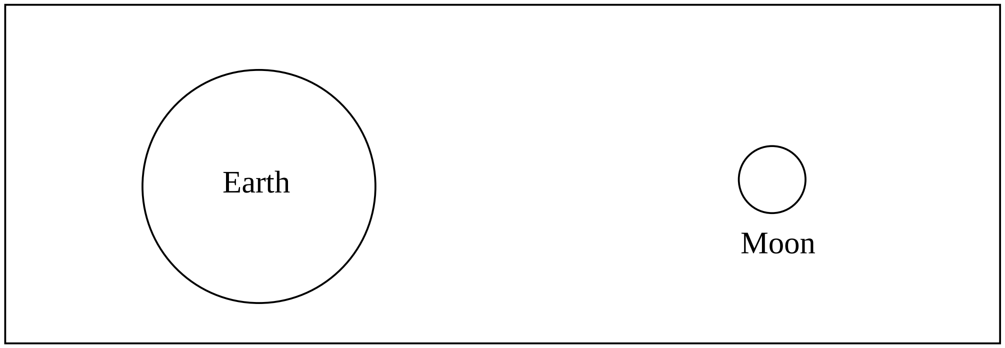

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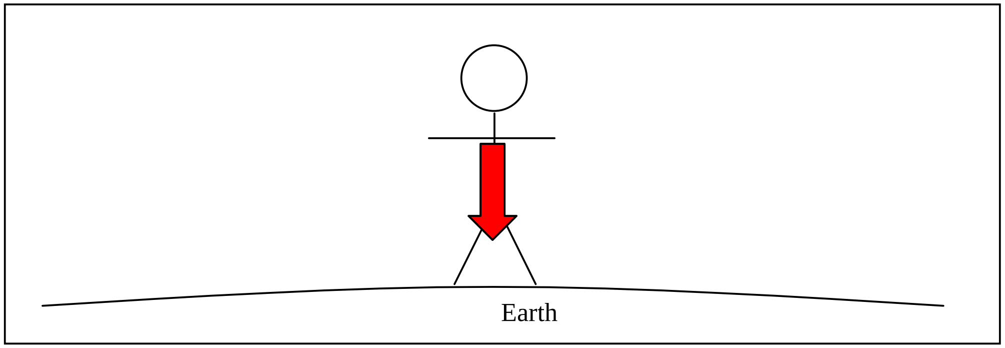

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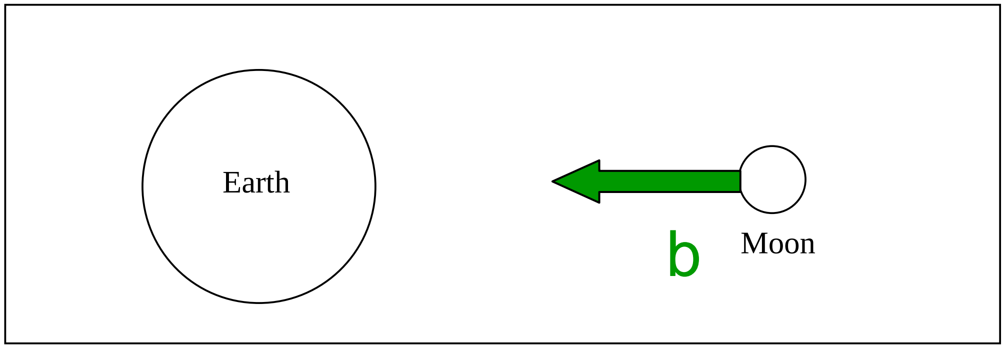

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Physics 221

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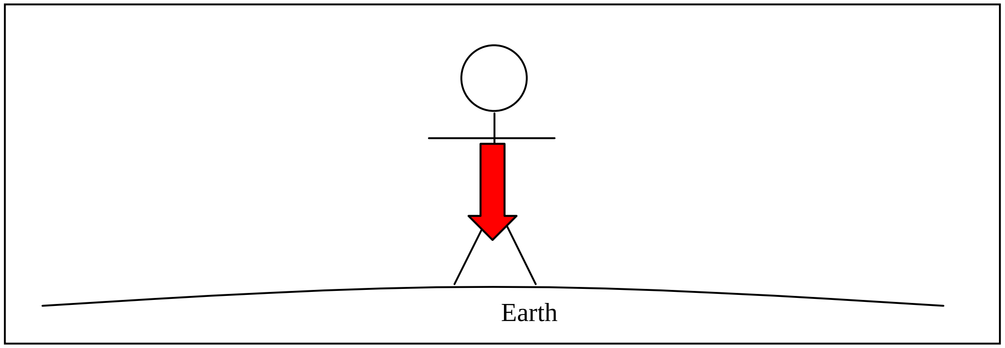

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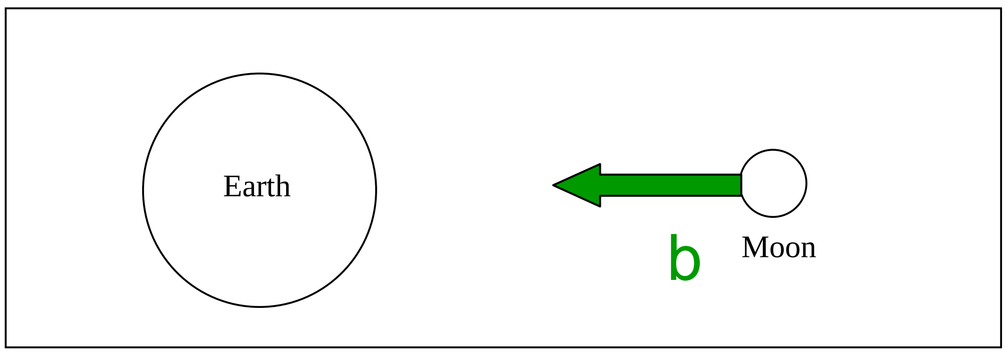

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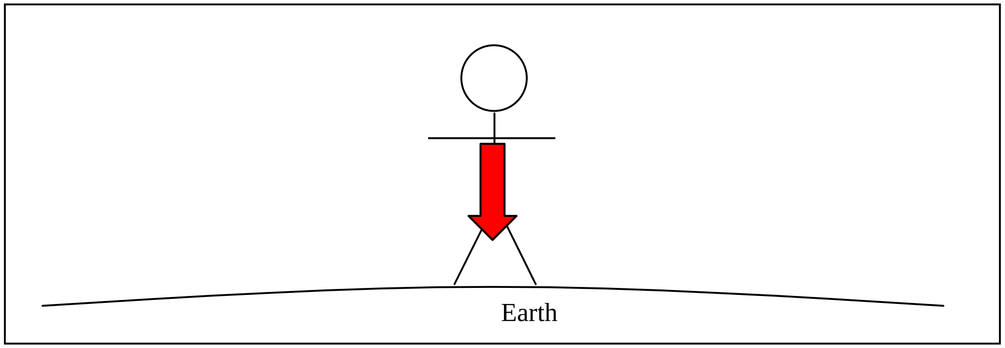

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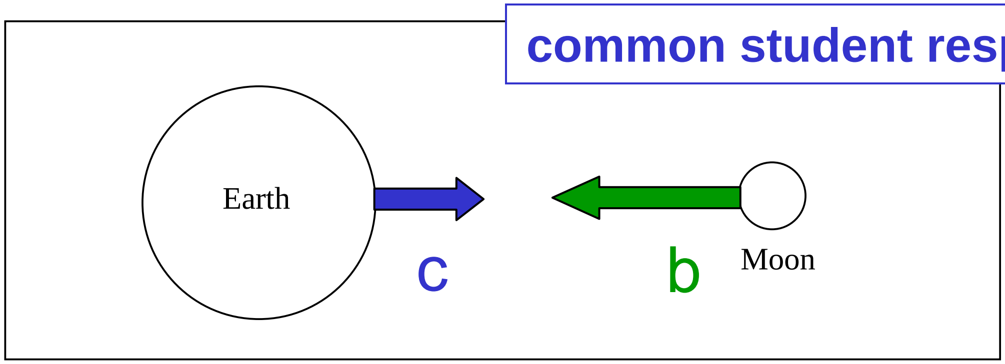

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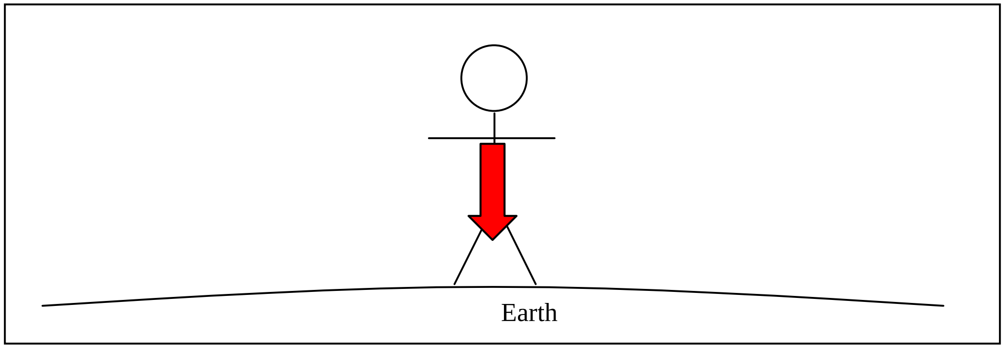

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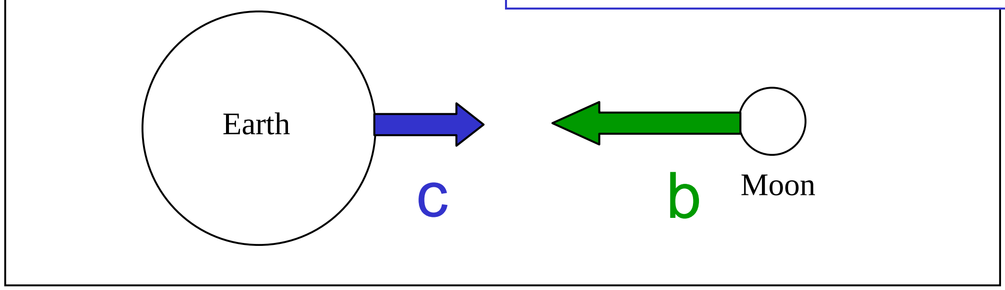

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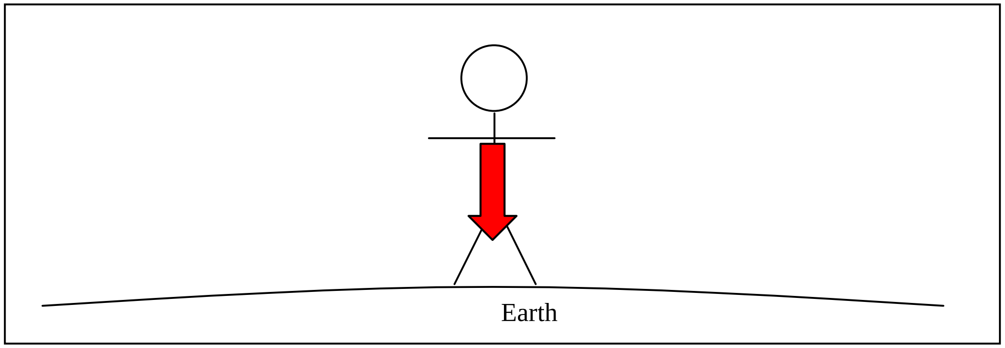

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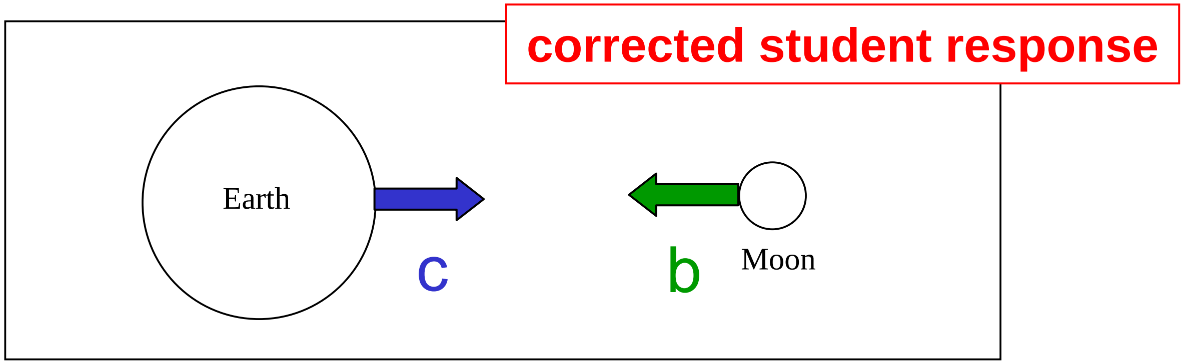

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The rings of the planet Saturn are composed of millions of chunks of icy debris. Consider a chunk of ice in one of Saturn's rings. Which of the following statements is true?

A. The gravitational force exerted by the chunk of ice on Saturn is **greater than** the gravitational force exerted by Saturn on the chunk of ice.

B. The gravitational force exerted by the chunk of ice on Saturn is **the same magnitude as** the gravitational force exerted by Saturn on the chunk of ice.

C. The gravitational force exerted by the chunk of ice on Saturn is **nonzero, and less than** the gravitational force exerted by Saturn on the chunk of ice.

D. The gravitational force exerted by the chunk of ice on Saturn is zero.

E. Not enough information is given to answer this question.

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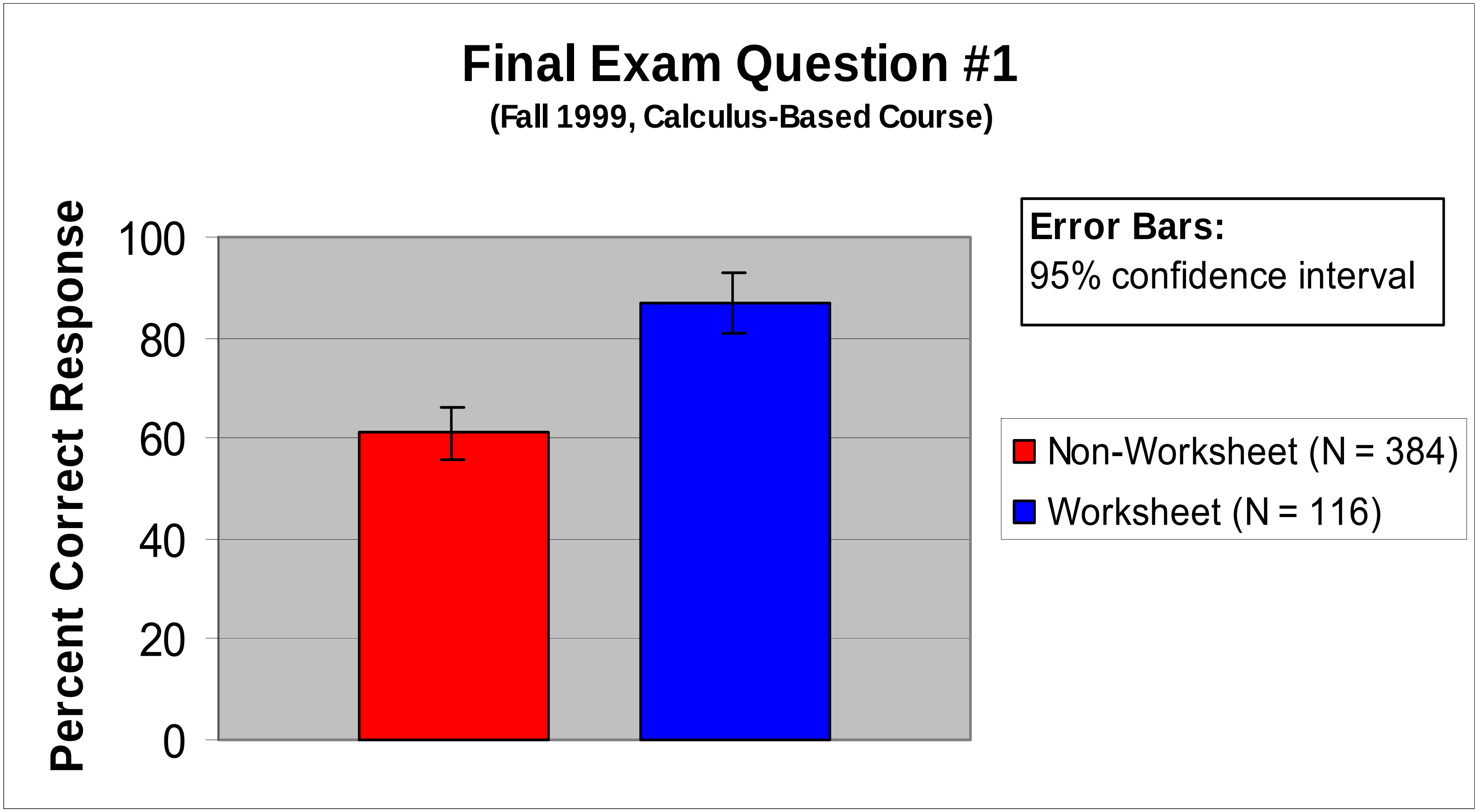
Final Exam Question #1
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Percent Correct Response
100
80
60
40
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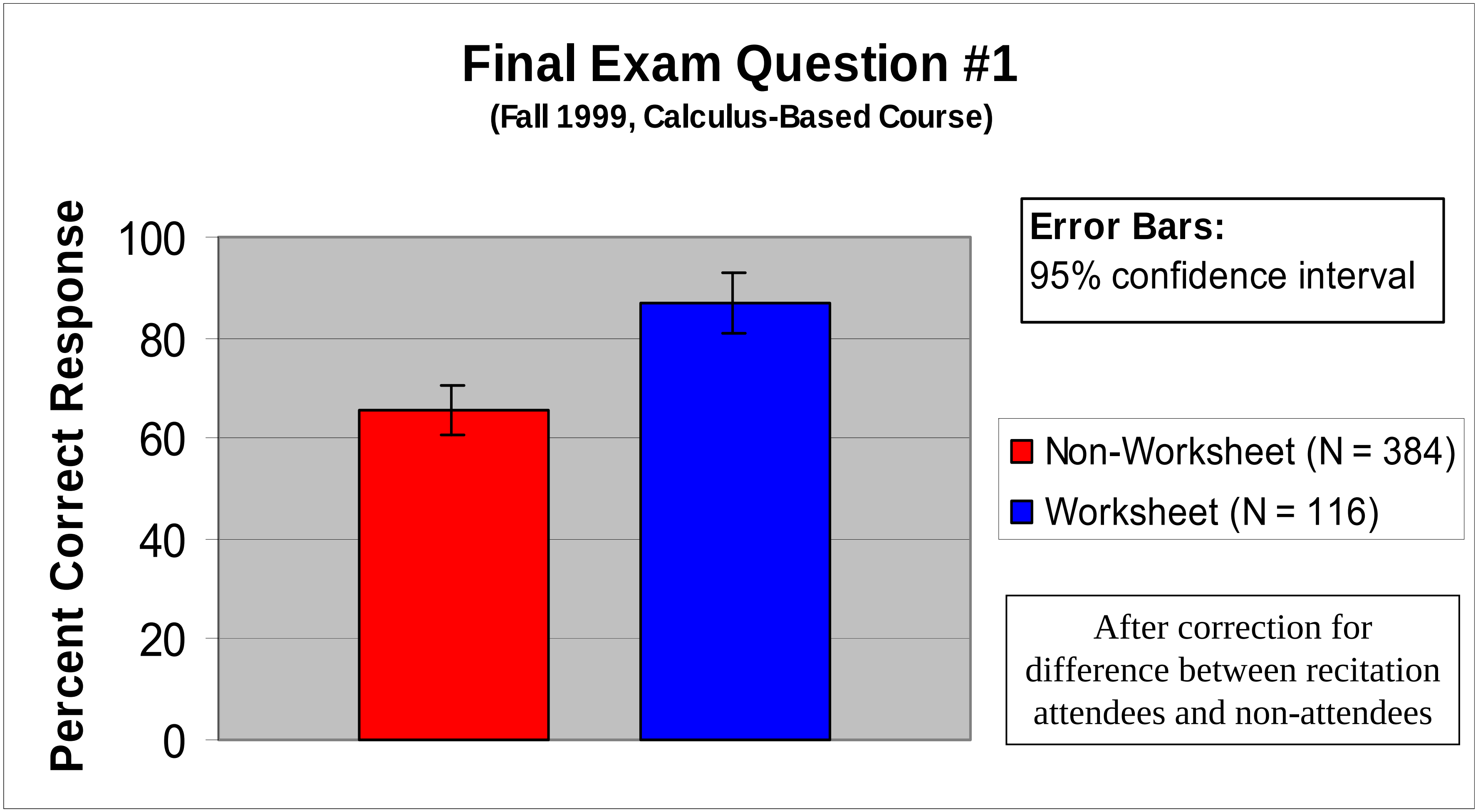
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)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Final Exam Question #2

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Two lead spheres of mass *M* are separated by a distance *r*. They are isolated in space with no other masses nearby. The magnitude of the gravitational force experienced by each mass is *F*. Now one of the masses is doubled, and they are pushed farther apart to a separation of 2*r*. Then, the magnitudes of the gravitational forces experienced by the masses are:

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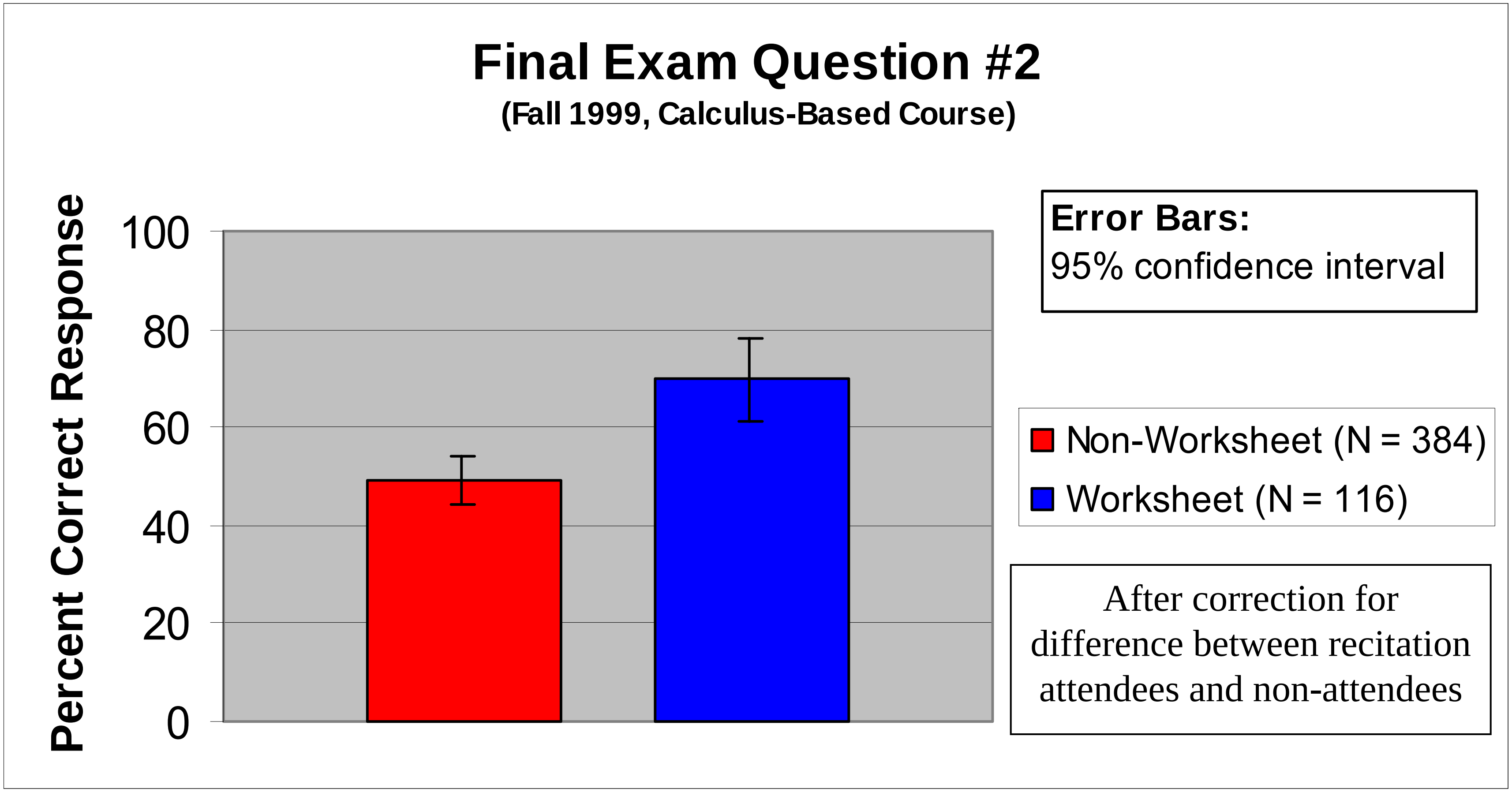
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1. Science Education as a Research Problem

   Example: Methods of physics education research

2. Research-Based Instructional Methods

   Principles and practices

3. Research-Based Curriculum Development

   A "model" problem: law of gravitation

4. Physics Course for Pre-Service Elementary Teachers

   Assessment and evaluation

5. Recent Work: Student Learning of Thermal Physics

   Research and curriculum development

Assessment of Instructional Effectiveness in a Physics Course for Preservice Teachers

In collaboration with Prof. Mani K. Manivannan, and undergraduate student peer instructor Tina N. Tassara

Supported in part by NSF grants #DUE-9354595, #9650754, and #9653079

New Inquiry-Based Elementary Physics Course for Nontechnical Students

- One-semester course, met 5 hours per week in lab -- focused on hands-on activities; no formal lecture.
- Taught at Southeastern Louisiana University for 8 consecutive semesters; average enrollment: 14
- Targeted especially at education majors, i.e., “teachers in training.”
- Primary topic: concepts of motion and force.
- Inquiry-based learning: targeted concepts are not told to students before they have worked to “discover” them through group activities.

Outline of Instructional Method

- **Prediction and Discussion:** Student groups predict outcome of various experiments, and debate their predictions with each other.
- **Experimentation:** Student groups design and implement (with guidance!) methods to test predictions.
- **Analysis and Discussion:** Student groups present results and analysis of their experiments, leading to class-wide discussion and stating of conclusions.
- **Assessment:** Students solve both written and practical problems involving concepts just investigated.

Example: Force and Motion

A cart on a low-friction surface is being pulled by a string attached to a spring scale. The velocity of the cart is measured as a function of time.

The experiment is done three times, and the pulling force is varied each time so that the spring scale reads 1 N, 2 N, and 3 N for trials #1 through #3, respectively. (The mass of the cart is kept the same for each trial.)

On the graph below, sketch the appropriate lines for velocity versus time for the three trials, and label them #1, #2, and #3.

Pre-instruction Discussion Question

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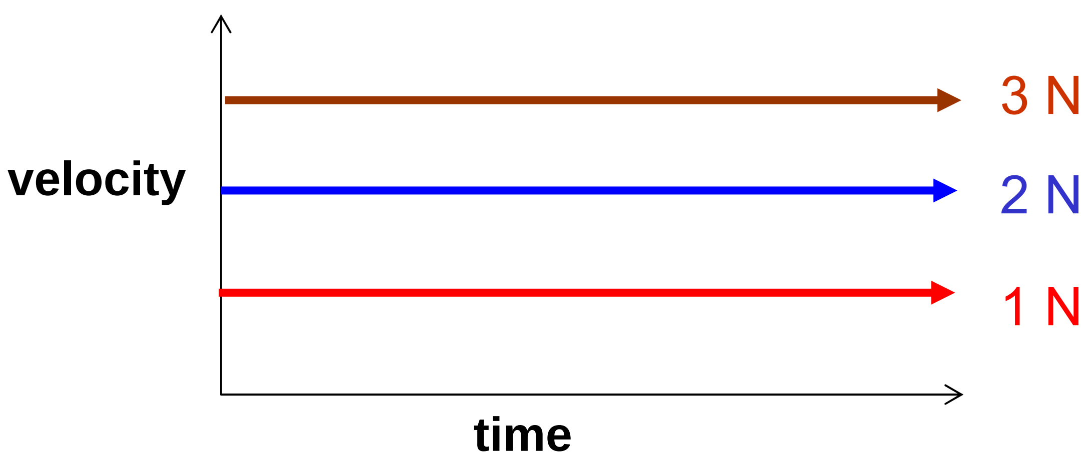
Common student response, pre-instruction



Sample Class Activity (summary):

Using the photogate timers, measure the velocity of the low-friction cart as it is pulled along the track.

Use the calibrated spring scale to pull the cart with a constant force of 0.20 newtons. Use the data to plot a graph of the cart's velocity as a function of time. Repeat these measurements for a force of 0.10 and 0.30 newtons.

Plot the results from these measurements on the same graph (use different colored pencils or different types of fitting lines).

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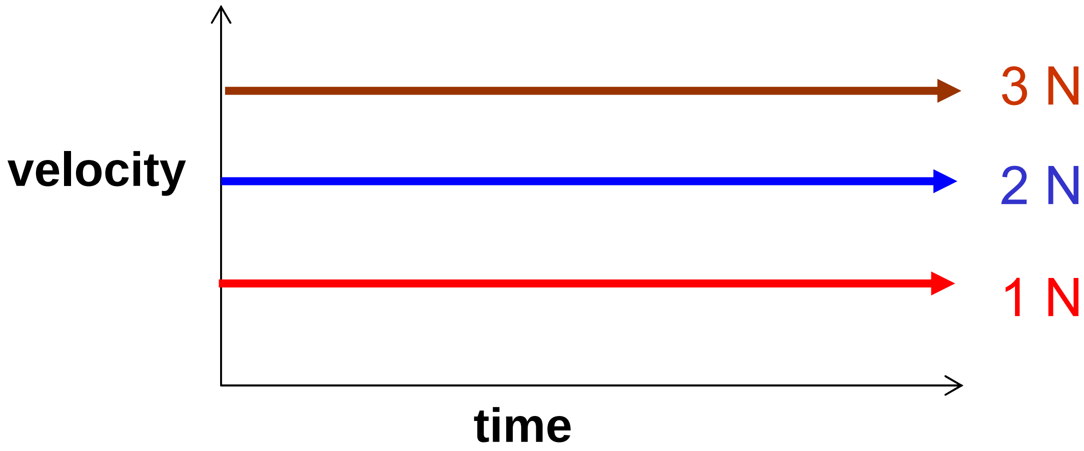

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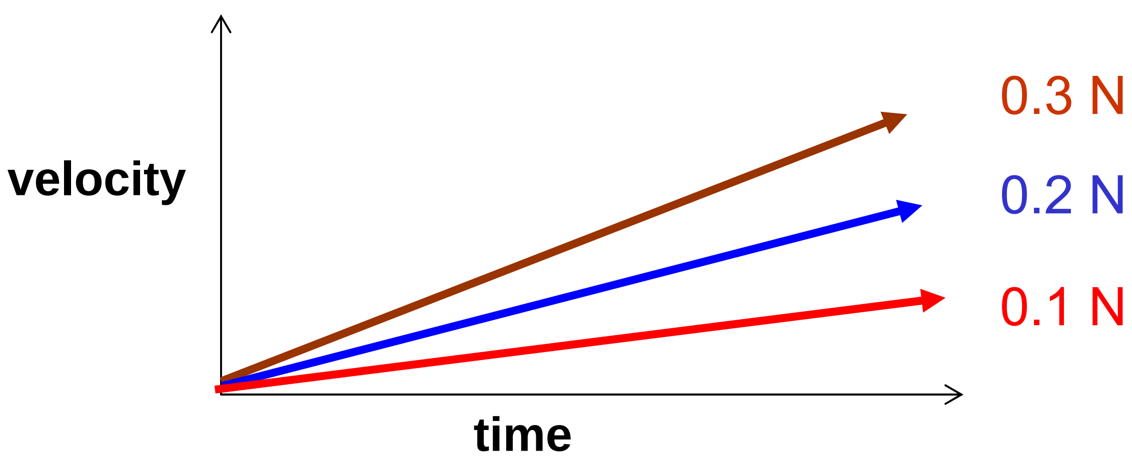
Experimental Result



What were the goals of instruction?

- Improve students' conceptual understanding of force and motion, energy, and other topics
- Develop students' ability to systematically plan, carry out and analyze scientific investigations
- Increase students' enjoyment and enthusiasm for learning and teaching physics

How well did we achieve our goals?

- For the most part, good student enthusiasm and enjoyment as documented by comments on anonymous questionnaires;
- Noticeable improvements in students' ability to plan and carry out investigations;
- Good conceptual learning on some topics (e.g., kinematics), but …
- ***Weak learning gains for most students on several key concepts in force and motion!***

Student Response

At first, most students were <u>required</u> to take course as part of their curriculum . . . Student response was mostly neutral, or negative.

Later, most students enrolled were education majors, taking course as elective . . . Student response became <u>very positive</u>.

Anonymous quotes from student evaluations:

- “The atmosphere is very laid back and happy. Great class. I loved it.”
- “ I feel I learned a lot about physics. I had ***<u>never</u>*** had any type of physics until now!! Thanks!!!”
- “I enjoyed the class. I am glad that I took it. I can now say that I successfully finished a physics class.”
- “I enjoyed the activities . . . I liked finding out our own answers.”

Overall Impact of New Elementary Physics Course

What's the bottom line for the students?

They:

- *Gain practice and experience with scientific investigation;*
- *Improve reasoning abilities and technical skills;*
- *Learn physics concepts;*

But:

- *Only a minority master force & motion concepts*

How did we test whether goals were achieved?

- Extensive pre- and post-testing using standard written conceptual diagnostic test items
- Intensive formative assessment: group quizzes and presentations every week
- Continuous evaluation of students’ written and verbal explanations of their thinking
- Individual post-instruction interviews with students to probe understanding in depth

Caution: Careful probing needed!

- It is ***very easy*** to overestimate students' level of understanding.
- Students ***frequently*** give correct responses based on incorrect reasoning.
- Students' written and verbal explanations of their reasoning are powerful diagnostic tools.

Overview of Four Years Experience

- Intensive inquiry-based physics courses may be an enjoyable and rewarding experience for preservice teachers.
- Effective learning of new physics concepts -- and "unlearning" of misconceptions -- is ***very time intensive.***
- Careful assessment of learning outcomes is <u>essential</u> for realistic appraisal of innovative teaching methods.

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5. Recent Work: Student Learning of Thermal Physics

   Research and curriculum development

Research on the Teaching and Learning of Thermal Physics

- Investigate student learning of classical and statistical thermodynamics
- Probe evolution of students' thinking from introductory through advanced-level course
- Develop research-based curricular materials

In collaboration with John Thompson, University of Maine

Student Learning of Thermodynamics

Recent studies of university students in general physics courses showed substantial learning difficulties with fundamental concepts, including heat, work, cyclic processes, and the first and second laws of thermodynamics.*

M. E. Loverude, C. H. Kautz, and P. R. L. Heron,* Am. J. Phys. ***70, 137 (2002);*

D. E. Meltzer, Am. J. Phys. ***72**, 1432 (2004);*

M. Cochran and P. R. L. Heron, Am. J. Phys. ***74**, 734 (2006).*

Research-Based Thermodynamics Curricular Materials

- Preliminary versions and initial testing of worksheets for:
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  - thermochemistry
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Preliminary testing in general physics and chemistry, and in junior-level thermal physics course

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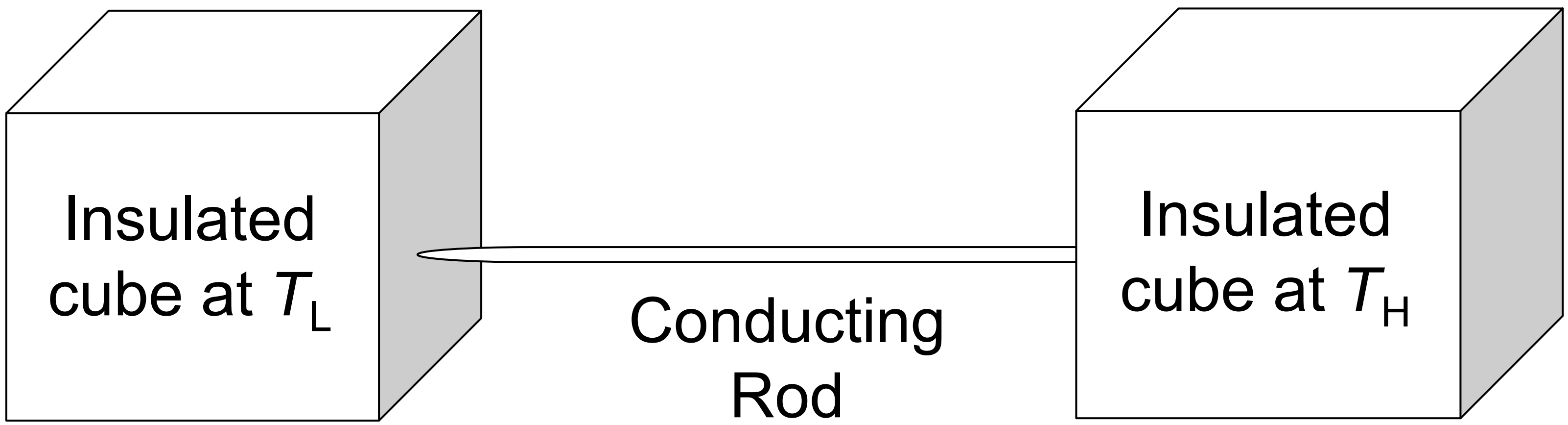
Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)



• Consider slow heat transfer process between two thermal reservoirs (insulated metal cubes connected by thin metal pipe)

- Does total energy change during process?
- Does total entropy change during process?

Entropy Tutorial

(draft by W. Christensen and DEM, undergoing class testing)

- Guide students to find that:

$$\Delta S_{total} = \frac{Q}{T_{cold\ reservoir}} - \frac{Q}{T_{hot\ reservoir}} > 0$$

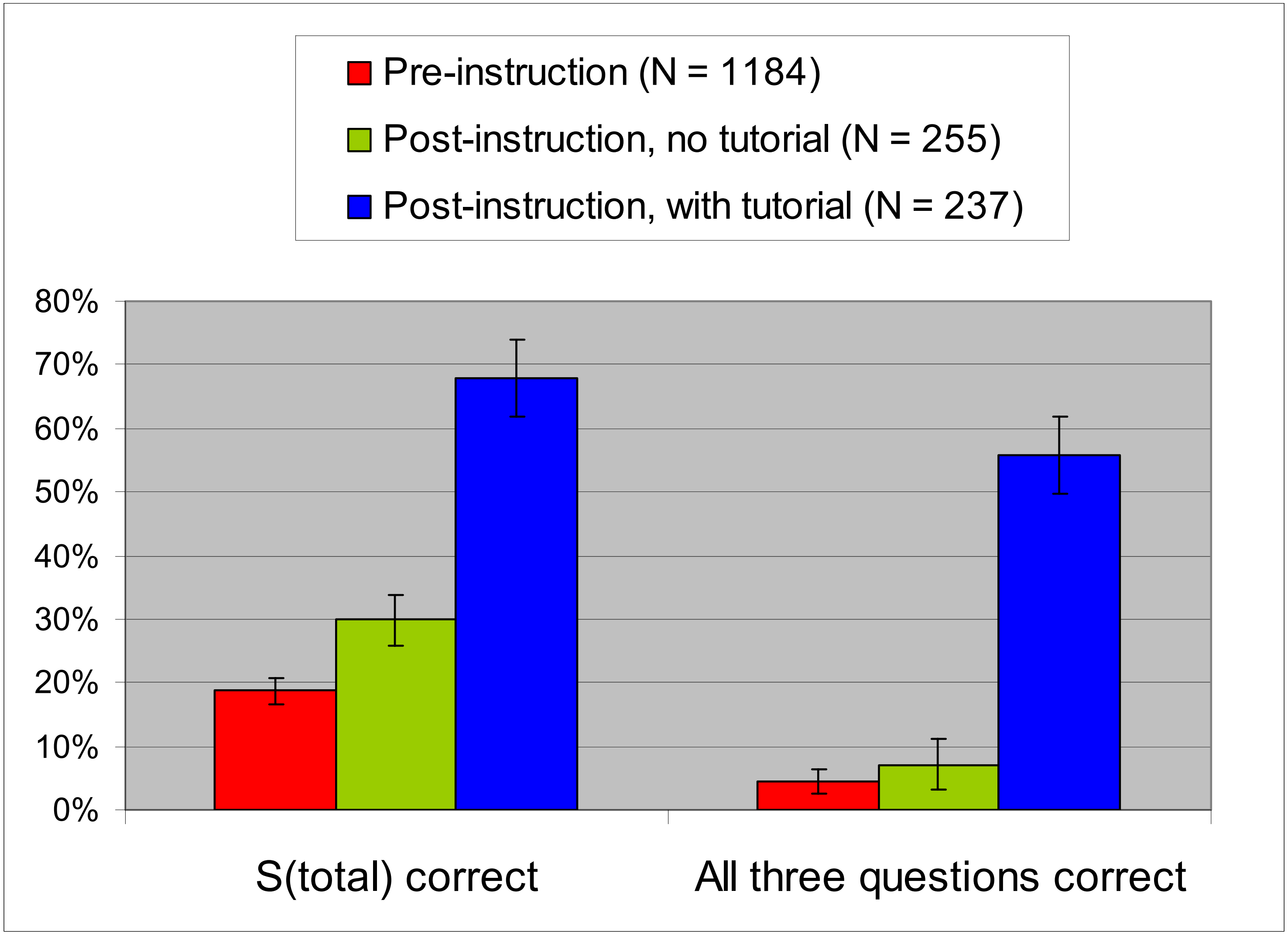
and that definitions of "system" and "surroundings" are arbitrary

Preliminary results are promising…

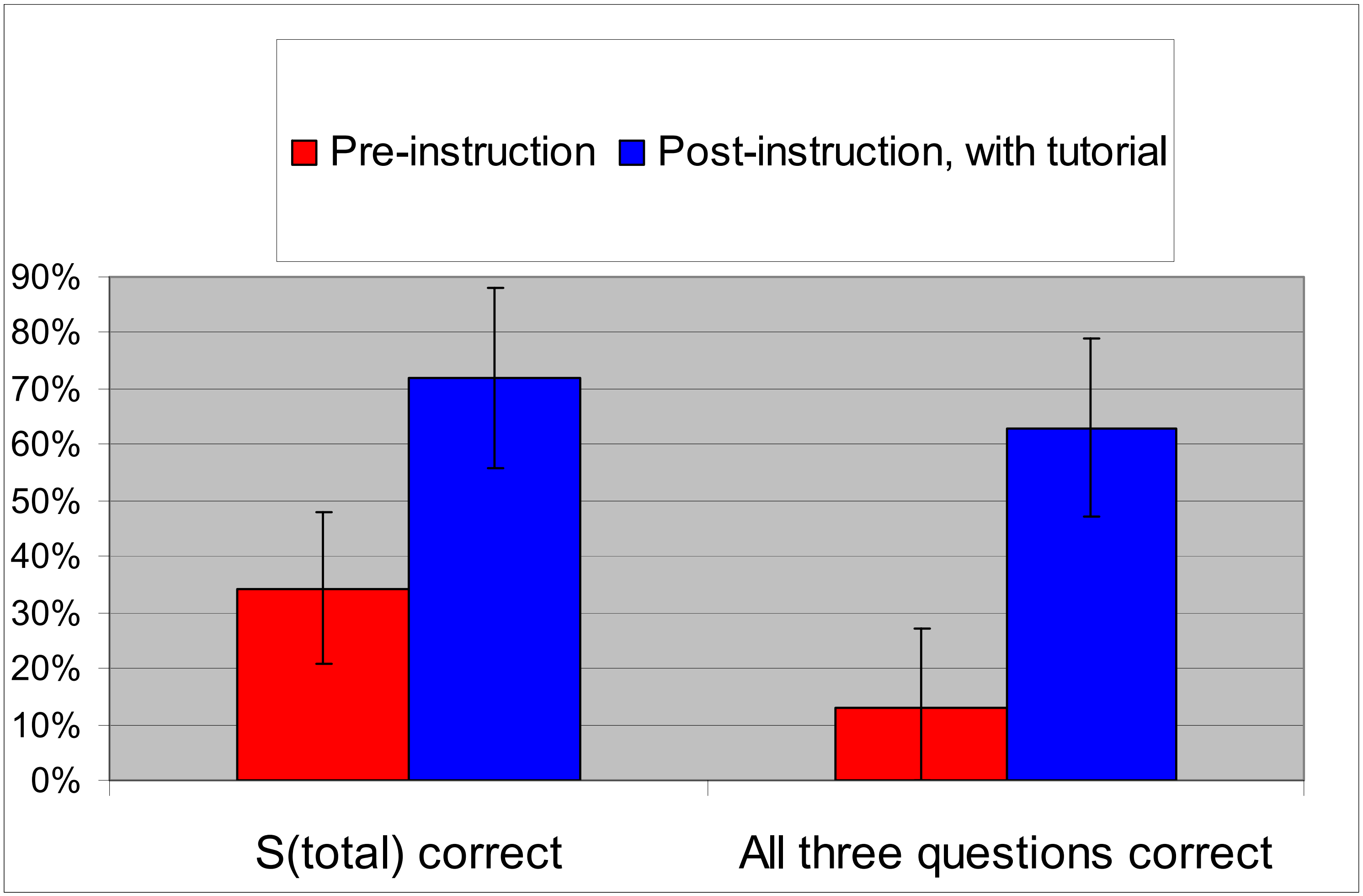
Responses to Spontaneous-Process Questions
Introductory Students

[Diagnostic quiz given to students consisting of three questions on change in entropy (S) in "spontaneous" processes]

Responses to Spontaneous-Process Questions
Introductory Students



Responses to Spontaneous-Process Questions
Intermediate Students (*N* = 32, Matched)



Summary

- Research on student learning lays basis for development of improved instructional materials in science education.
- "Interactive-engagement" instruction using research-based curricula can improve student learning.
- Ongoing development and testing of instructional materials lays the basis for new directions in research, holds promise for sustained improvements in learning.

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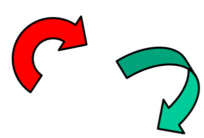

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