Strategies and Methods of Research-Based Development in Physics Education

David E. Meltzer

College of Teacher Education and Leadership

Arizona State University

Mesa, Arizona, USA

Supported in part by U.S. National Science Foundation

Grant Nos. DUE 9981140, PHY 0406724, PHY 0604703, and DUE 0817282

Collaborators

- Tom Greenbowe (Iowa State University; Chemistry)
- John Thompson (U. Maine; Physics)
- Michael Loverude (California State U., Fullerton; Physics)
- Warren Christensen (North Dakota State U.; Physics)

Students

- Jack Dostal (ISU M.S. 2005)
- Ngoc-Loan Nguyen (ISU M.S. 2003)
- Tom Stroman (ISU graduate student)

Funding

- U.S. NSF Division of Undergraduate Education
- U.S. NSF Division of Physics

Outline

1. Physics Education as a Research Problem

Methods of physics education research

2. Probing the Structure of Students' Knowledge

Example: Students' ideas about equipotentials

3. Research-Based Instructional Methods

Guiding student inquiry

4. Research-Based Curriculum Development

A "model" problem: law of gravitation

Outline

1. Physics Education as a Research Problem

Methods of physics education research

2. Probing the Structure of Students' Knowledge

Example: Students' ideas about equipotentials

3. Research-Based Instructional Methods

Guiding student inquiry

4. Research-Based Curriculum Development

A "model" problem: law of gravitation

Physics Education As a Research Problem

Within the past 30 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

Methods of PER

- Develop and test diagnostic instruments that assess student understanding

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

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.

Role of Researchers in Physics Education

- Carry out in-depth investigations of student thinking in physics
  - provide basis for “pedagogical content knowledge”

- Develop and assess courses and curricula:
  - for introductory and advanced undergraduate courses
  - for physics teacher preparation

Research Basis for Improved Learning

Research Basis for Improved Learning

- *"Pedagogical Content Knowledge"* (Shulman, 1986): Knowledge needed to teach a *specific topic* effectively, beyond general knowledge of content and teaching methods

Research Basis for Improved Learning

- *"Pedagogical Content Knowledge"* (Shulman, 1986): Knowledge needed to teach a *specific topic* effectively, beyond general knowledge of content and teaching methods

"…the ways of representing and formulating a subject that make it comprehensible to others…

Research Basis for Improved Learning

- *"Pedagogical Content Knowledge"* (Shulman, 1986): Knowledge needed to teach a *specific topic* effectively, beyond general knowledge of content and teaching methods

  "…the ways of representing and formulating a subject that make it comprehensible to others…an understanding of what makes the learning of specific topics easy or difficult…

Research Basis for Improved Learning

- *"Pedagogical Content Knowledge"* (Shulman, 1986): Knowledge needed to teach a *specific topic* effectively, beyond general knowledge of content and teaching methods

  "…the ways of representing and formulating a subject that make it comprehensible to others…an understanding of what makes the learning of specific topics easy or difficult…knowledge of the [teaching] strategies most likely to be fruitful…"

Research on Student Learning: Some Key Results

- Students' *subject-specific* conceptual difficulties 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.
  - need to stress reasoning instead of memorization

Research on Student Learning: Some Key Results

- Students' *subject-specific* conceptual difficulties 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.
  - need to stress reasoning instead of memorization

Uncovering Students' Ideas

- Students enter with specific beliefs and behaviors regarding learning:
  - beliefs regarding how they *should* study and learn
  - actual behaviors, how they really *do* study and learn
- Students' minds are not "blank slates"
  - Students' have pre-instruction ideas related to content areas
    - Some ideas may represent "misconceptions" and/or lead to learning difficulties
    - Some ideas may be useful building blocks for further learning

Uncovering Students' Ideas

- Strategies for revealing students' ideas:
  - Pre-assessments: pre-instruction tests, surveys, etc.
  - Predictions regarding experiments/investigations
  - Systematic Research Investigations

Tradeoffs: More extensive knowledge of students' ideas is helpful in planning instruction, but requires additional time and effort to acquire.

Addressing Students' Ideas

(1) concept-related learning difficulties

- Guide students to elicit and address specific learning difficulties
  - direct methods (students are guided to "confront" these difficulties by exploring discrepancies and contradictions)
  - "indirect" methods (students are guided to refine their ideas to "reconcile" them to experts' concepts).
    - "bridging" between more familiar and less familiar concepts
    - "weaving" loosely connected initial ideas into more complete understanding

Addressing Students’ Ideas

(2) behavior-related learning difficulties

- Guide students to implement effective and efficient learning methods
  - emphasize deep and thoughtful learning, and thorough investigation
  - avoid memorizing, and superficial and simplistic approaches
  - focus on developing understanding of general principles and connections among ideas

Guiding by Inquiry

- Students explore concepts through process of investigation and discussion.
- Students don’t receive targeted ideas that are fully and clearly developed in advance of their investigative activity.
- Students are asked to offer hypotheses or predictions regarding the outcome of investigations.
- Instructors ask students questions—or guide students to ask their own questions—rather than provide either direct answers or detailed formulations of generalized principles.
- Carefully structured question or activity sequences are often used to guide this process, both with and without use of equipment and materials.

Guiding by Inquiry

- Students explore concepts through process of investigation and discussion.
- Students don’t receive targeted ideas that are fully and clearly developed in advance of their investigative activity.
- Students are asked to offer hypotheses or predictions regarding the outcome of investigations.
- Instructors ask students questions—or guide students to ask their own questions—rather than provide either direct answers or detailed formulations of generalized principles.
- Carefully structured question or activity sequences are often used to guide this process…developed through research…

Guiding Students' Problem-Solving Activities

- emphasize having students engage in a wide variety of problem-solving activities during class time, in contrast to spending most of the time listening to an instructor speak.

Tradeoffs: Targeting students' specific difficulties improves learning, but may require additional preparation and instructional time.

Outline

1. Physics Education as a Research Problem

    Methods of physics education research

2. Probing the Structure of Students' Knowledge

    Example: Students' ideas about equipotentials

3. Research-Based Instructional Methods

    Guiding student inquiry

4. Research-Based Curriculum Development

    A "model" problem: law of gravitation

“Concept Cluster”

– Robert Karplus [AJP **49**, 238 (1982)]

“Concept Cluster”

“Central to a concept cluster is an empirical or theoretical relationship[*] *among several physical variables…*

"Concept Cluster"

"Central to a concept cluster is an empirical or theoretical relationship[*] *among several physical variables…*

[*e.g., $\boldsymbol{F} = m\boldsymbol{a}$ and $W = \boldsymbol{F}\cdot\Delta\boldsymbol{s}$]

"Concept Cluster"

"Central to a concept cluster is an empirical or theoretical relationship[*] among several physical variables…there is considerable freedom in the choice of quantities to be defined and derived. The exact choices that are made will determine the structure that is obtained…

[*e.g., $\boldsymbol{F} = m\boldsymbol{a}$ and $W = \boldsymbol{F}\cdot\Delta\boldsymbol{s}$]

"Concept Cluster"

"Central to a concept cluster is an empirical or theoretical relationship[*] among several physical variables…there is considerable freedom in the choice of quantities to be defined and derived. The exact choices that are made will determine the structure that is obtained…it would appear that necessary linking of the concepts in a cluster requires teaching that ultimately deals with the entire cluster as an entity."

– Robert Karplus [AJP **49**, 238 (1982)]

[*e.g., $\boldsymbol{F} = m\boldsymbol{a}$ and $W = \boldsymbol{F}\cdot\Delta\boldsymbol{s}$]

Instruction must promote knowledge organization

Instruction must promote knowledge organization

"….instruction can at least try to ensure (a) that students acquire knowledge which is in well-organized hierarchical form,

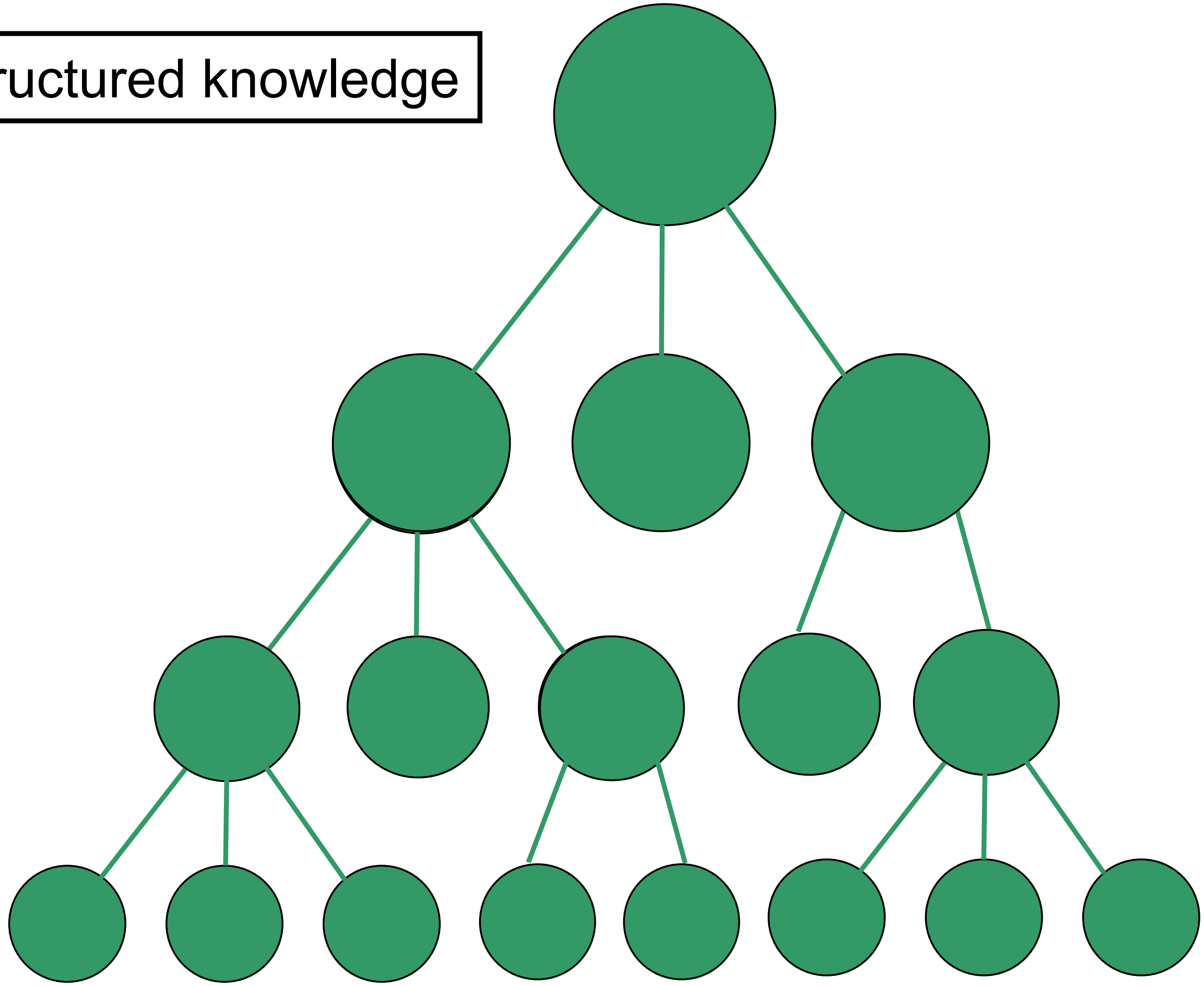
– Frederick Reif [AJP 63, 17 (1995)]

Instruction must promote knowledge organization

"….instruction can at least try to ensure (a) that students acquire knowledge which is in well-organized hierarchical form, and (b) that they can exploit such organization to help them remember and retrieve pertinent information."

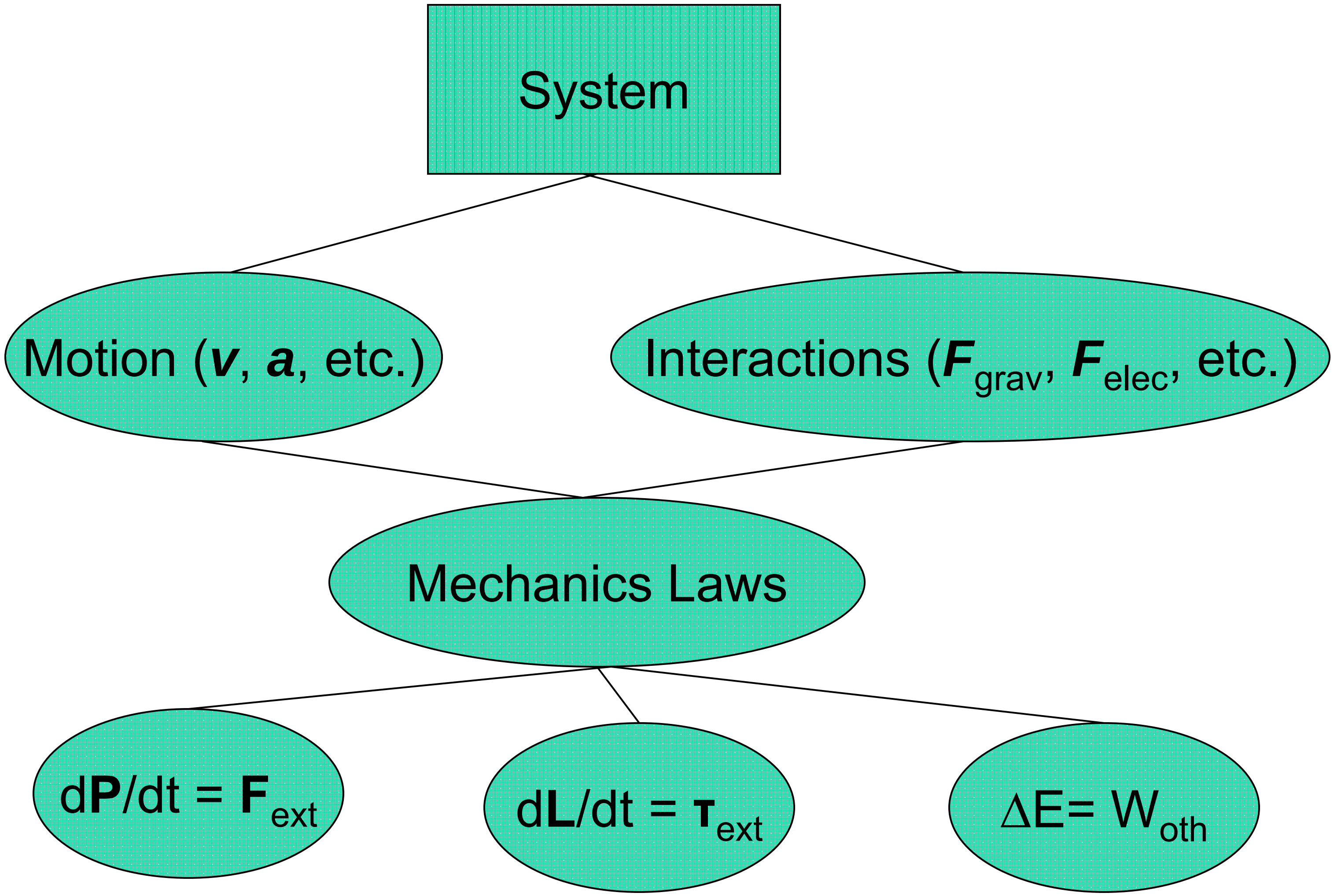
– Frederick Reif [AJP 63, 17 (1995)]

Well-structured knowledge



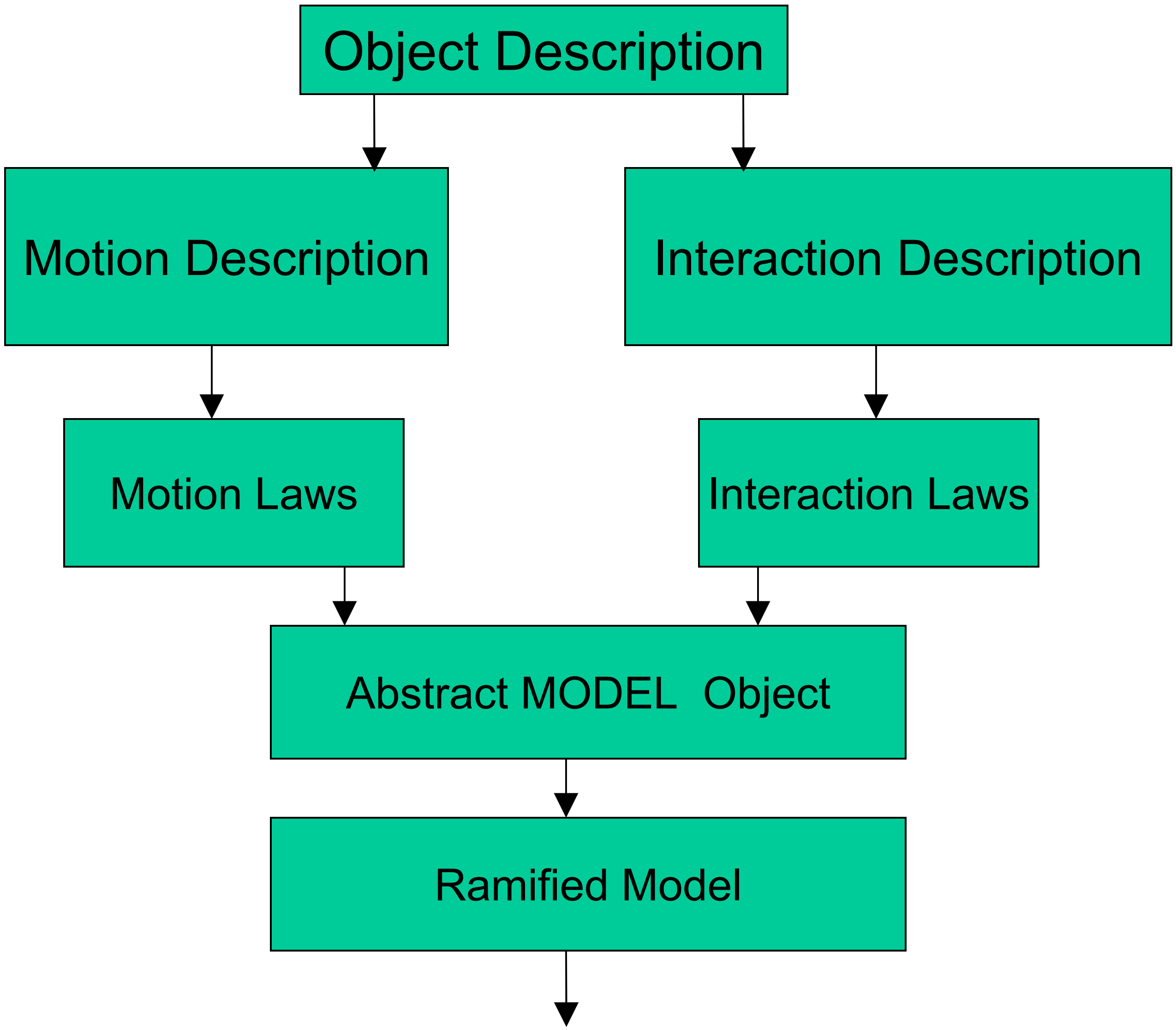
[F. Reif, Am. J. Phys. (1995)]

Example (F. Reif): Mechanics Overview

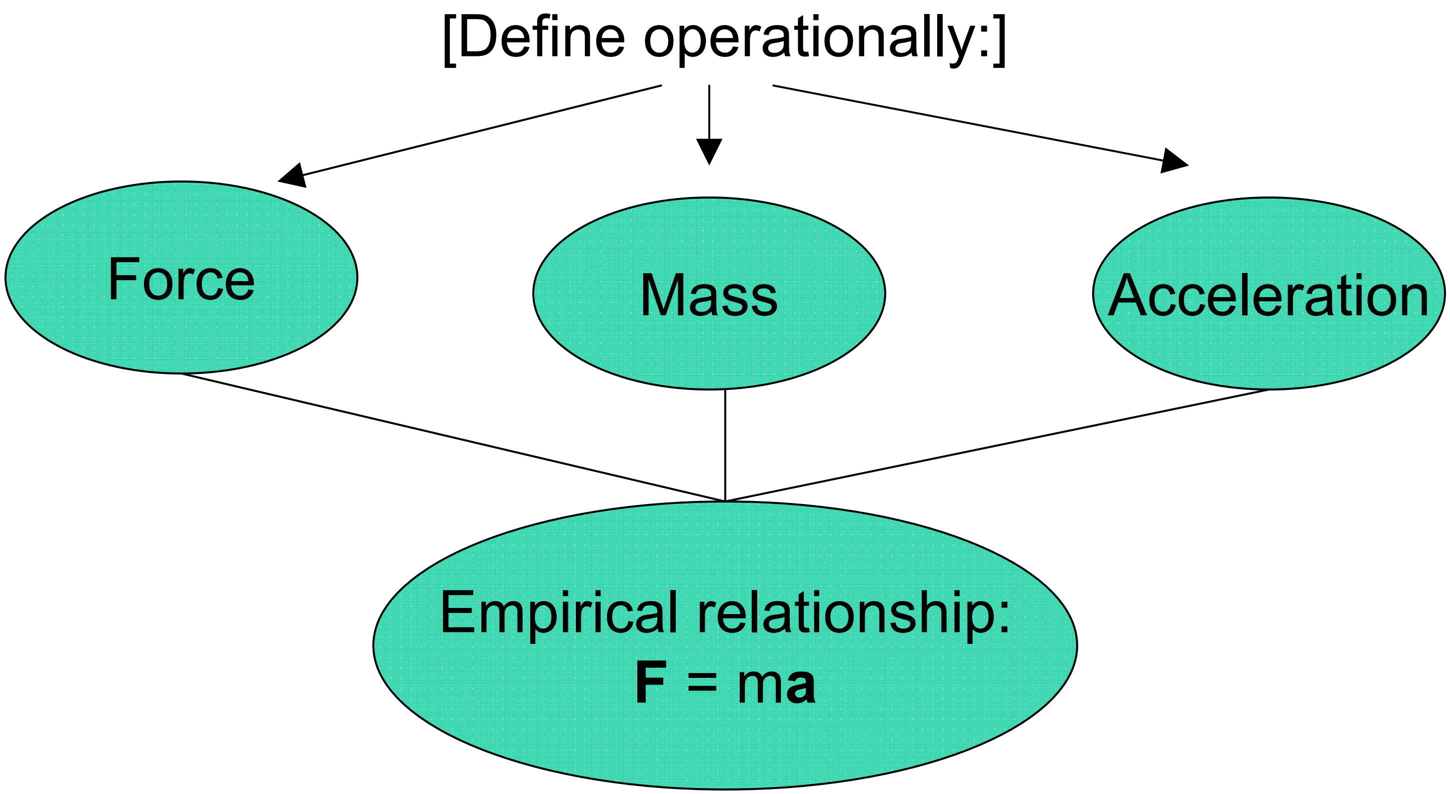


Another Perspective: Model Development

D. Hestenes, AJP *55*, 440 (1987)

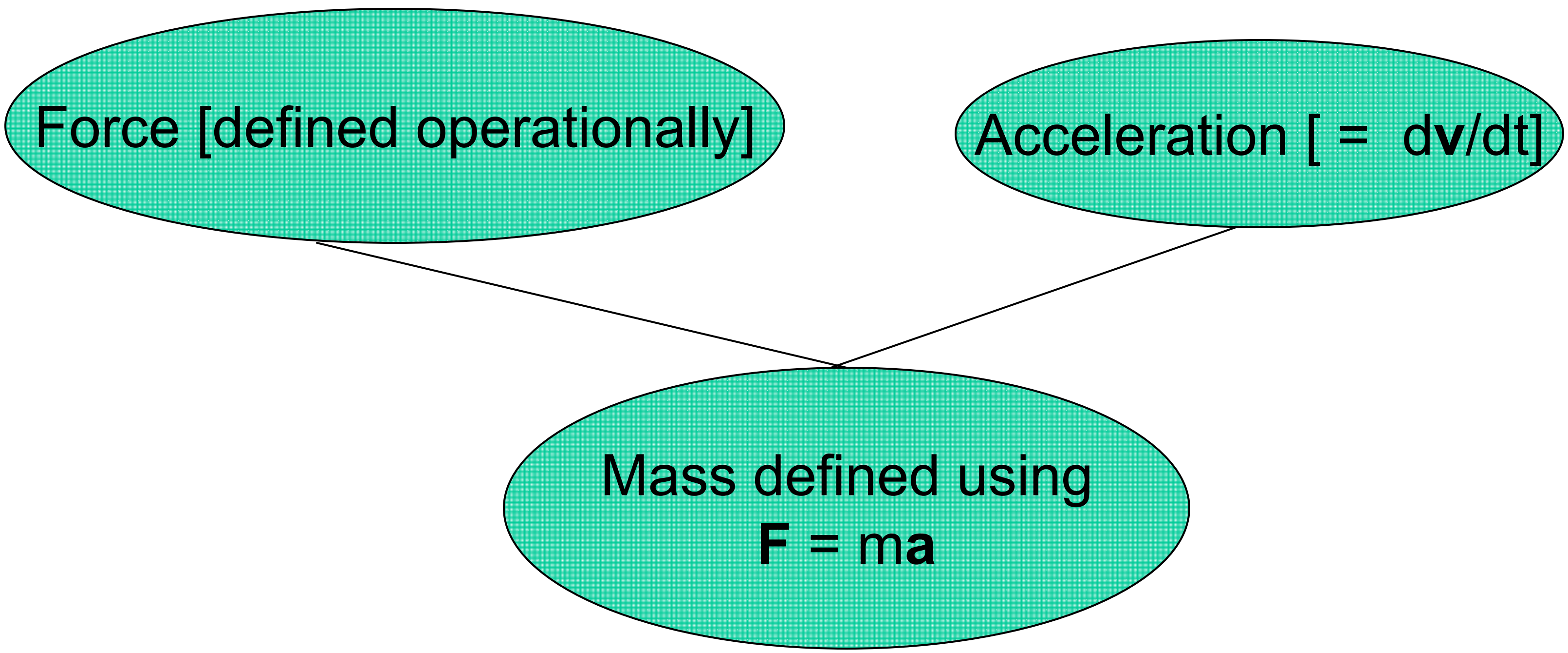


Concept Cluster (R. Karplus): Newton's second law



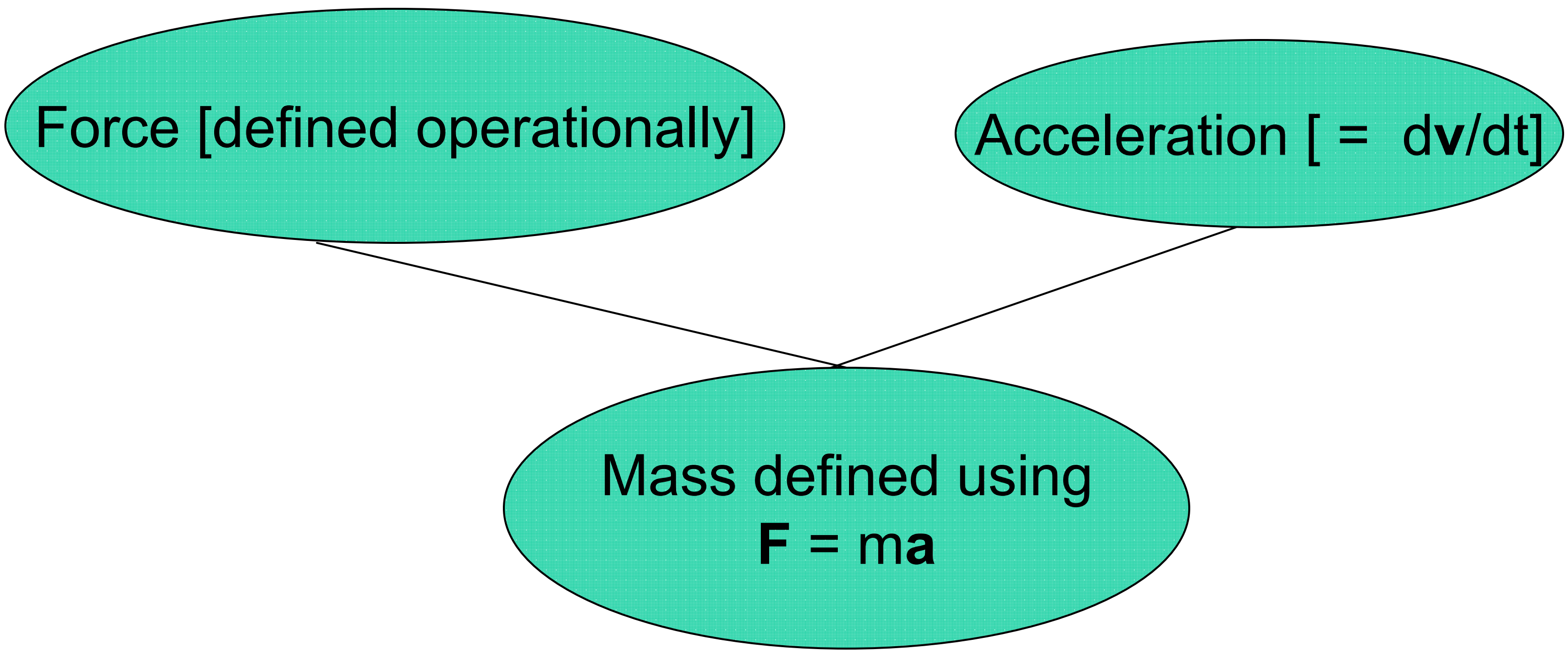
Concept Cluster (R. Karplus): Newton's second law

[*alternative concept cluster*]

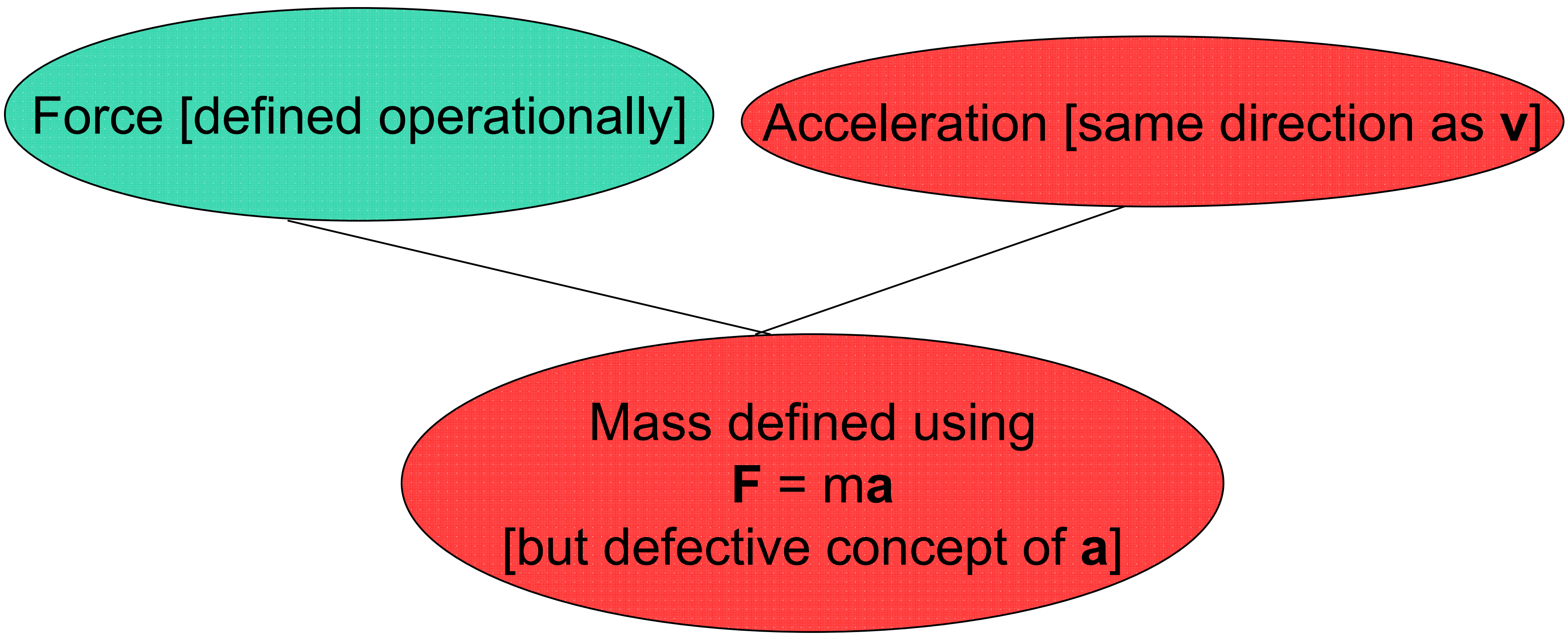


Concept Clusters have diverse representations

[*alternative concept cluster*]



[*flawed concept cluster*]



Learning and Knowledge Structure

- Difficulties in understanding and applying specific physical ideas form obstacles to learning;
- Inadequate *organization* of students' ideas plays a central role in hindering understanding.
- It may be difficult or impossible to differentiate unambiguously between a *difficulty with a specific idea* and *inadequate linking with related ideas*.

Learning and Knowledge Structure

- Difficulties in understanding and applying specific physical ideas form obstacles to learning;
- Inadequate *organization* of students' ideas plays a central role in hindering understanding.
- It may be difficult or impossible to differentiate unambiguously between a *difficulty with a specific idea* and *inadequate linking with related ideas*.

A Schematic Model for Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

A Schematic Model for Students' Knowledge Structure

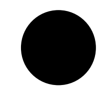
[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

Archery Target: three concentric rings

A Schematic Model for Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

Archery Target: three concentric rings

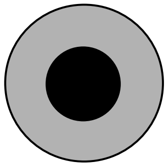


- Central black bull's-eye: what students know well
  - *tightly linked network of well-understood concepts*

A Schematic Model for Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

Archery Target: three concentric rings

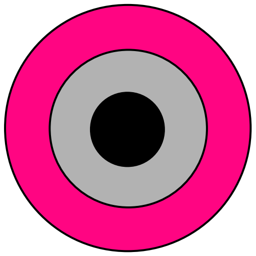


- Central black bull's-eye: what students know well
  - *tightly linked network of well-understood concepts*
- Middle "gray" ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*

A Schematic Model for Students' Knowledge Structure

[E. F. Redish, *AJP* (1994), *Teaching Physics* (2003)]

Archery Target: three concentric rings



- Central black bull's-eye: what students know well
  - *tightly linked network of well-understood concepts*
- Middle "gray" ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*
- Outer "white" region: what students don't know at all
  - *disconnected fragments of poorly understood ideas*

Knowledge in Development: “Flawed” Models

“A flawed mental model may share a number of propositions with a correct mental model, but they are interconnected according to an incorrect organizing principle.”

– M. Chi and R. Roscoe, in *Reconsidering Conceptual Change* (2002), p. 7.

Schematic Representation of Knowledge Structure…

“correct” and stable knowledge element

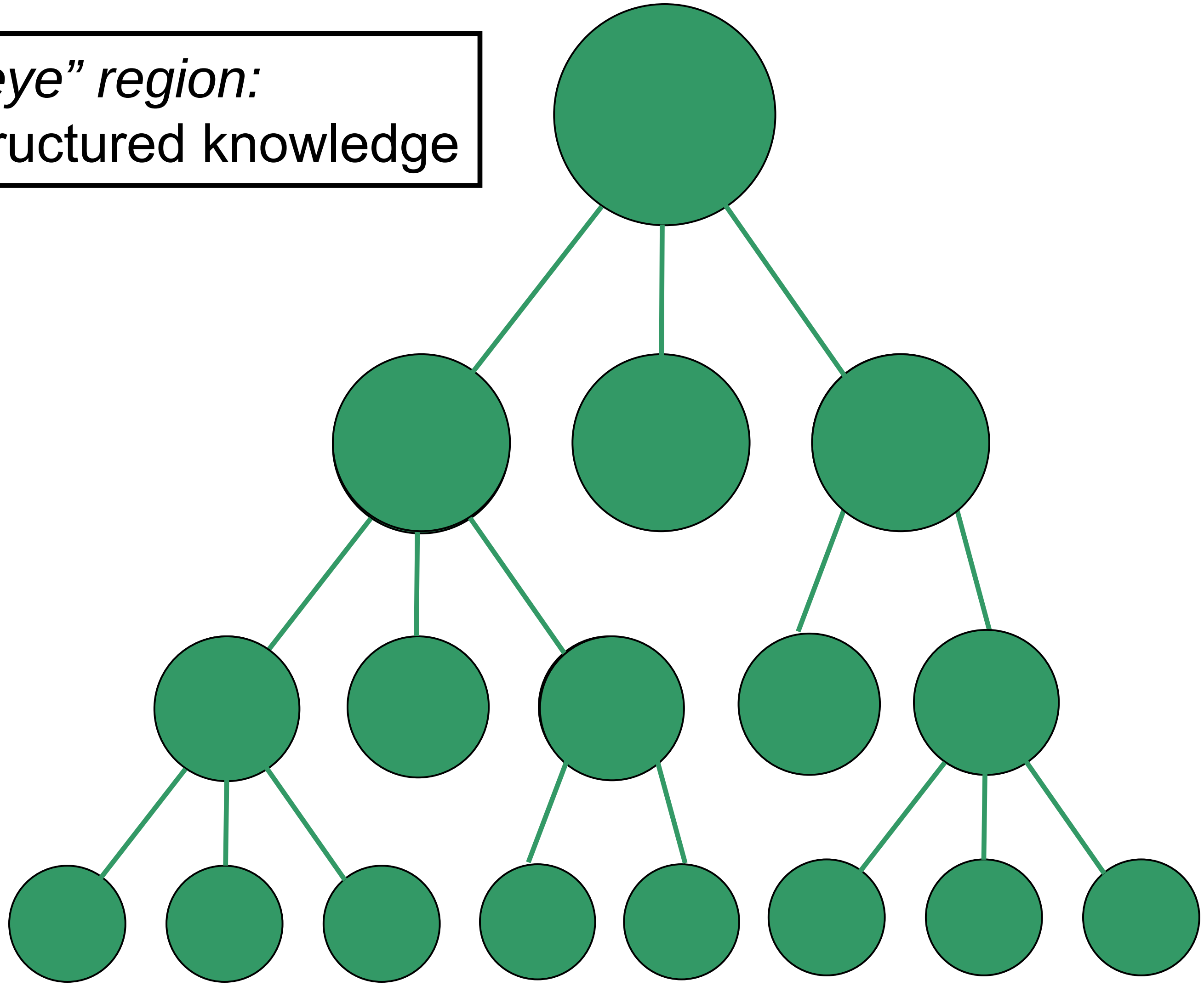
“incorrect” or unstable knowledge element

ill-defined idea, highly unstable

consistent, reliable link

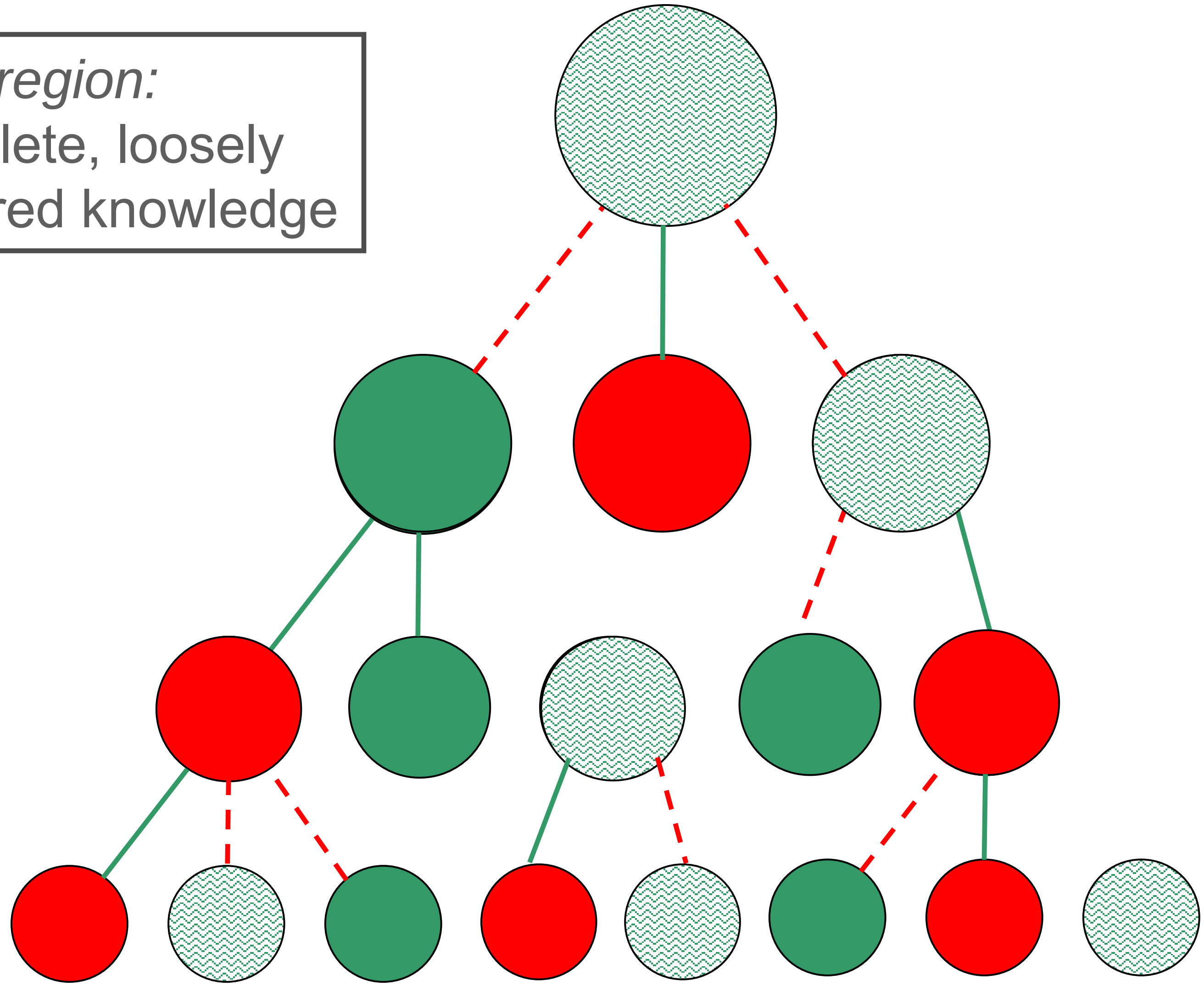
inconsistent or “incorrect” link

"Bulls-eye" region:
Well-structured knowledge



[F. Reif, Am. J. Phys. (1995)]

"Gray" region:
incomplete, loosely structured knowledge



“White” region:
incoherent ideas

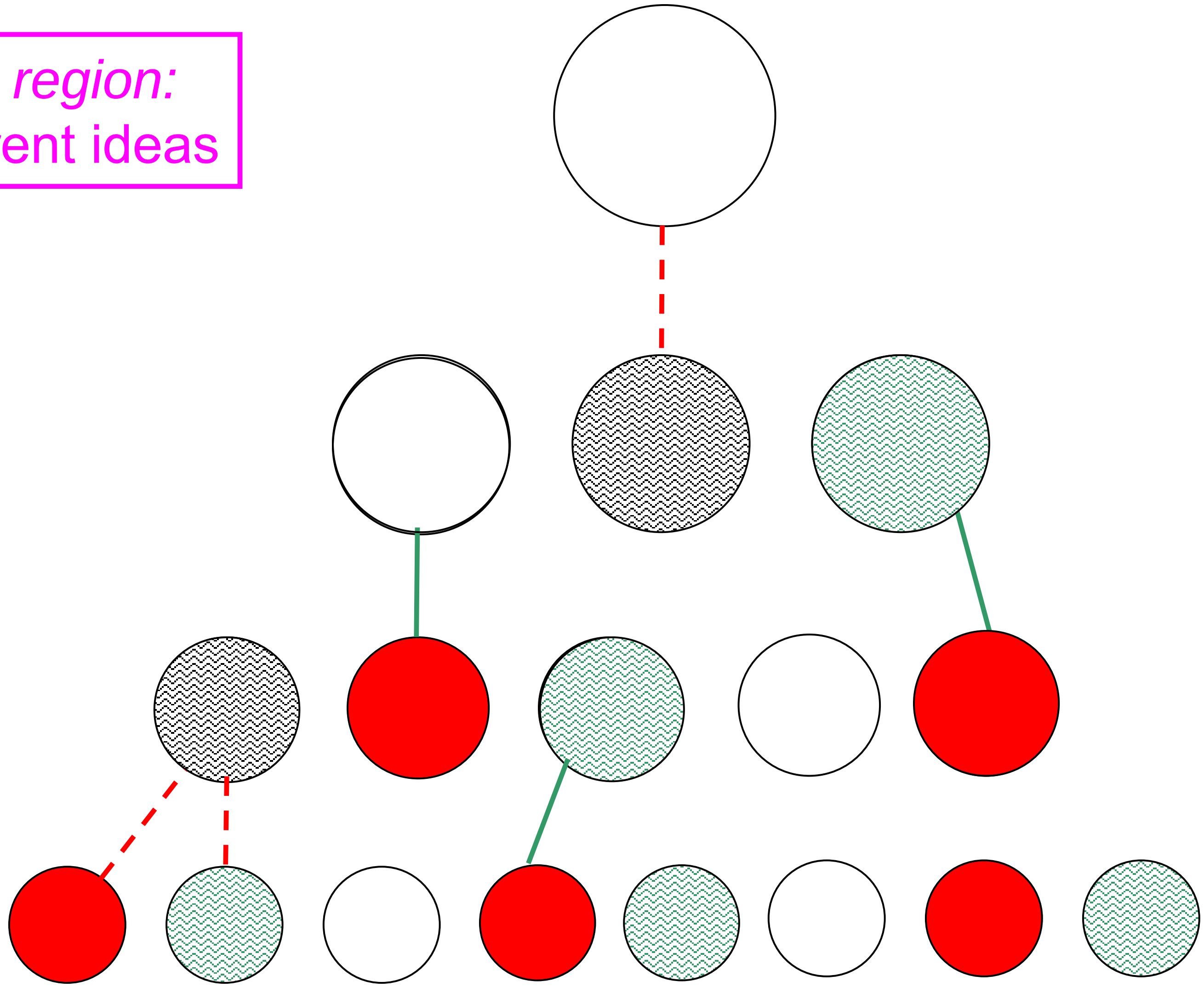


Diagram Coding

"Knowledge elements" (ovals) may represent:

- well-defined, stable concepts
- models "correct" within a certain context (e.g., particle model)
- simple naïve ideas or intuitive rules (e.g., "closer means stronger")
- "correct" but unstable and inconsistent ideas
- well-defined but incorrect ideas (e.g., $\mathbf{v} \propto \mathbf{F}$)
- vague, poorly defined notions

Diagram Coding

“Links” (lines) may represent:

- valid theoretical or empirical relationship ***with*** strong association, i.e.: high probability of one knowledge element being accompanied by the other

- invalid but strong association

- valid, but inconsistent or unreliable association

Teaching Effectiveness, Region by Region

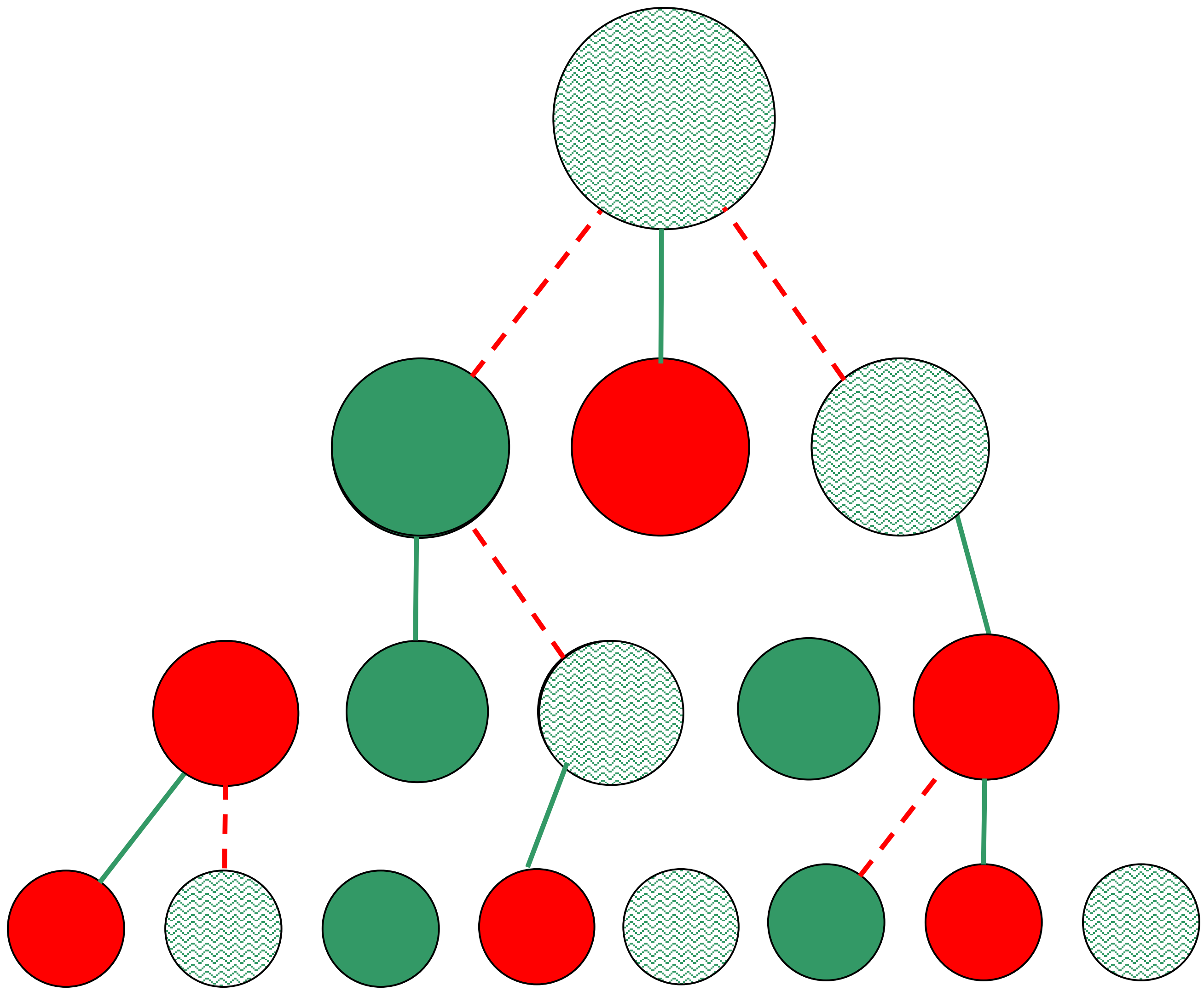
- *In central black region:* difficult to make significant relative gains
- *In white region:* learning gains minor, infrequent, and poorly retained.
- *Teaching most effective when targeted at gray:* Analogous to substance near phase transition; a few key concepts and links can catalyze substantial leaps in student understanding.

Teaching Effectiveness, Region by Region

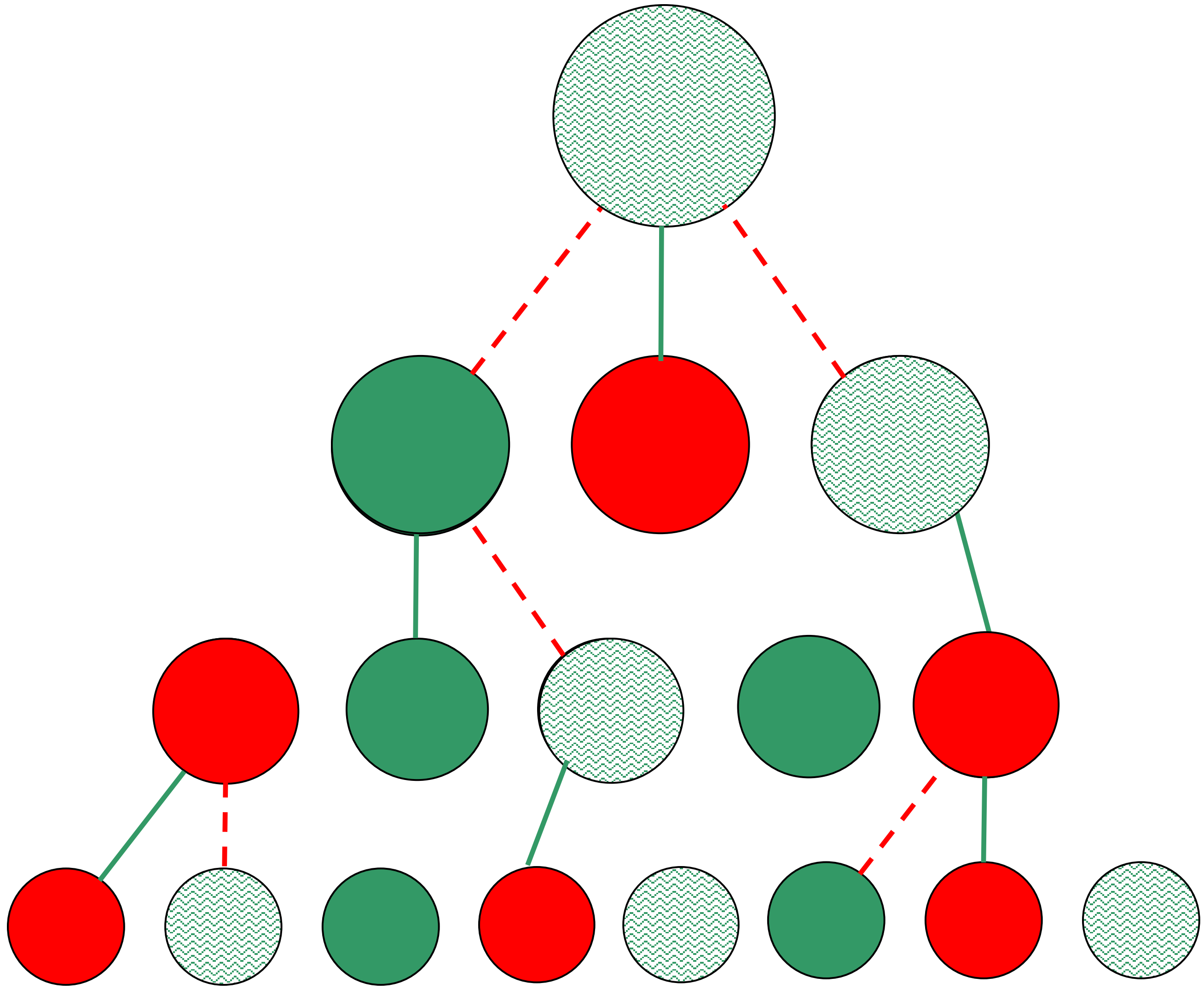
- *In central black region:* difficult to make significant relative gains

- *In white region:* learning gains minor, infrequent, and poorly retained.

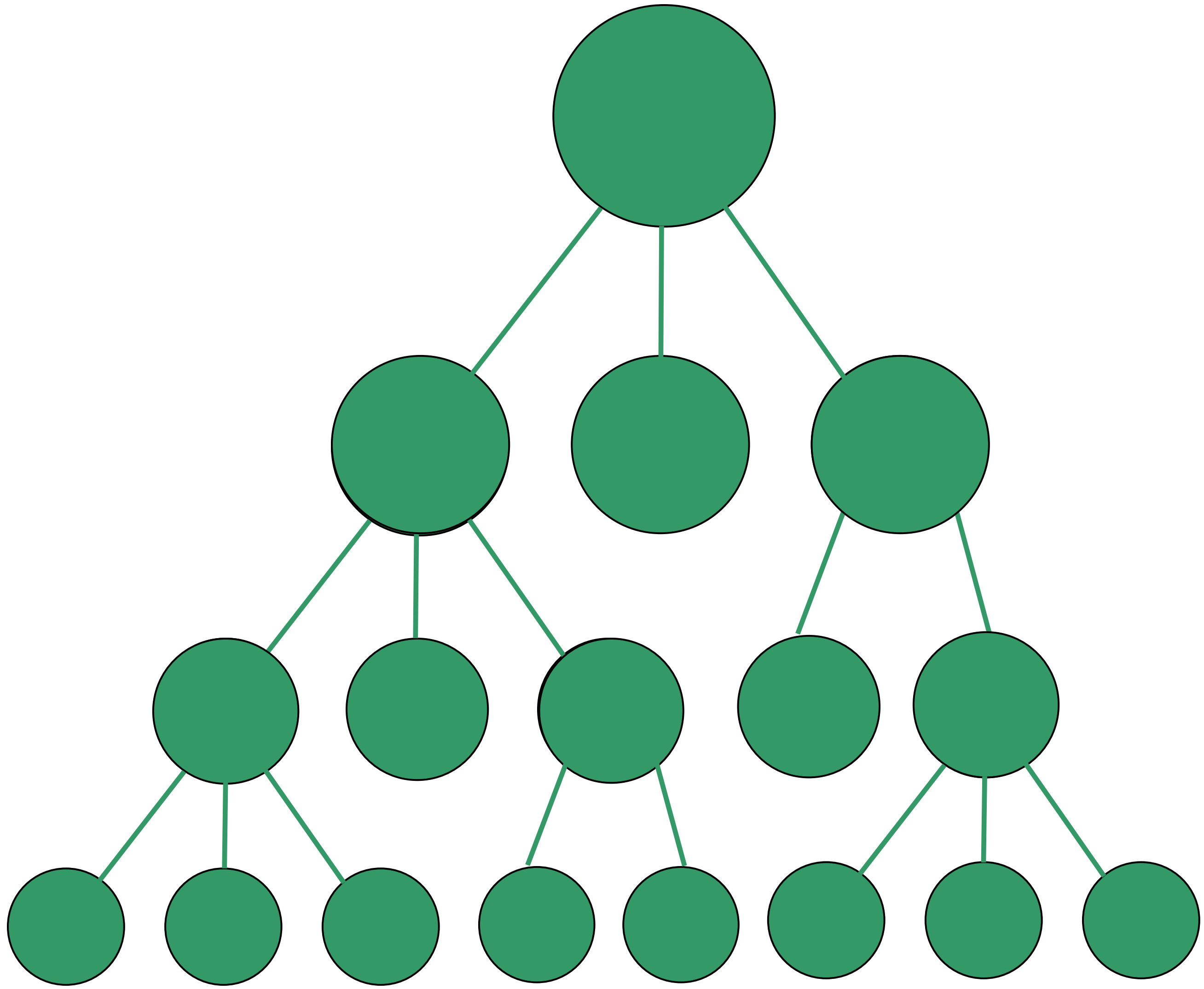
- *Teaching most effective when targeted at gray:* Analogous to substance near phase transition; a few key concepts and links can catalyze substantial leaps in student understanding.



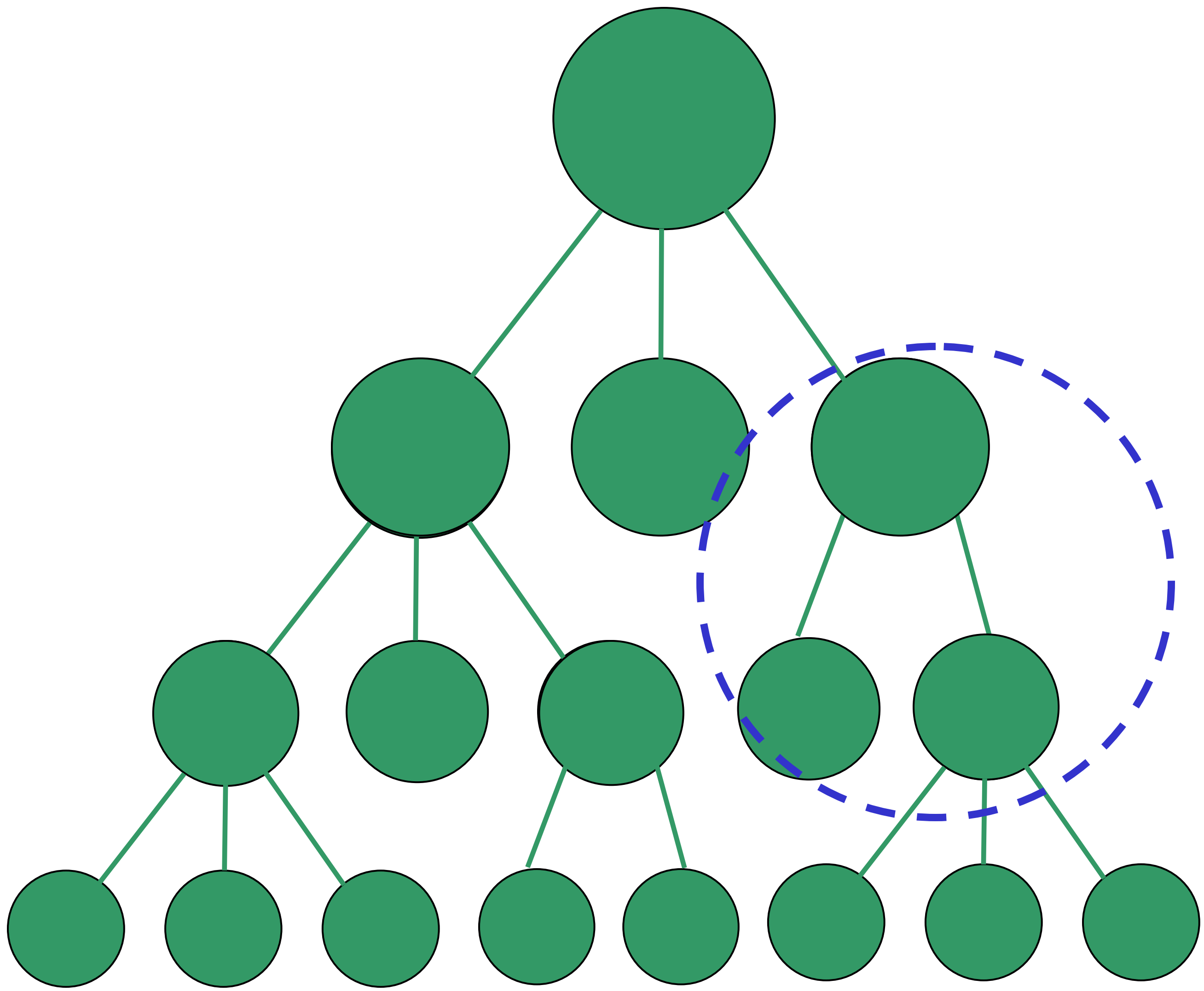
Research Task: map out gray region



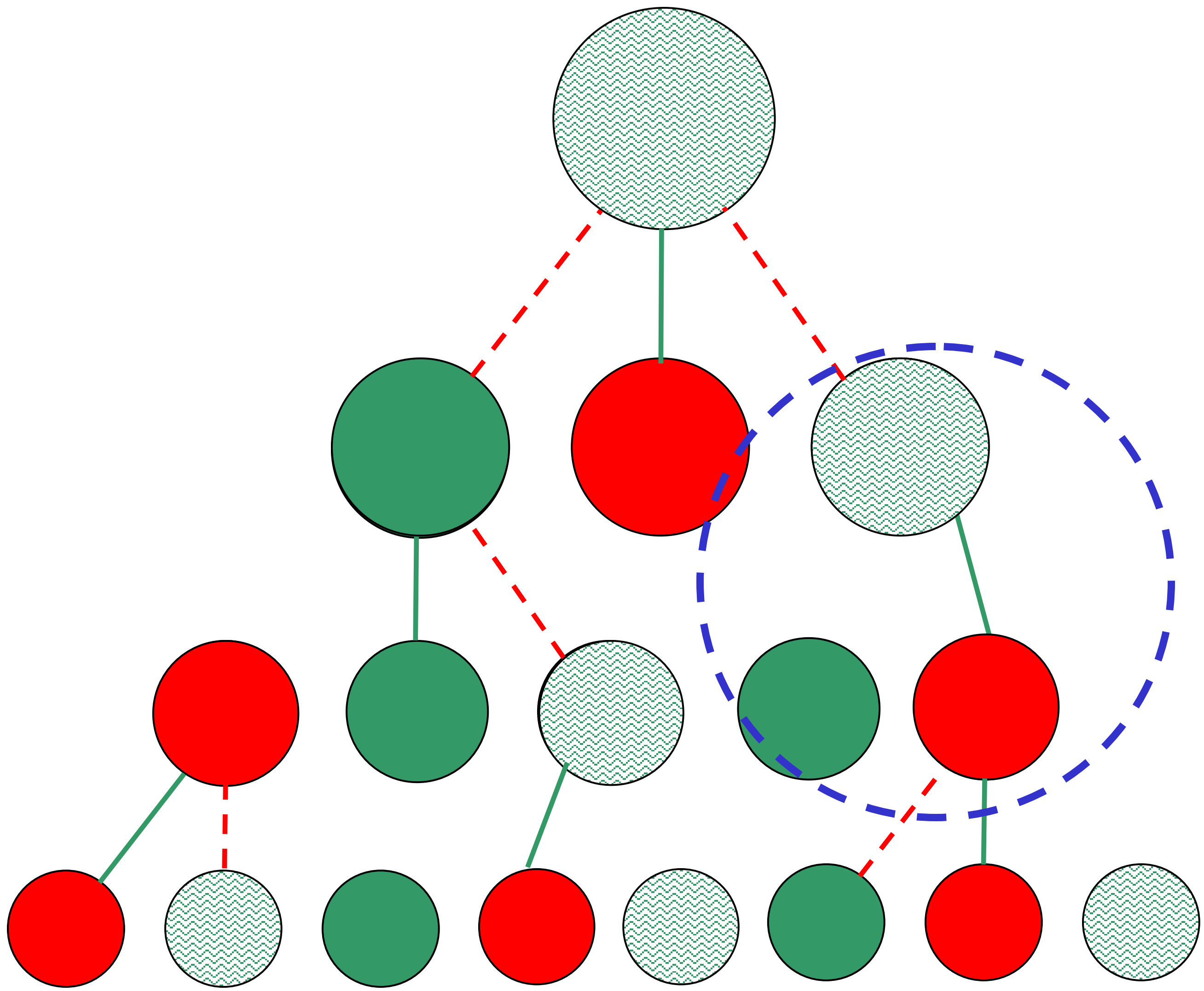
Instructional Task: address difficulties in gray region



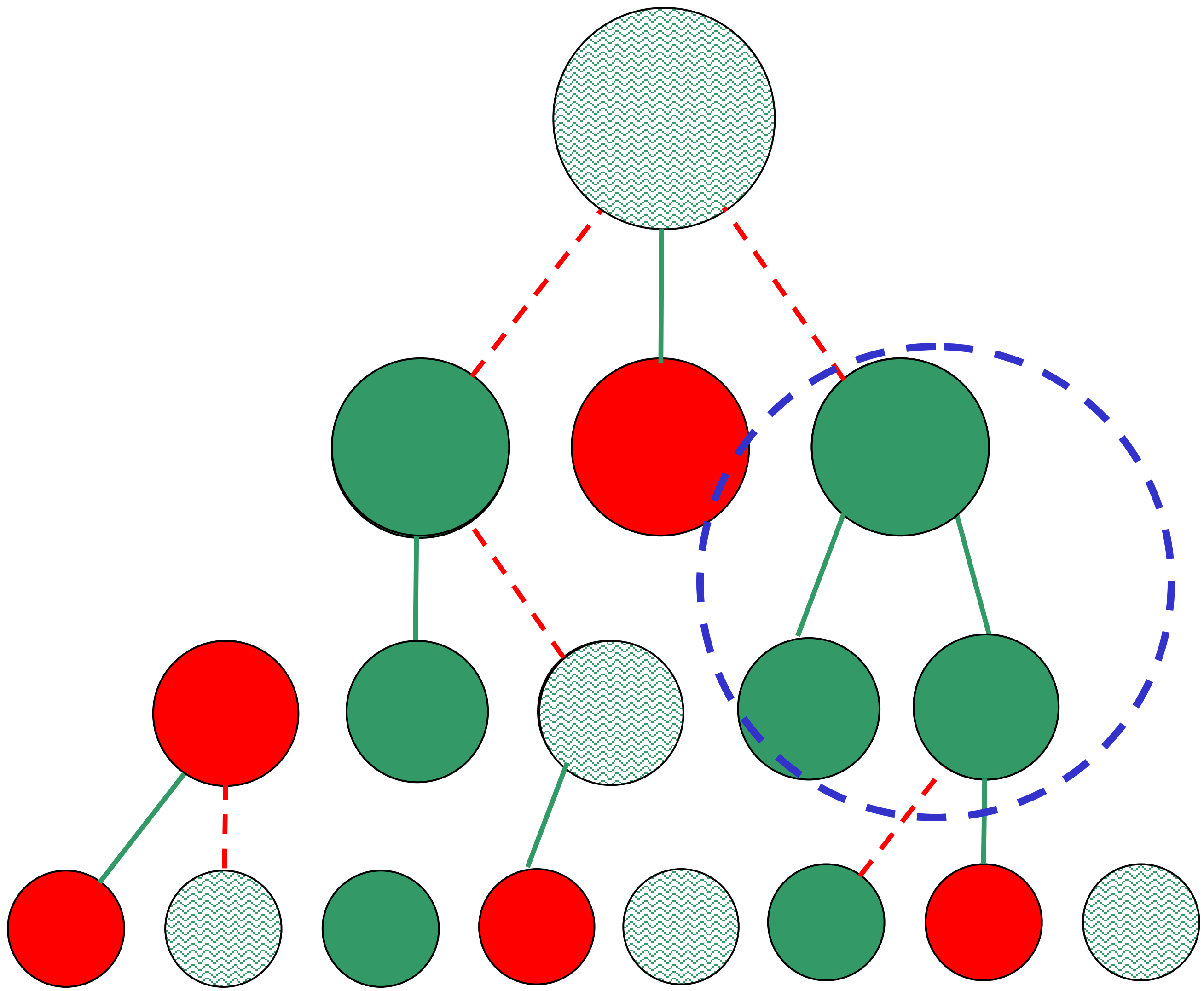
Instructional Goal: well-organized set of coherent concepts



Instructional Task #1: identify a target concept cluster



Research Task: probe targeted cluster



Instructional Task #2: address and resolve obstacles to learning

Some Empirical Examples

- Entropy and Second Law of Thermodynamics
  – from Ph.D. work of Warren Christensen
- Electric Fields and Forces

[Data from Iowa State University (ISU)]

Some Empirical Examples

- Entropy and Second Law of Thermodynamics
  - from Ph.D. work of Warren Christensen

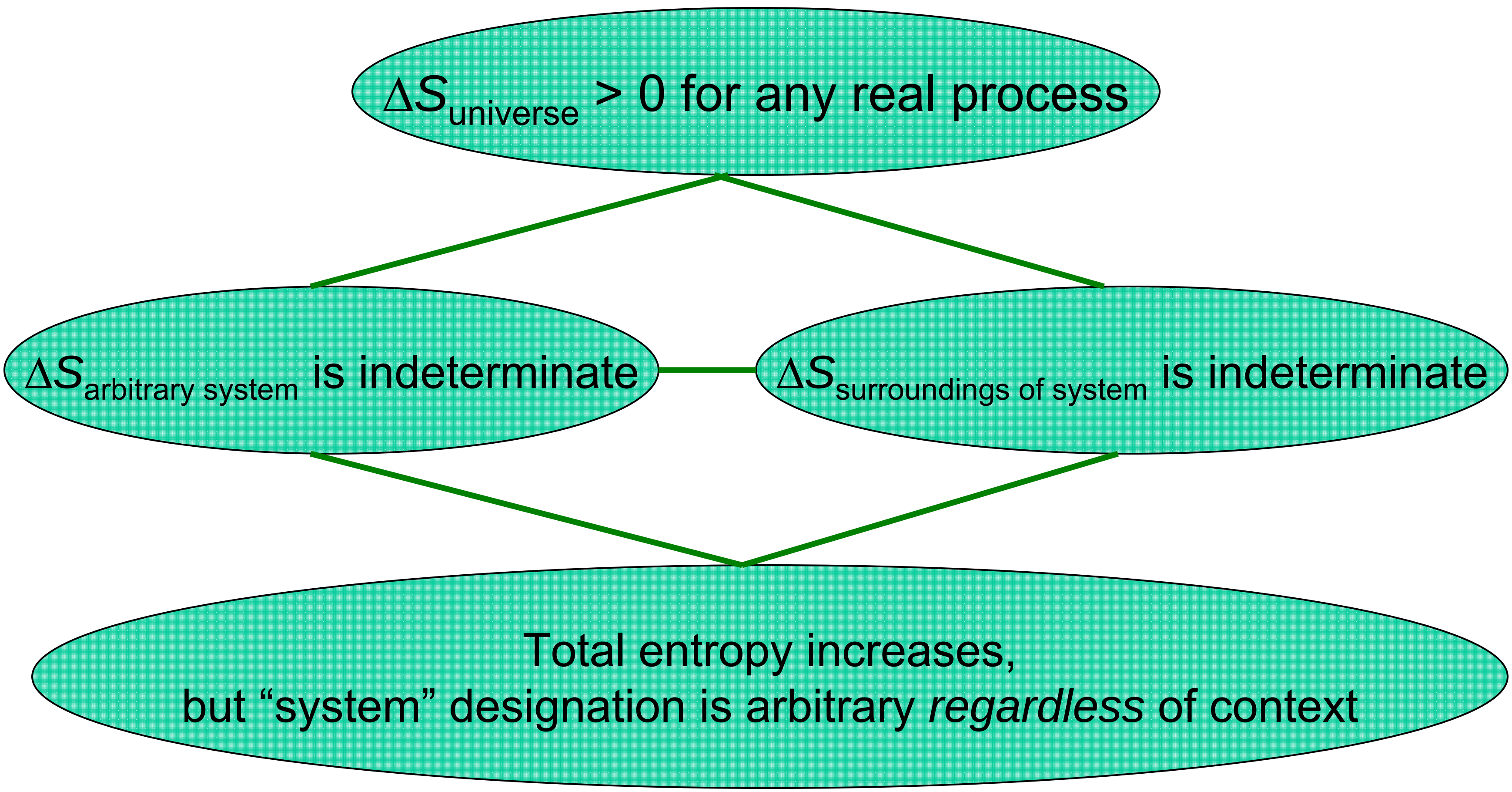
- Electric Fields and Forces

Some Empirical Examples

- Entropy and Second Law of Thermodynamics
  – from Ph.D. work of Warren Christensen

- Electric Fields and Forces

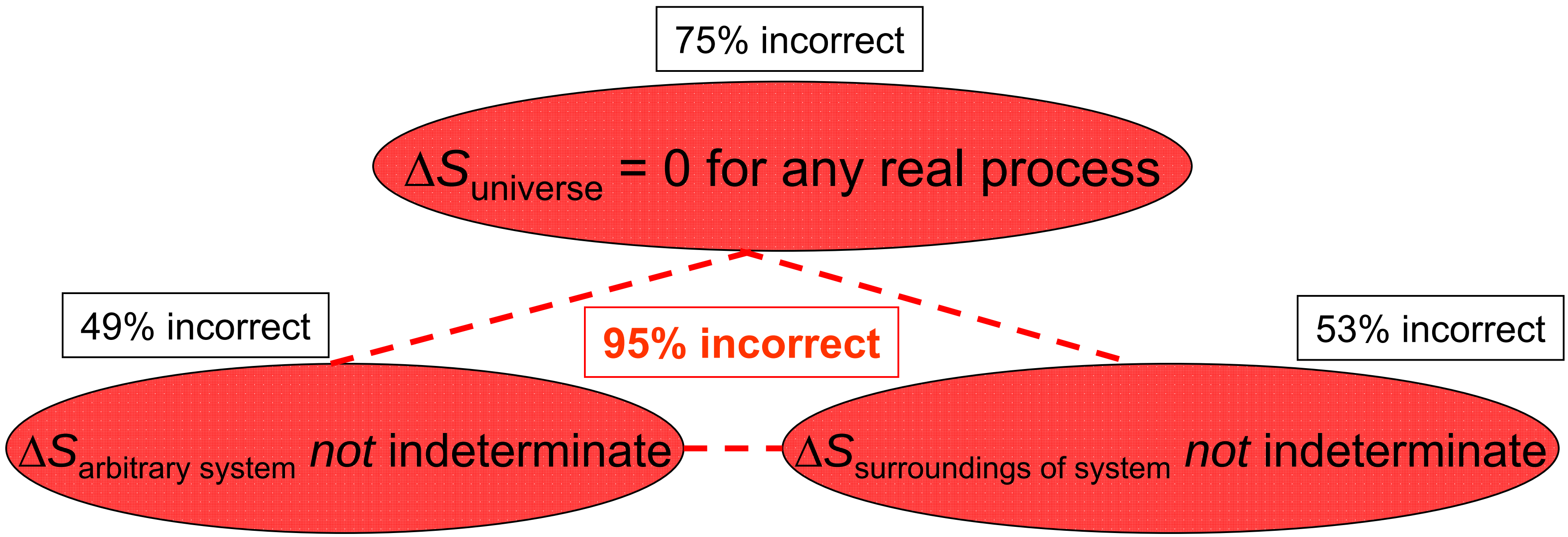
Entropy-Increase Concept Cluster



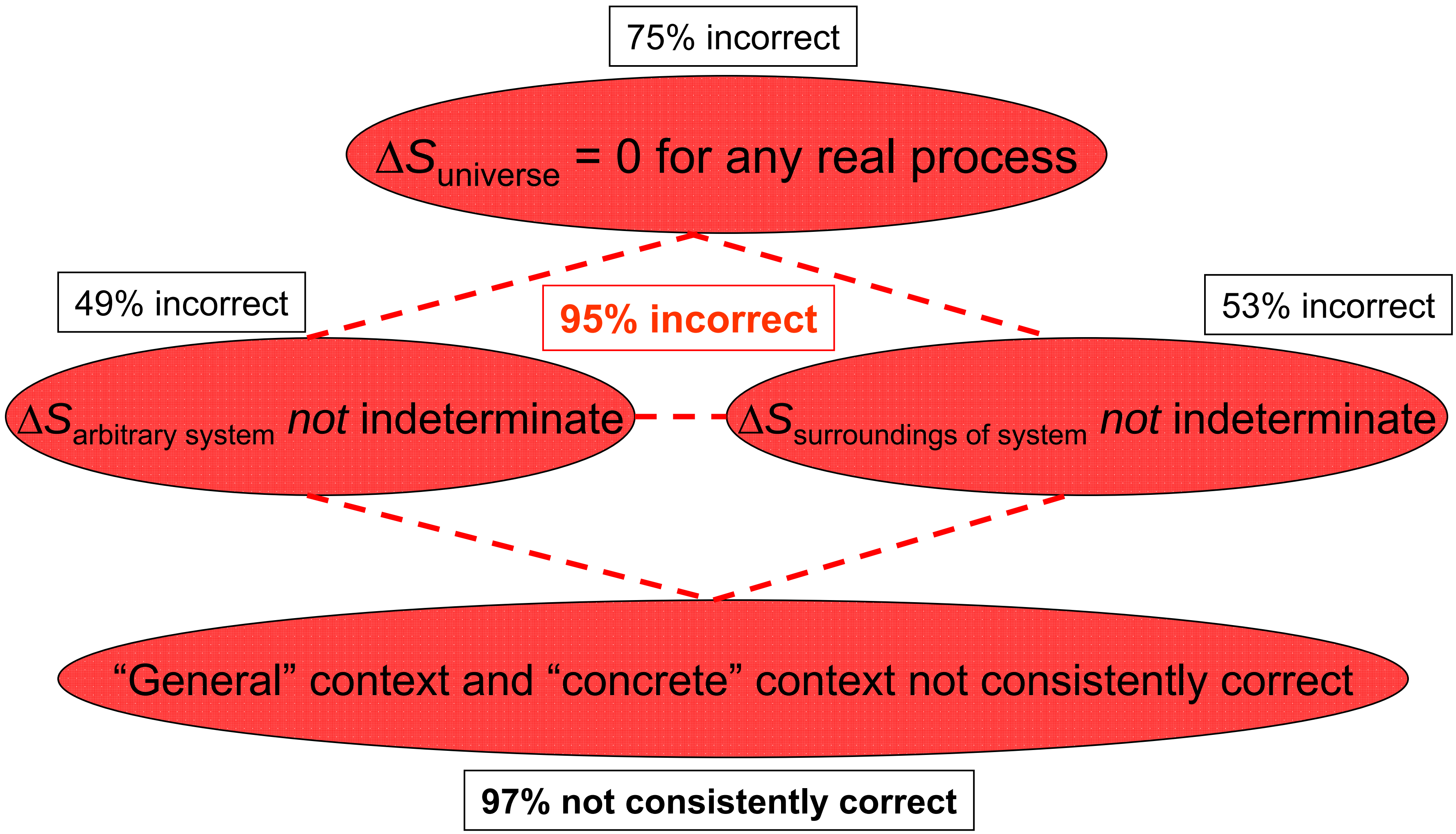
Entropy-Increase Concept Cluster

$\Delta S_{universe} > 0$ for any real process

Pre-Instruction Structure



Pre-Instruction Structure



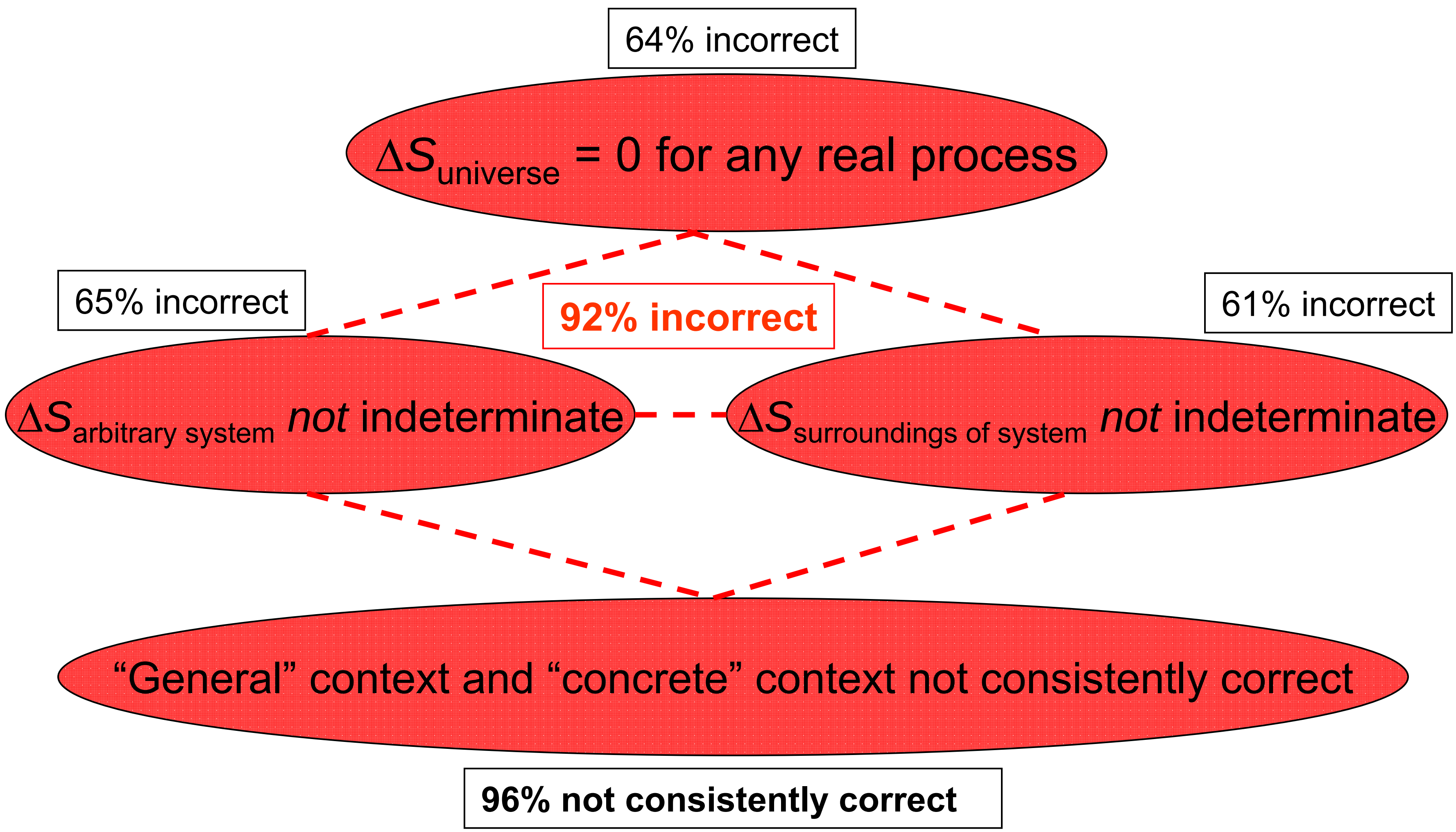
Pre-Instruction Structure

75% incorrect

$\Delta S_{universe}$ = 0 for any real process

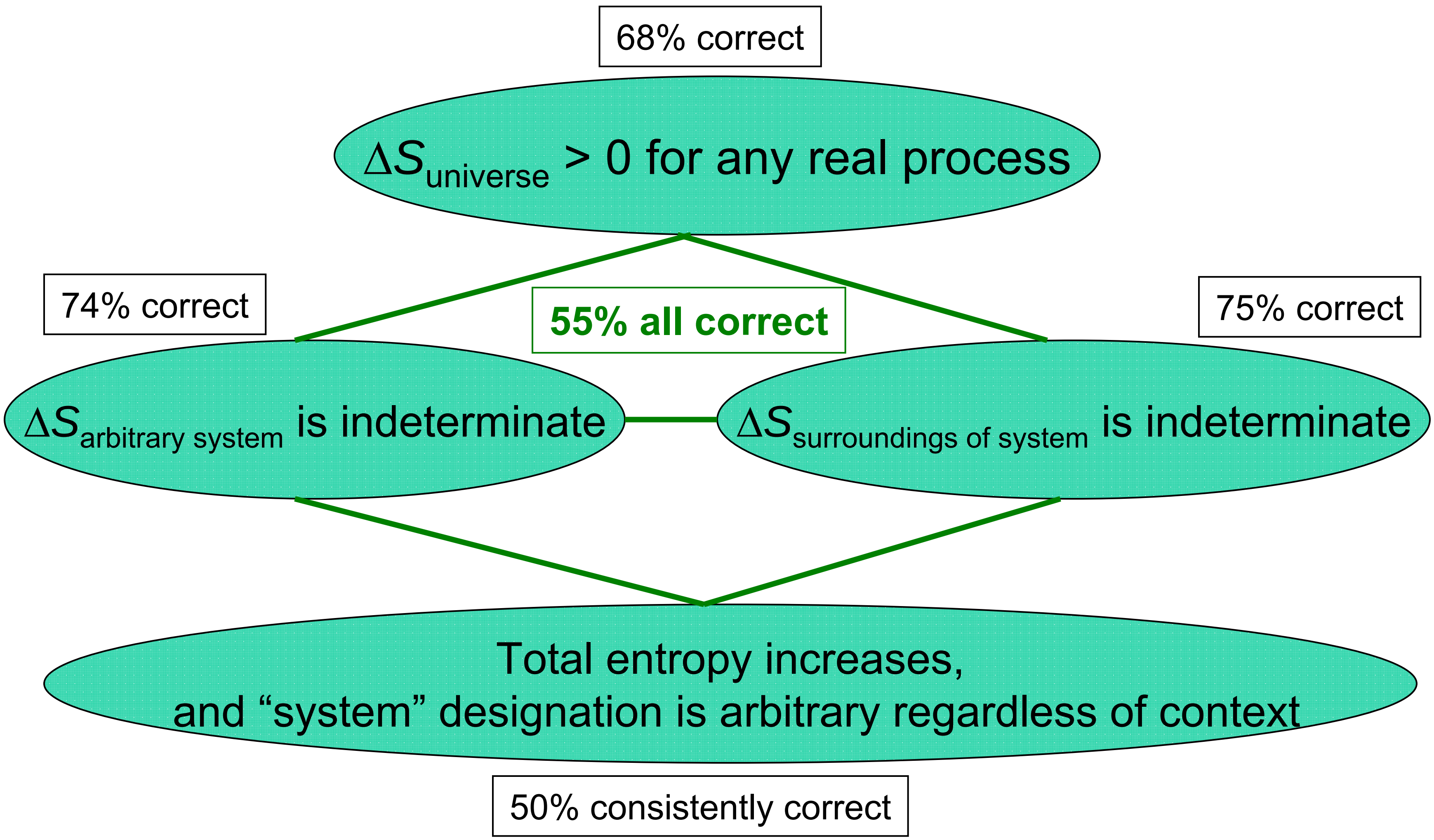
Post-Instruction

[no special instruction]



Post-Instruction, With Research-Based Tutorial

["Two-Blocks" Tutorial]



Investigating Students' Reasoning Through Detailed Analysis of Response Patterns

- Pattern of multiple-choice responses may offer evidence about students' mental models.
  - R. J. Dufresne, W. J. Leonard, and W. J. Gerace, 2002.
  - L. Bao, K. Hogg, and D. Zollman, "Model Analysis," 2002.

- Time-dependence of response pattern may give insight into evolution of students' thinking.
  - R. Thornton, "Conceptual Dynamics," 1997
  - D. Dykstra, "Essentialist Kinematics," 2001
  - L. Bao and E. F. Redish, "Concentration Analysis," 2001

Students’ Understanding of Representations in Electricity and Magnetism

- Analysis of responses to multiple-choice diagnostic test “Conceptual Survey in Electricity and Magnetism” (Maloney, O’Kuma, Hieggelke, and Van Heuvelen, 2001)
- Administered 1998-2001 in algebra-based physics course at Iowa State [interactive-engagement instruction] (*N* = 299; matched sample)
- Additional data from students’ written explanations of their reasoning (2002, unmatched sample: pre-instruction, *N* = 72; post-instruction, *N* = 66)

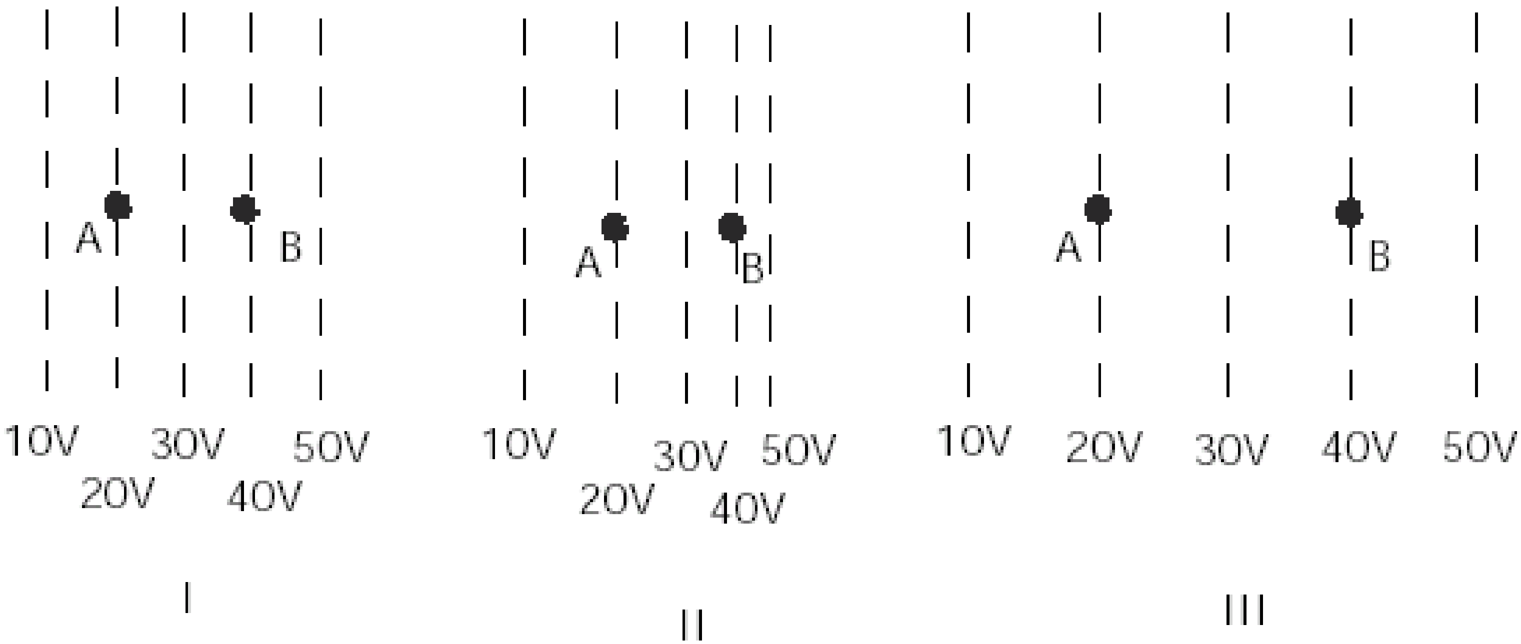
Characterization of Students' Background and Understanding

- Only about one third of students have had any previous exposure to electricity and/or magnetism concepts.
- *Pre-Instruction*: Responses to questions range from clear and acceptable explanations to uncategorizable outright guesses.
- *Post-Instruction*: Most explanations fall into fairly well-defined categories.

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

#18

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.

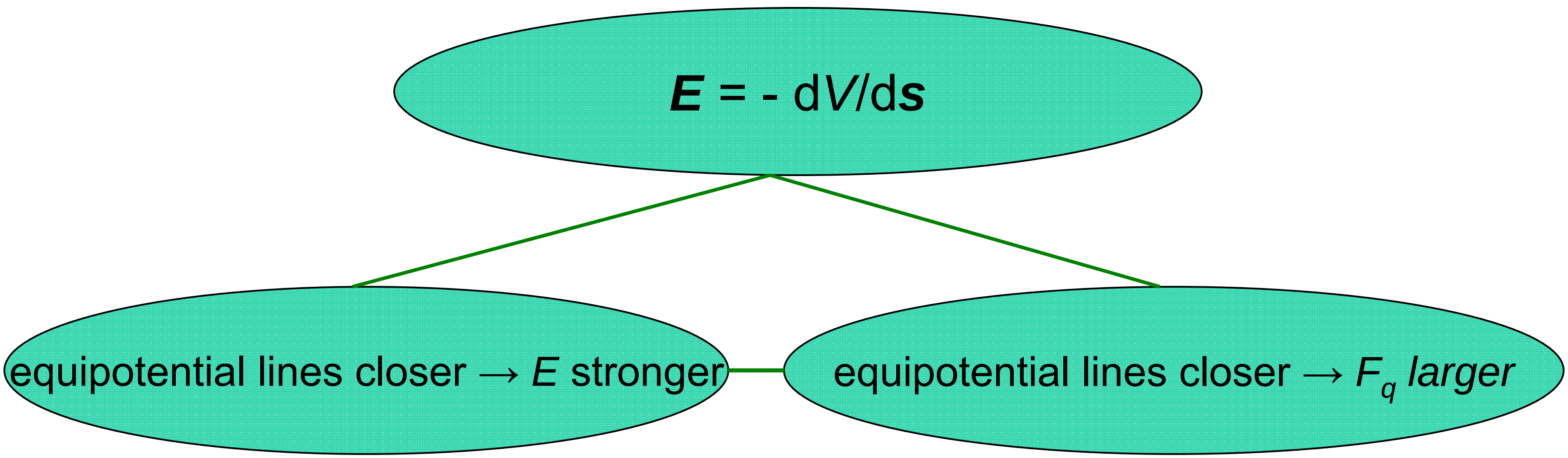


How does the magnitude of the electric field at B compare for these three cases?

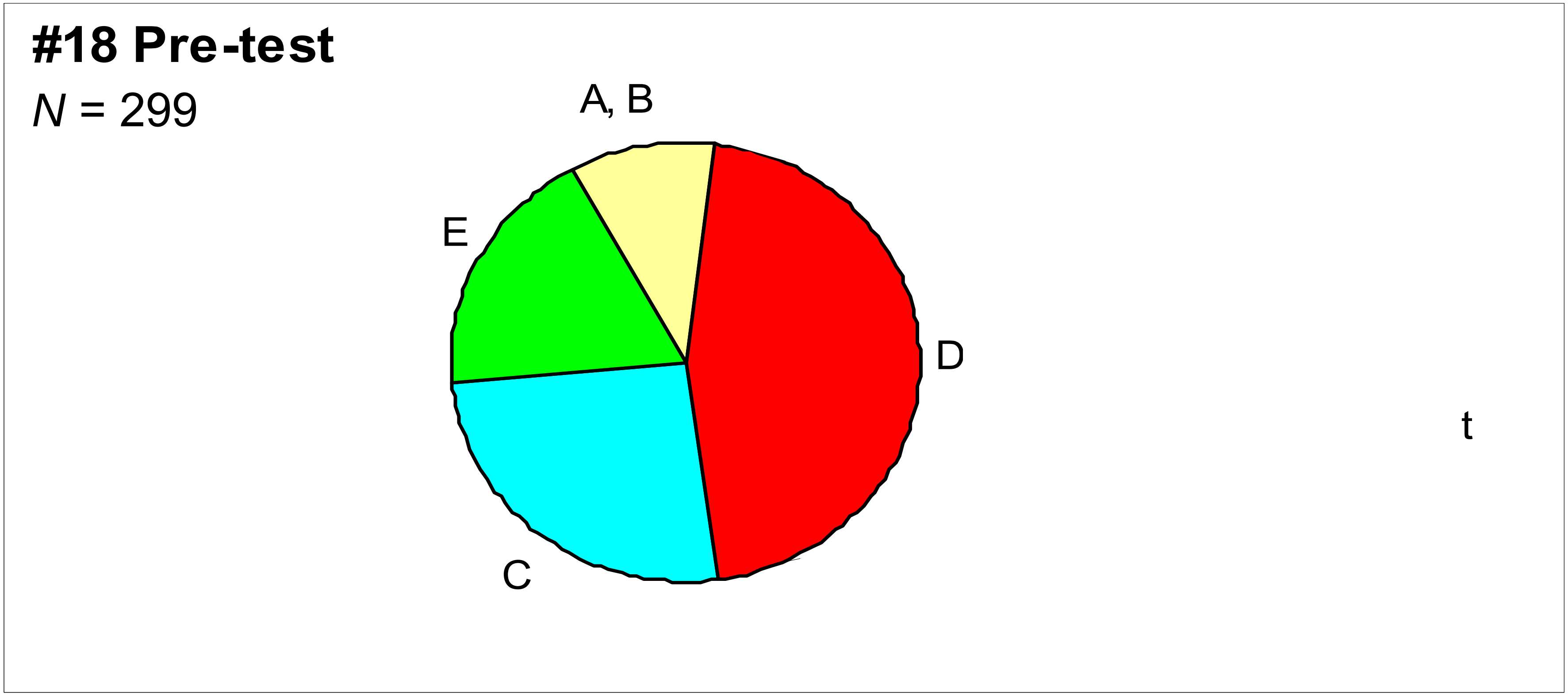
(a) I > III > II
(b) I > II > III
(c) III > I > II
(d) II > I > III **[correct]**
(e) I = II = III

closer spacing of equipotential lines ⇒ larger magnitude field

Electric Potential/Field Concept Cluster



Pre-Instruction



"D": *closer spacing of equipotential lines ⇒ stronger field*

[correct]

Correct Answer, Incorrect Reasoning

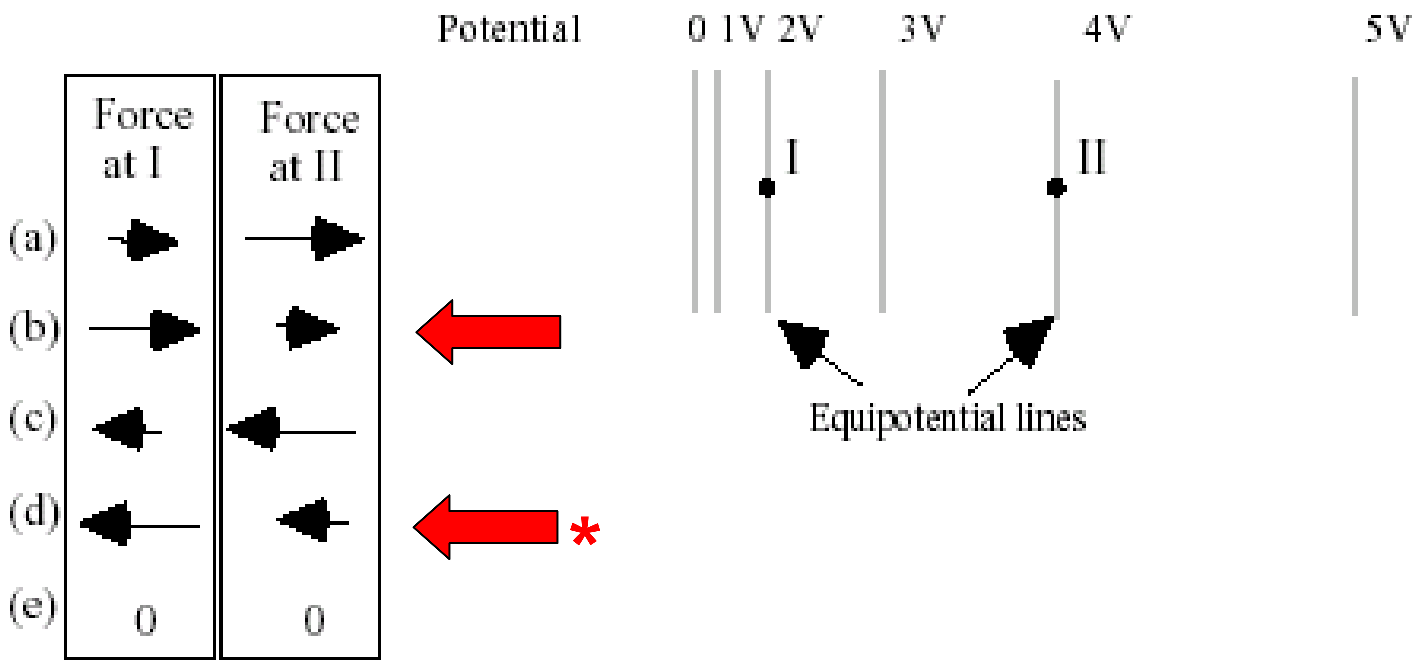
- Nearly half of pre-instruction responses are correct, despite the fact that most students say they have not studied this topic

- Explanations offered include:
  - “chose them in the order of closest lines”
  - “magnitude decreases with increasing distance”
  - “greatest because 50 [V] is so close”
  - “more force where fields are closest”
  - “because charges are closer together”
  - “guessed”

students’ initial “intuitions” may influence their learning

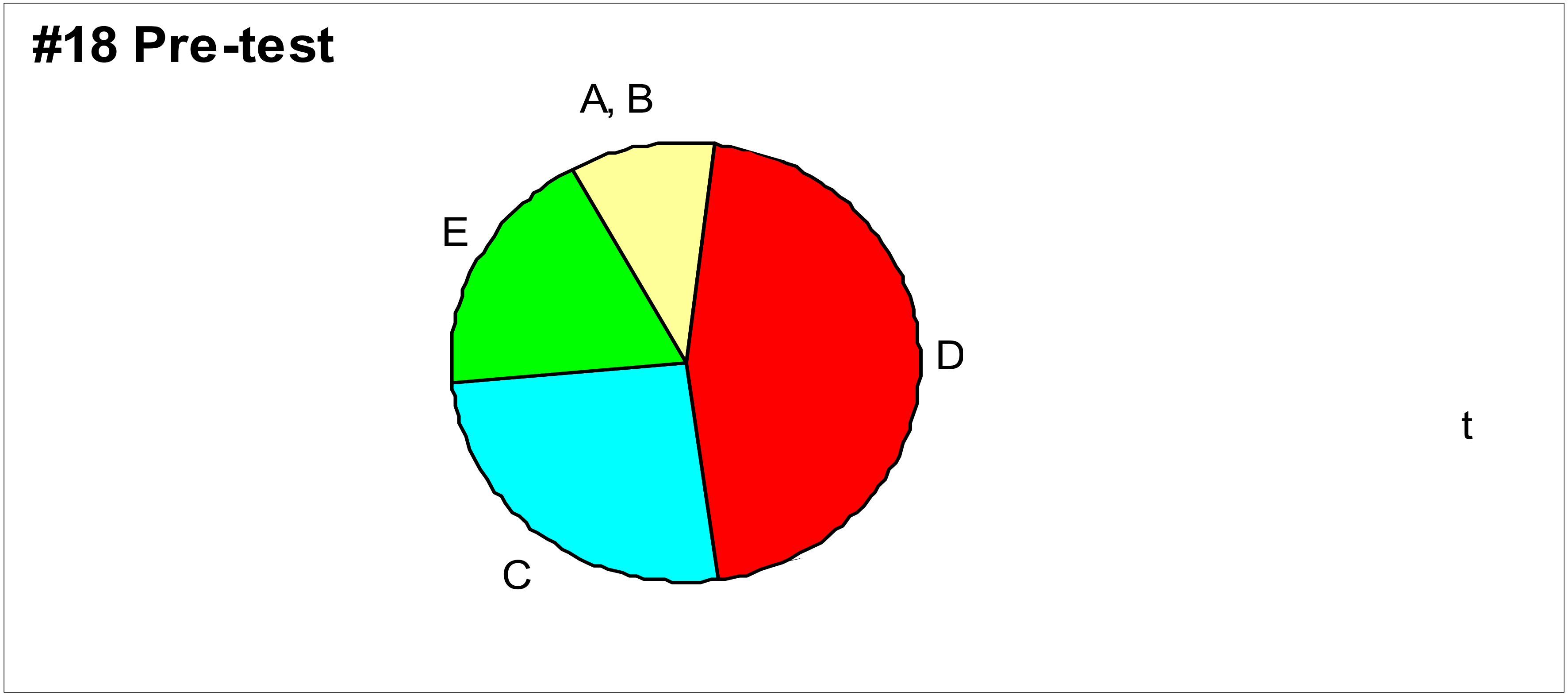
#20

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?



(b) or (d) consistent with correct answer on #18

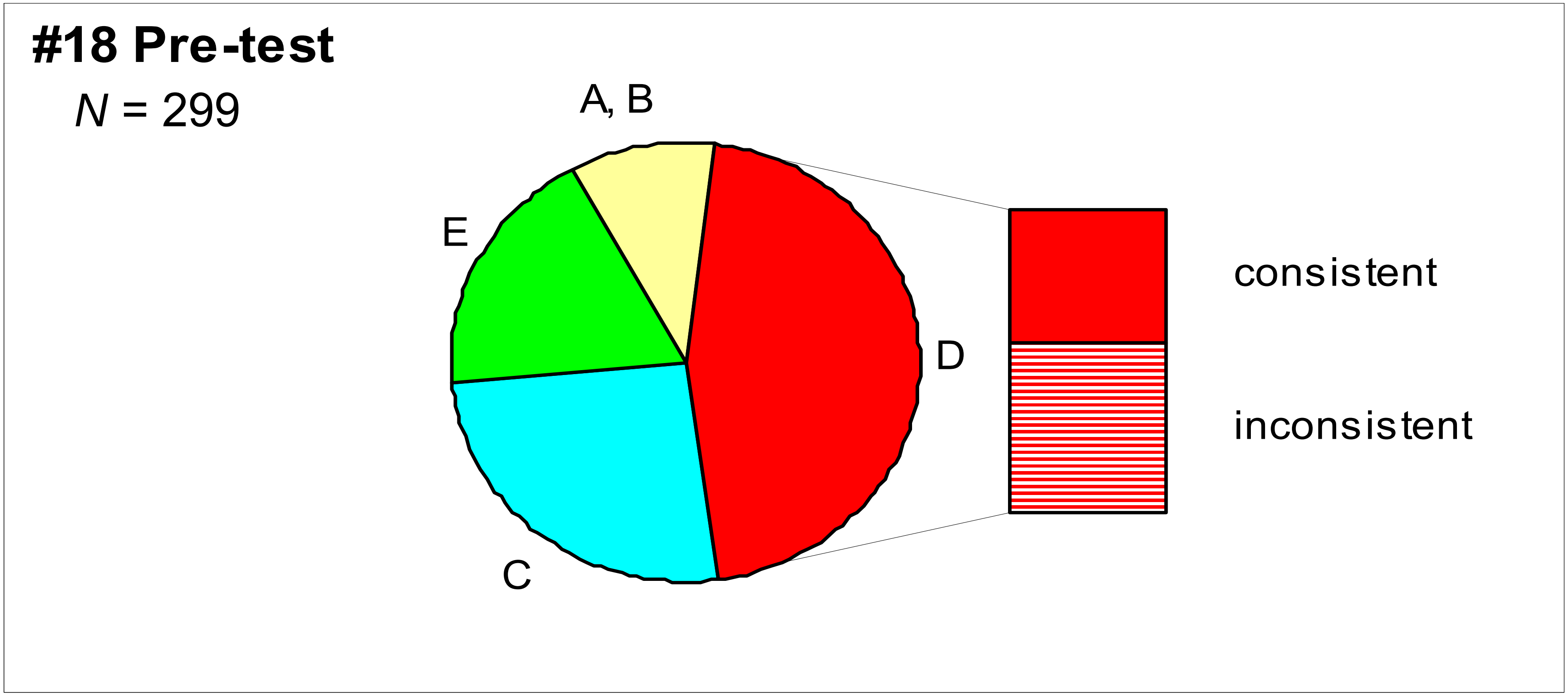
Pre-Instruction



"D": *closer spacing of equipotential lines ⇒ stronger field*

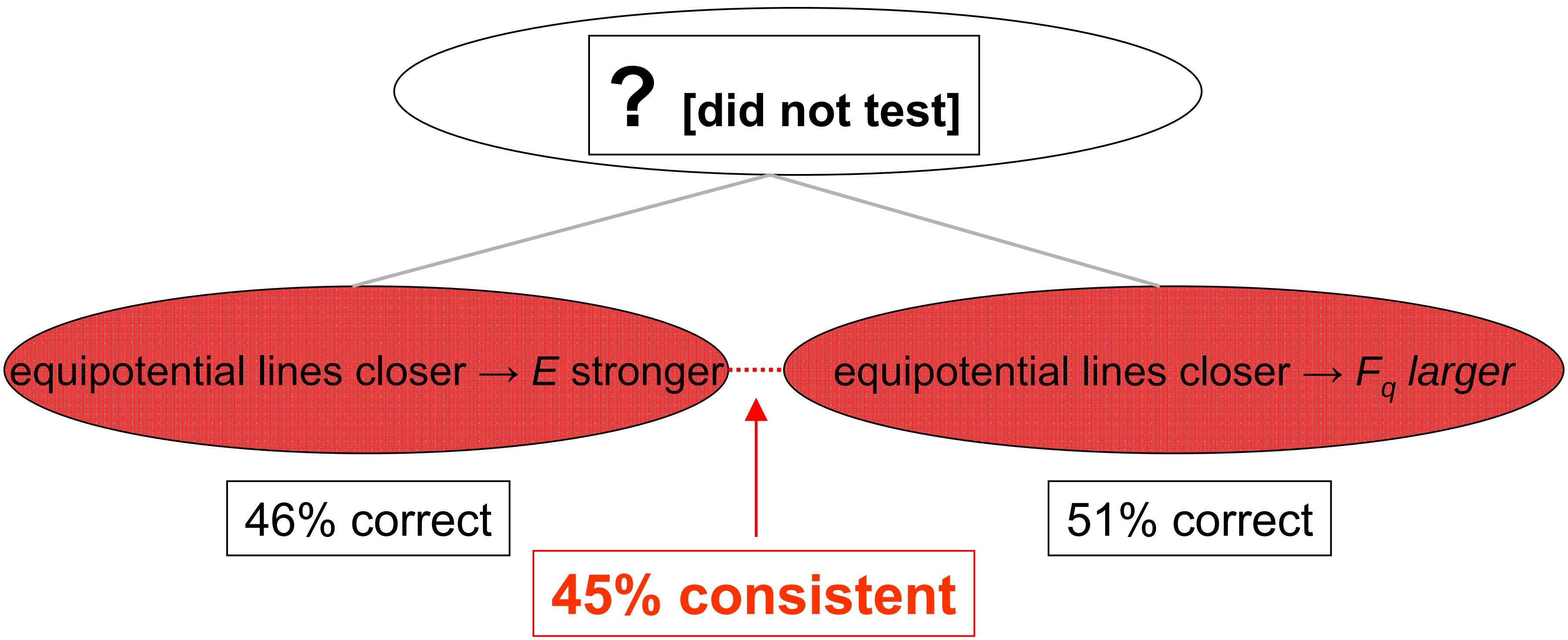
[correct]

Pre-Instruction

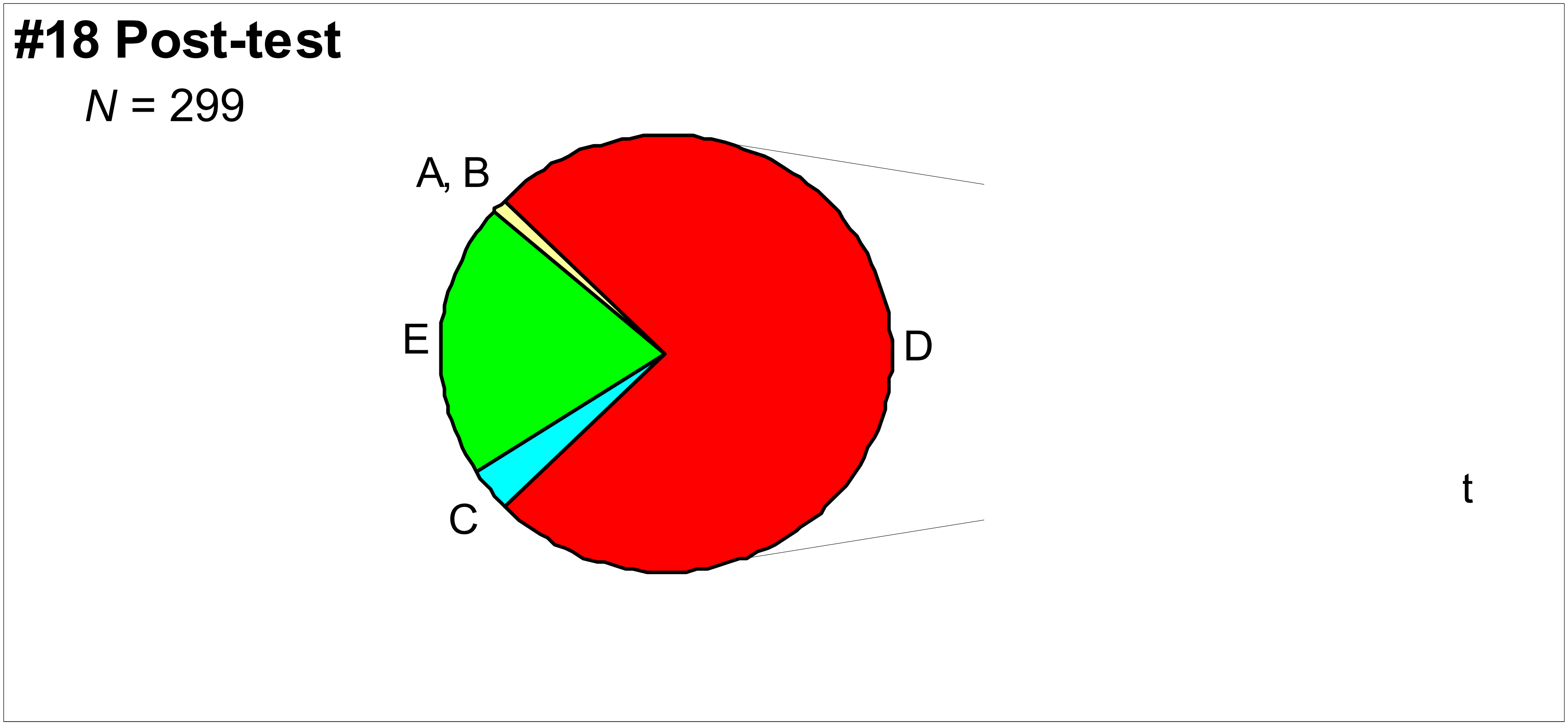


“consistent”: *consistent with answer on #20* *(but some guesses)*

Pre-Instruction, ISU (1998-2001)

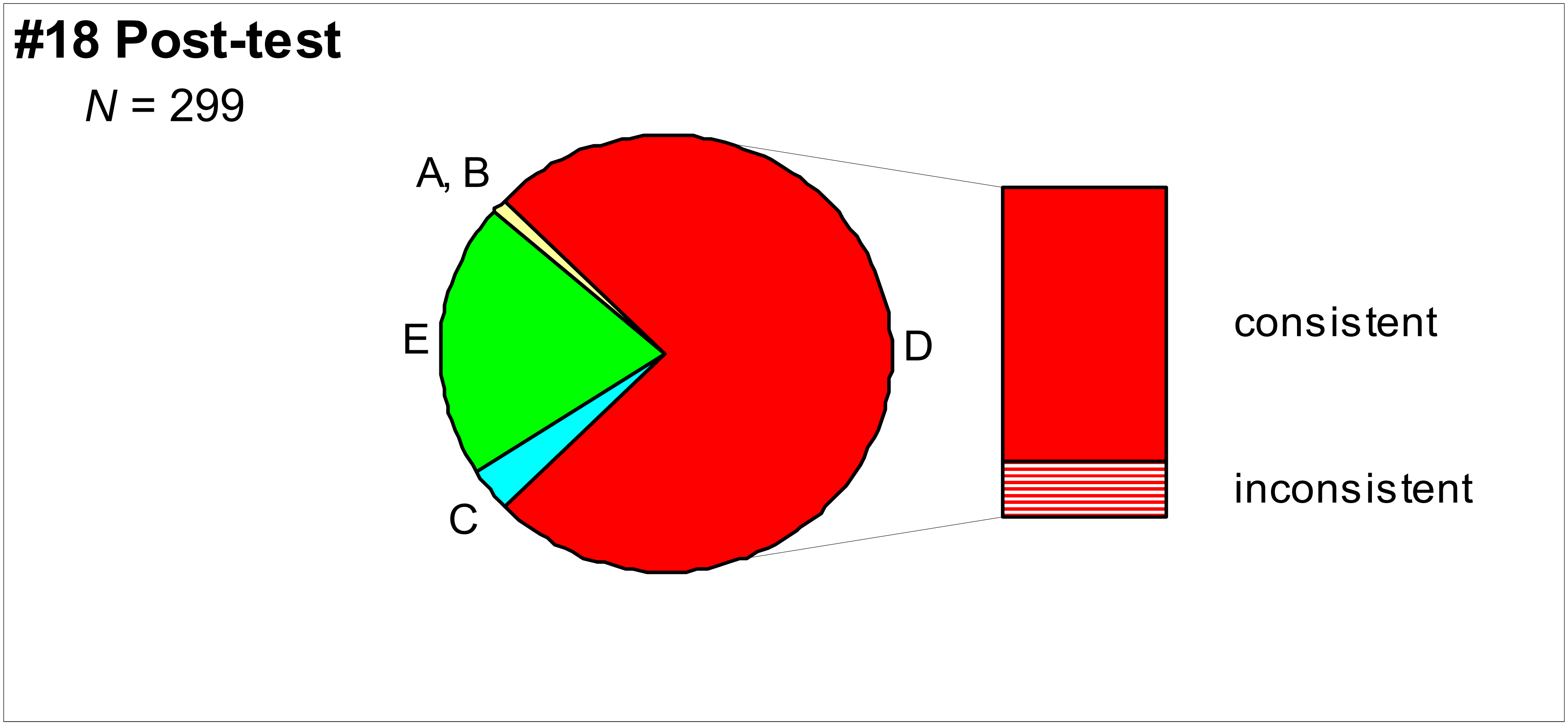


Post-Instruction



- **Sharp increase in correct responses**

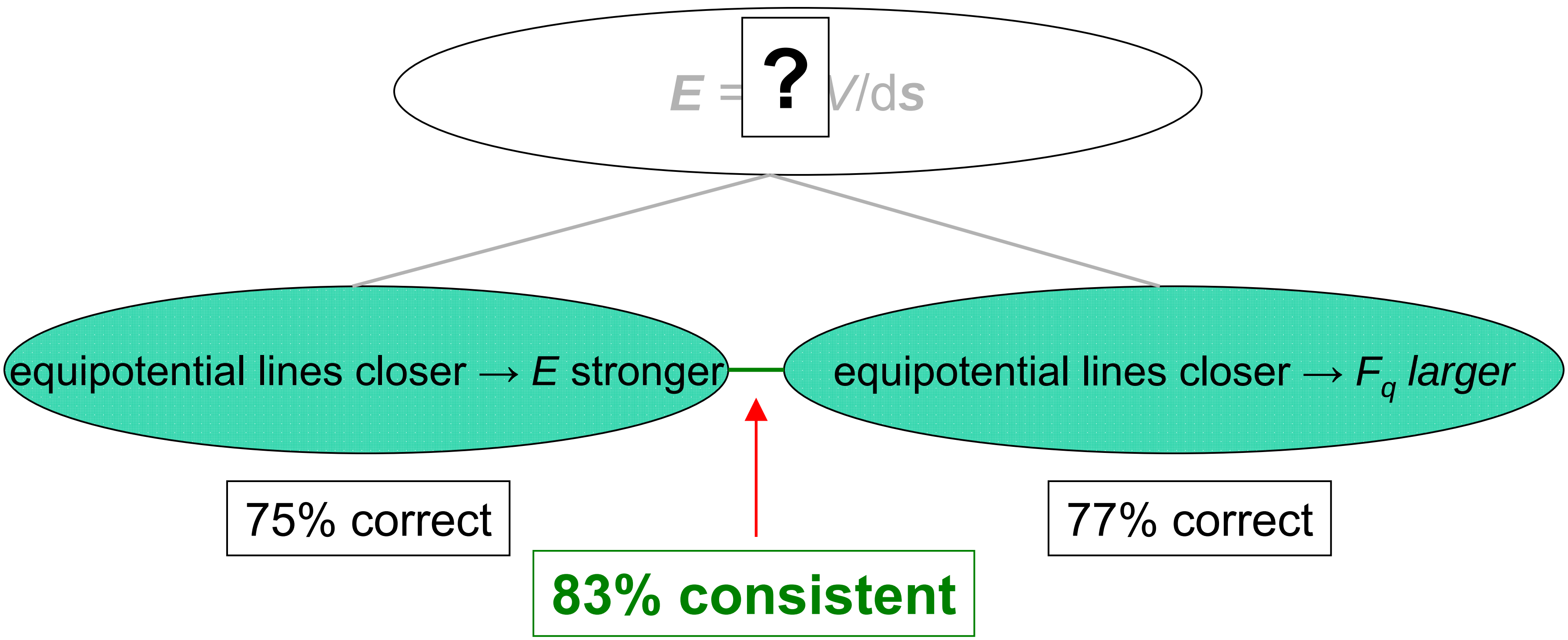
Post-Instruction



- **Correct responses *more consistent* with other answers**

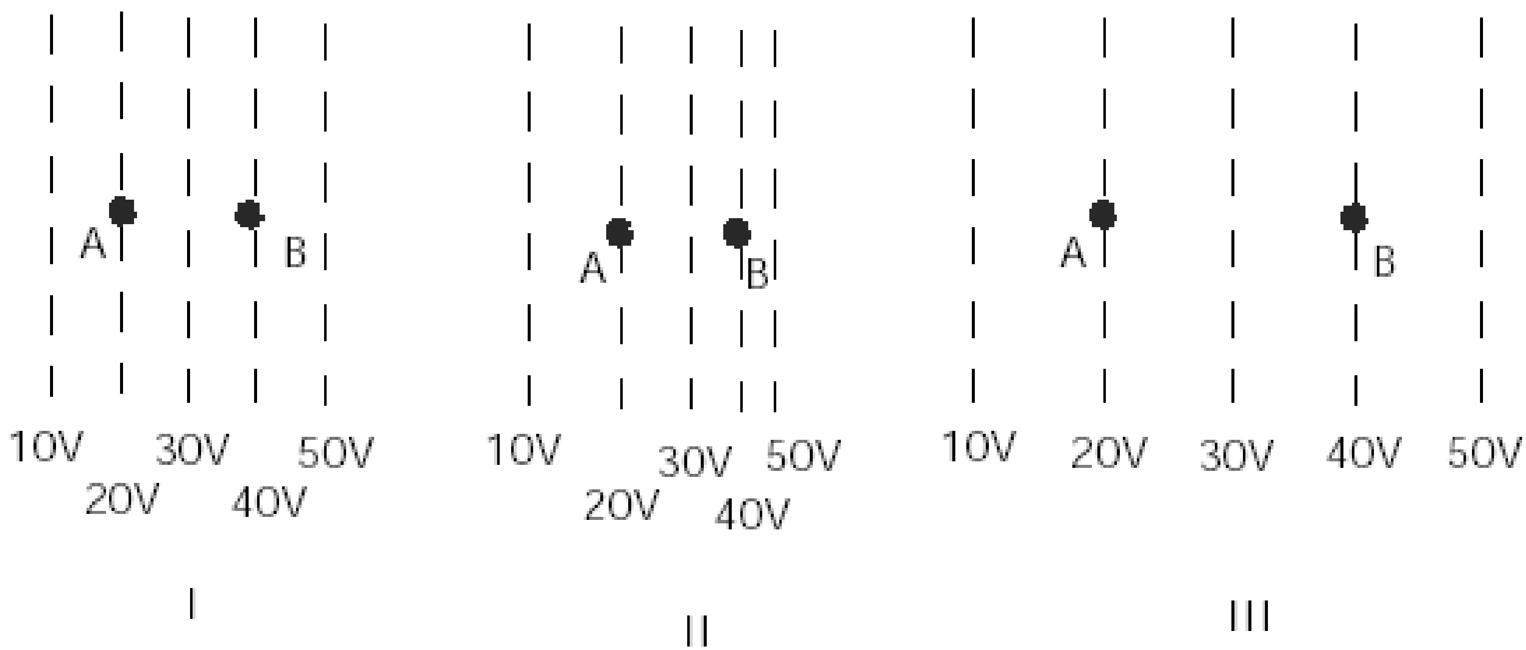
(and most explanations actually are consistent)

Post-Instruction, ISU (1998-2001)



#18

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.

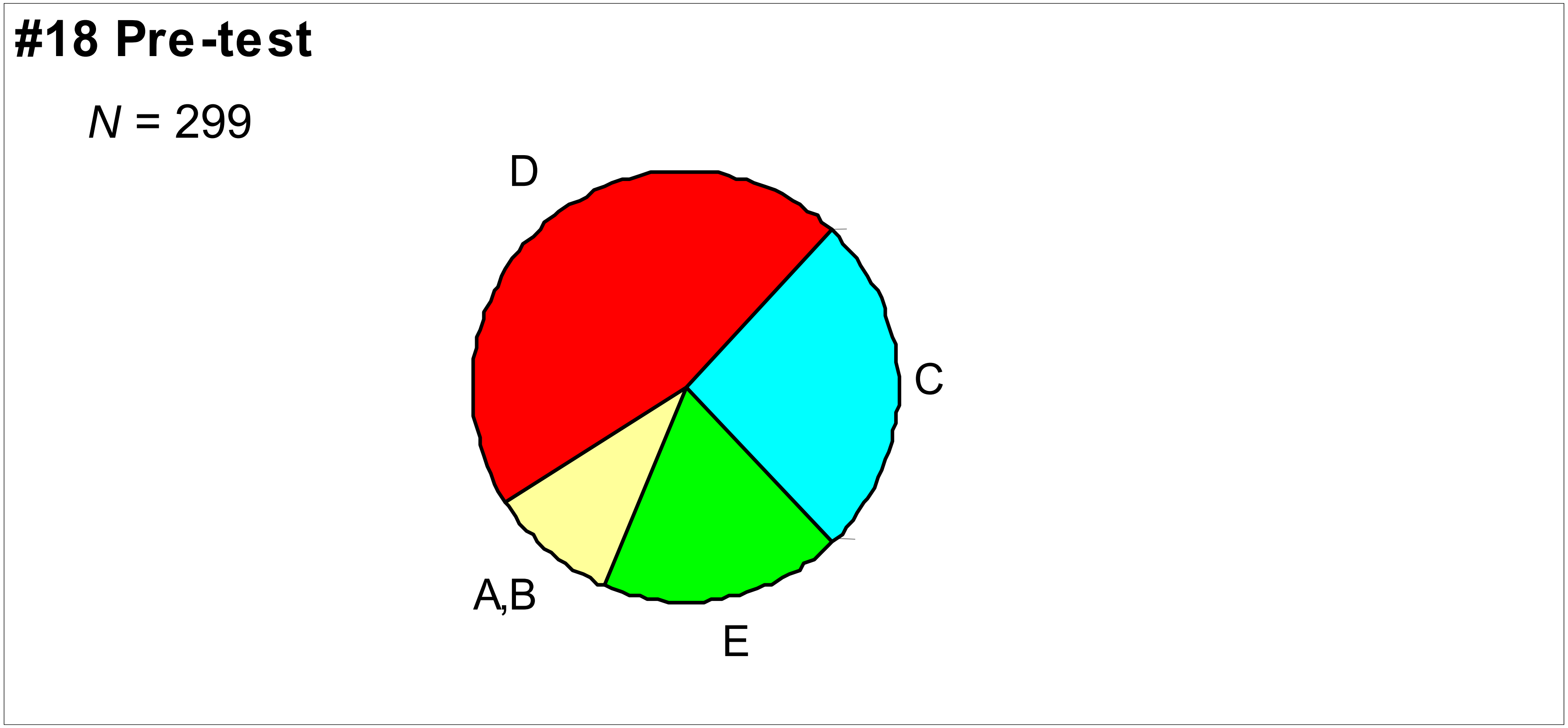


How does the magnitude of the electric field at B compare for these three cases?

(a) I > III > II
(b) I > II > III
(c) III > I > II
(d) II > I > III
(e) I = II = III

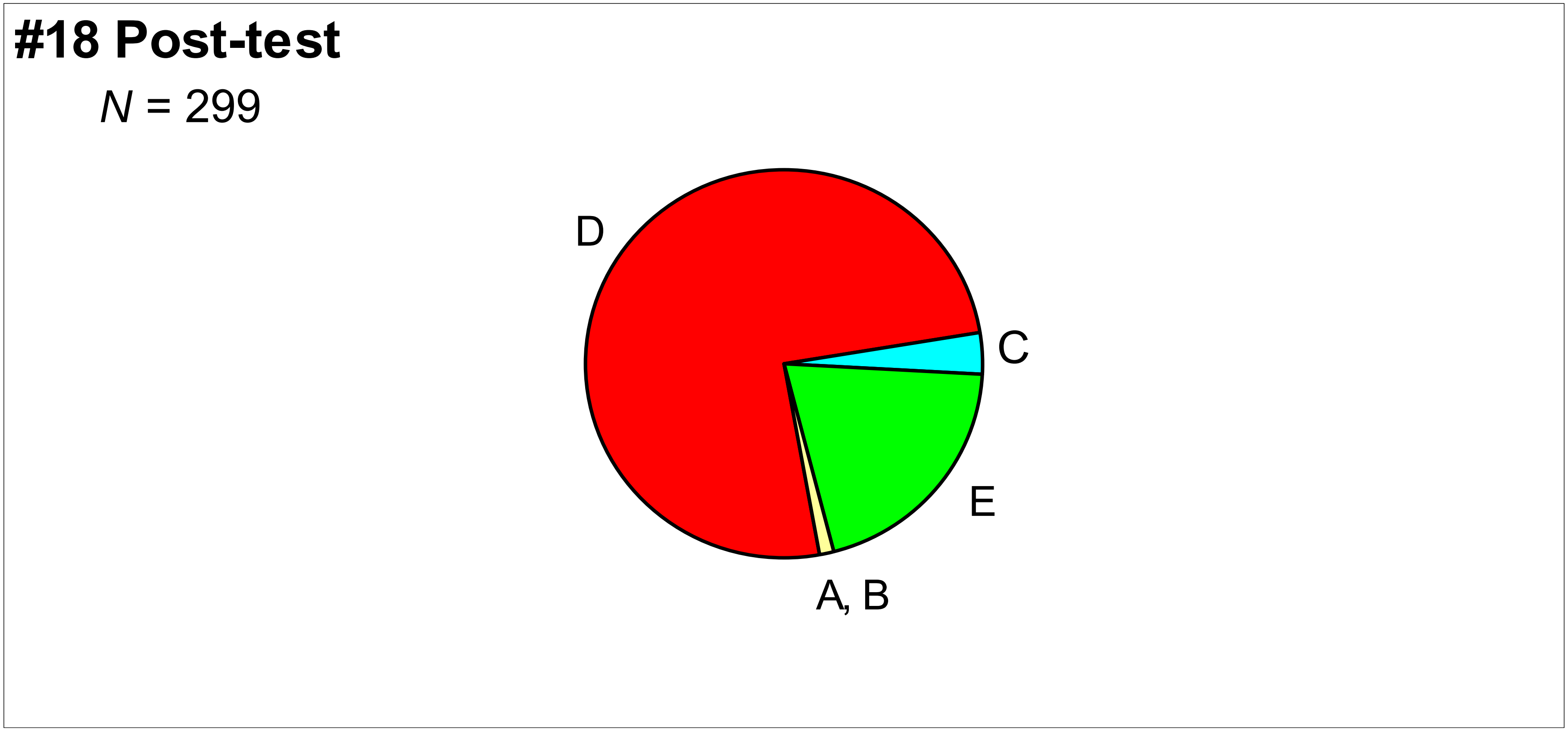
closer spacing of equipotential lines ⇒ <u>smaller</u> magnitude field

Pre-Instruction



"C": *wider spacing of equipotential lines ⇒ stronger field*

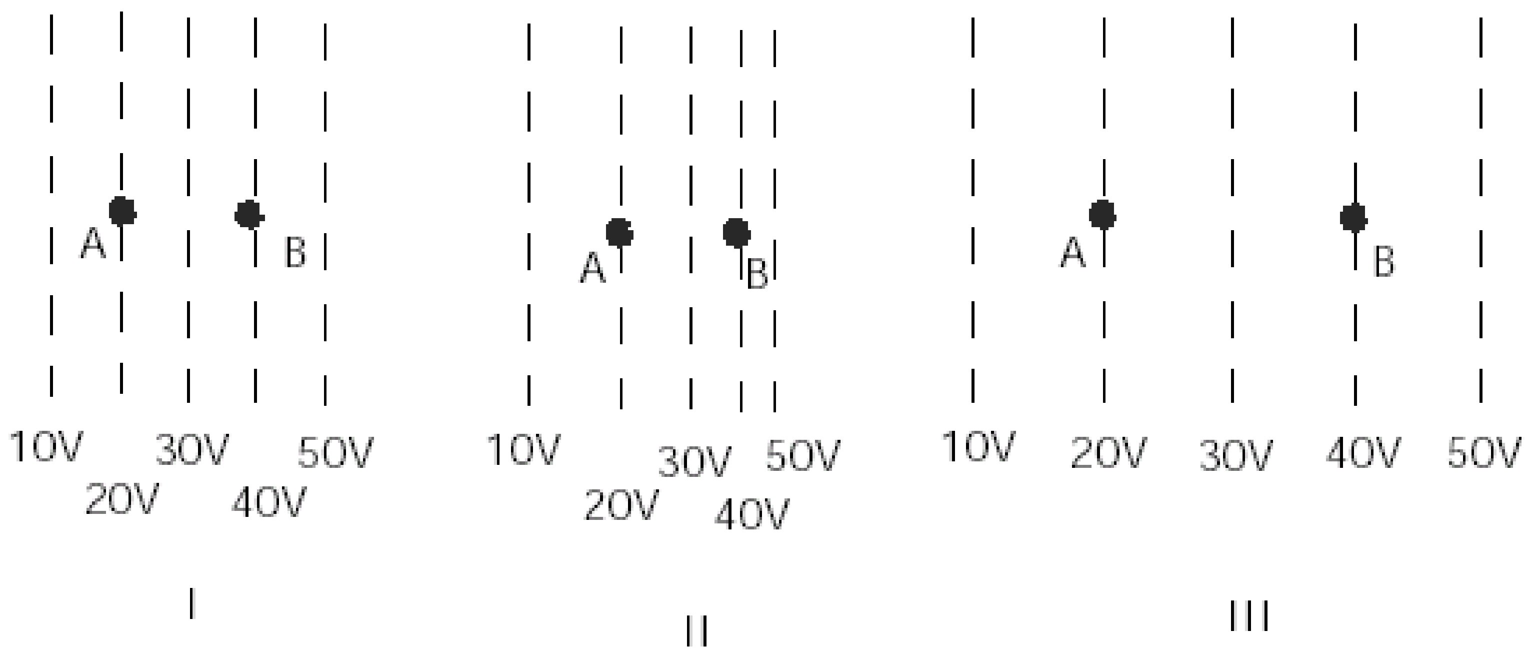
Post-Instruction



- **Proportion of responses in this category drastically reduced**

#18

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.



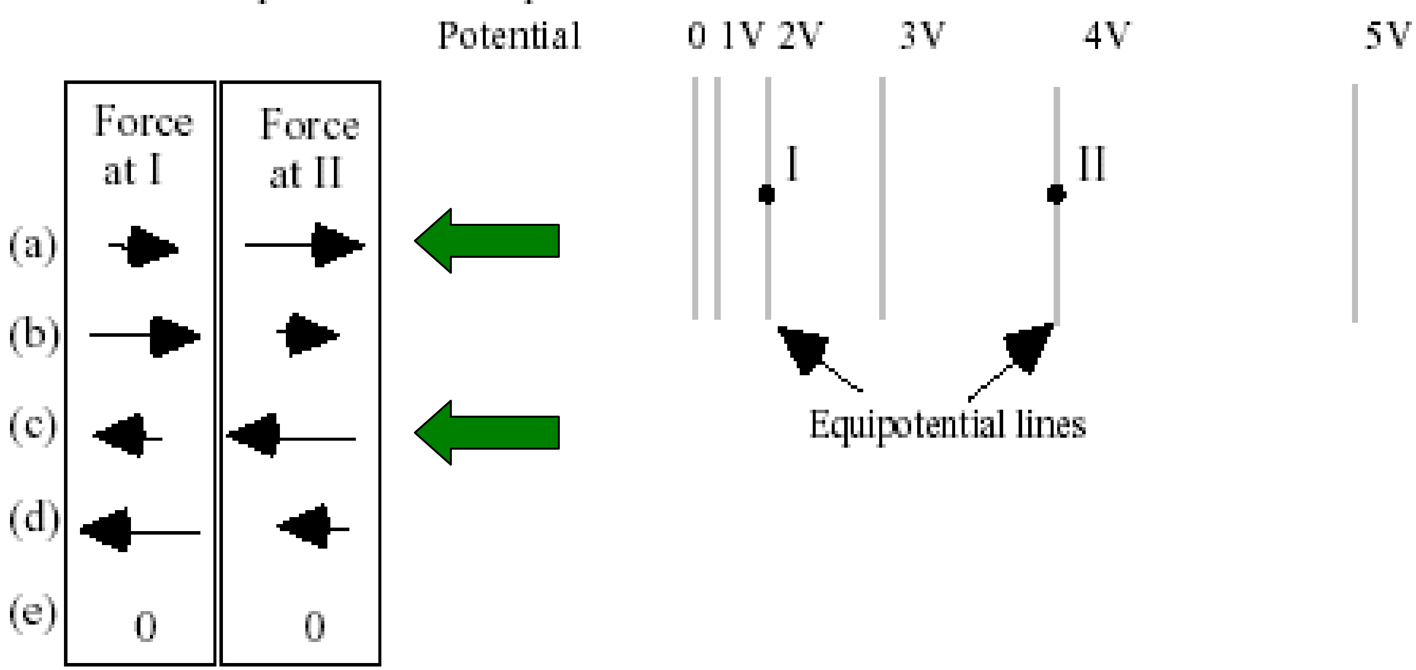
How does the magnitude of the electric field at B compare for these three cases?

(a) I > III > II
(b) I > II > III
(c) III > I > II
(d) II > I > III
(e) I = II = III

Field magnitude at point B equal in all cases

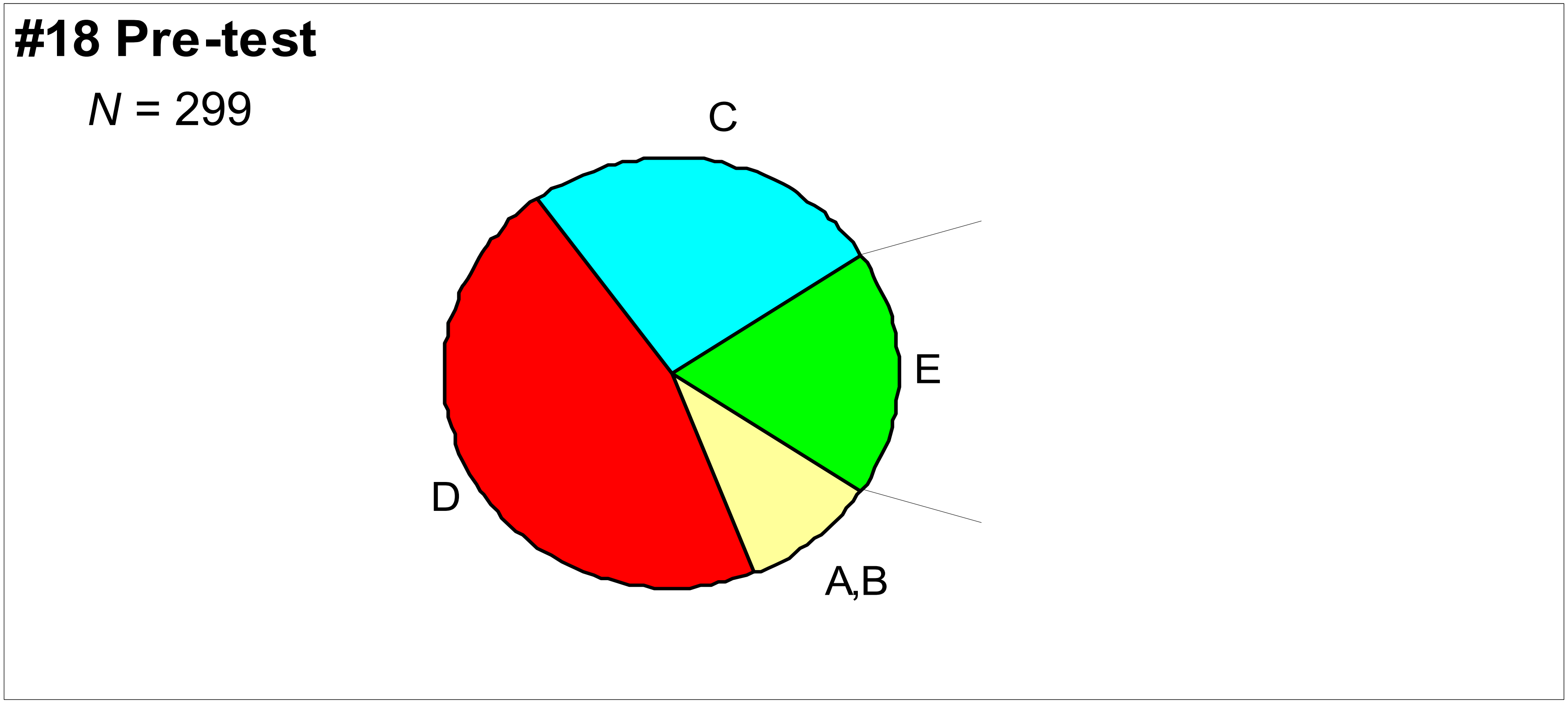
#20

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?



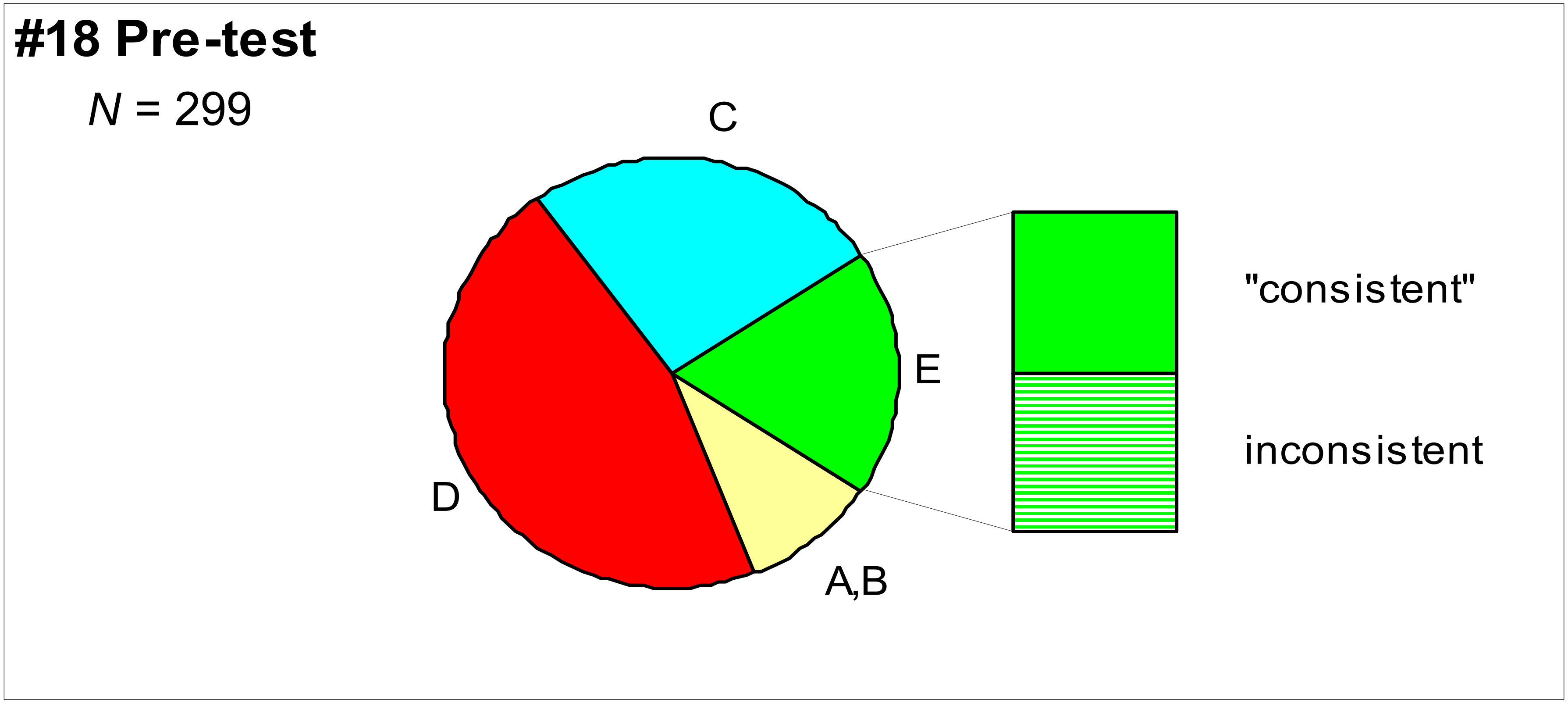
(a) or (c) consistent with “E” response on #18

Pre-Instruction



“E”: *magnitude of field scales with value of potential at point*

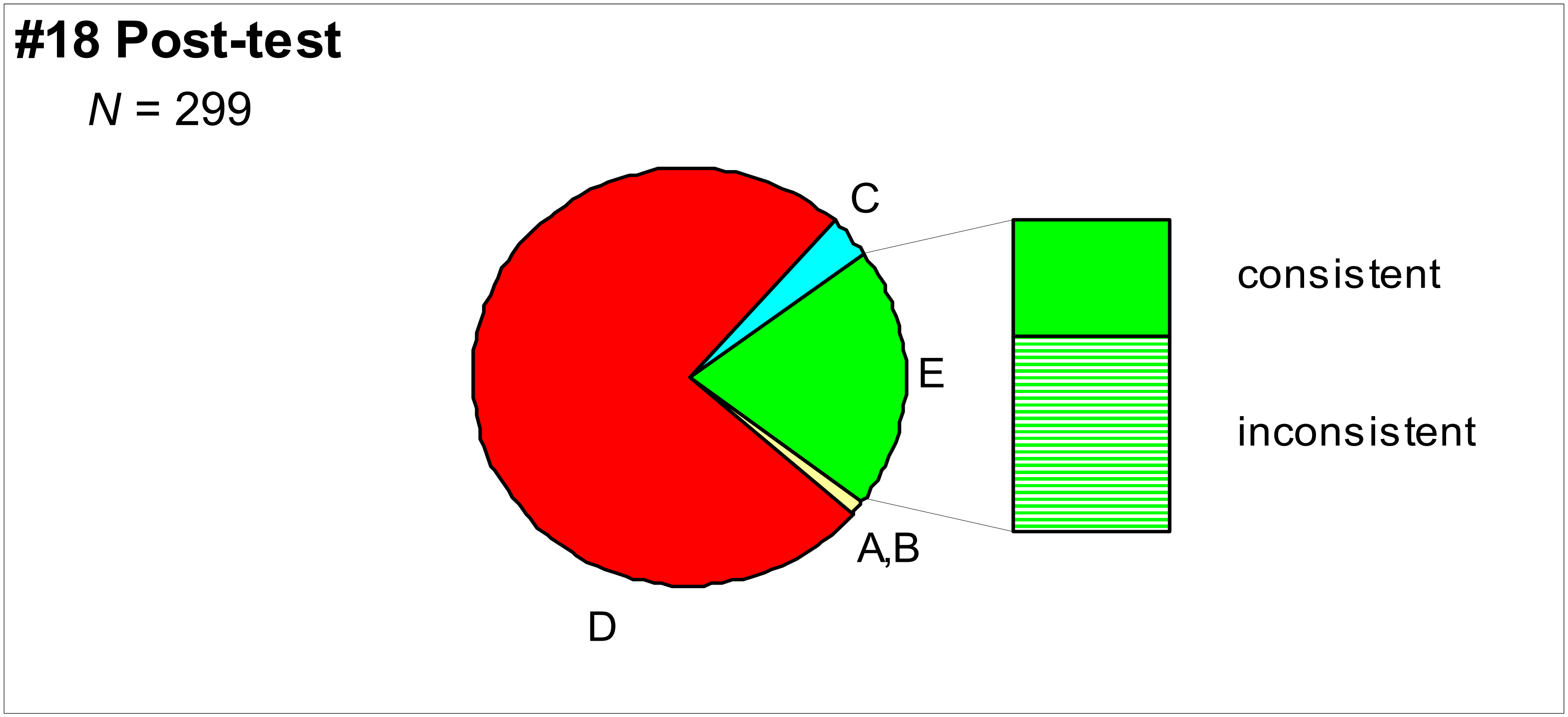
Pre-Instruction



“E”: ***magnitude of field scales with value of potential at point***

“consistent”: ***consistent with answer on #20*** ***(but many guesses)***

Post-Instruction



- **Proportion of responses in this category virtually unchanged**
- **Incorrect responses *less consistent* with other answers**

Students' Explanations Consistent Pre- and Post-Instruction [i.e., for $E_{B,\mathrm{I}} = E_{B,\mathrm{II}} = E_{B,\mathrm{III}}$]:

- Examples of pre-instruction explanations:
  - "they are all at the same voltage"
  - "the magnitude is 40 V on all three examples"
  - "the voltage is the same for all 3 at *B*"
  - "the change in voltage is equal in all three cases"

- Examples of post-instruction explanations:
  - "the potential at *B* is the same for all three cases"
  - "they are all from 20 V – 40 V"
  - "the equipotential lines all give 40 V"
  - "they all have the same potential"

Some Student Conceptions Persist, Others Fade

- Initial association of wider spacing with larger field magnitude effectively resolved through instruction
  - Proportion of “C” responses drops to near zero

- Initial tendency to associate field magnitude with magnitude of potential at a given point persists even after instruction
  - Proportion of “E” responses remains $\approx$ 20%
    - ➢ *But less consistently applied after instruction: for students with “E” on #18, more discrepancies between responses to #18 and #20 **after** instruction*

Insights Gained from Analysis of Incorrect Student Responses

- Even in the absence of previous instruction, students' responses manifest reproducible patterns that may influence learning trajectories.
- Analysis of pre- and post-instruction responses discloses consistent patterns of change in student reasoning that may assist in design of improved instructional materials.

Outline

1. Physics Education as a Research Problem

    Methods of physics education research

2. Probing the Structure of Students' Knowledge

    Example: Students' ideas about equipotentials

3. Research-Based Instructional Methods

    Guiding student inquiry

4. Research-Based Curriculum Development

    A "model" problem: law of gravitation

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 and targeted problem-solving activities.

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

Guiding Students to Express and Explain their Reasoning Process

Socratic Questioning: Using a sequence of "leading" questions to guide student thinking

- Questions provide hints but not clear-cut answers
- Lead students to express their reasoning:
  - in verbal form (by interacting with instructors and other students)
  - In written form (through writing explanations on quiz, homework, and exam problems)
- This can help students more clearly expose—and therefore modify—their own thought processes.

Tradeoffs: When students explain their reasoning they may learn better, but instructor feedback is more complex and time-consuming.

Use of Rapid Feedback

- Instruction providing rapid responses to in-class or on-line problem-solving activity *[“rapid” = minute-to-minute time scale]*

  - Hints and suggestions
  - Leading questions
  - Assessments of correct or incorrect responses

- Includes feedback from instructors through frequent questions and answers

- Includes feedback from fellow students through small-group interaction.

Key Themes of Research-Based Instruction

- Emphasize qualitative, non-numerical questions to reduce unthoughtful "plug and chug."

- Make extensive use of multiple representations and varied contexts 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.

Key Themes of Research-Based Instruction

- Emphasize qualitative, non-numerical questions to reduce unthoughtful “plug and chug.”

- Make extensive use of multiple representations and varied contexts 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.

Difficulties in Changing Representations or Contexts

- Students are often able to solve problems in ***one*** form of representation (e.g. in the form of a graph), but ***unable*** to solve the same problem when posed in a different representation (e.g., using "ordinary" language).

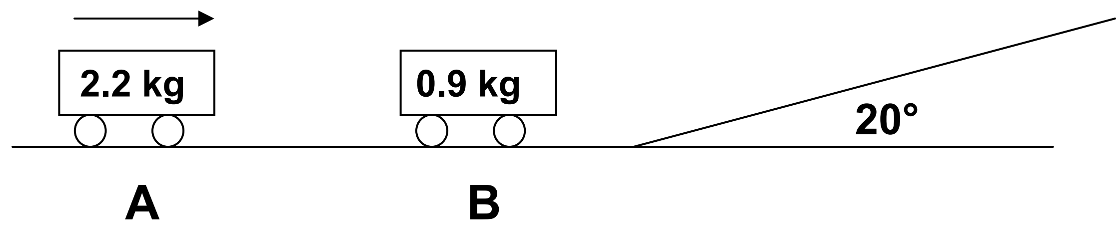
- Students are often able to solve problems in a "science" context (e.g., a textbook problem using "science" language), but ***unable*** to solve the same problem in a "real world" context (using "ordinary" words).

Changing Contexts:

Textbook Problems and "Real" Problems

- **"Standard" Textbook Problem:**

Cart A, which is moving with a constant velocity of 3 m/s, has an inelastic collision with cart B, which is initially at rest as shown in Figure 8.3. After the collision, the carts move together up an inclined plane. Neglecting friction, determine the vertical height *h* of the carts before they reverse direction.



Changing Contexts:
Textbook Problems and "Real" Problems

- **"Context-Rich" Problem:** *[Heller and Hollabaugh, Am. J. Phys. (1992)]*

  You are helping your friend prepare for the next skate board exhibition. For her program, she plans to take a running start and then jump onto her heavy-duty 15-lb stationary skateboard. She and the skateboard will glide in a straight line along a short, level section of track, then up a sloped concrete wall. She wants to reach a height of at least 10 feet above where she started before she turns to come back down the slope. She has measured her maximum running speed to safely jump on the skateboard at 7 feet/second. She knows you have taken physics, so she wants you to determine if she can carry out her program as planned. She tells you that she weighs 100 lbs.

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)*

“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”]

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

Results of Assessment

- Learning gains on qualitative problems are well above national norms for students in traditional courses.

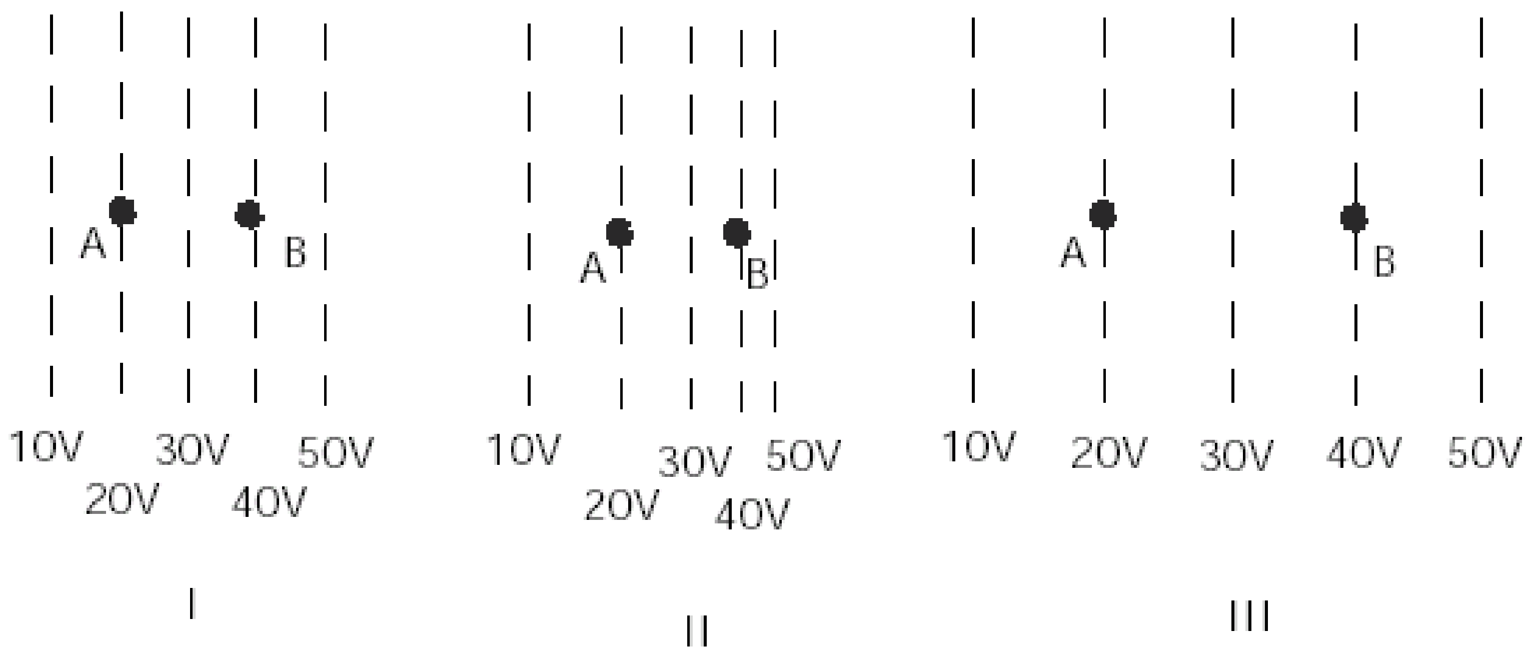
- Performance on quantitative problems is comparable to (or slightly better than) that of students in traditional courses.

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).*

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

Assessment Data

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

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

Assessment Data

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

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

Assessment Data

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
National sample (algebra-based)	402	**27%**	**43%**
National sample (calculus-based)	1496	**37%**	**51%**
ISU 1998	70	**30%**	
ISU 1999	87	**26%**	
ISU 2000	66	**29%**	

Assessment Data

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%**
ISU 1998	70	**30%**	**75%**
ISU 1999	87	**26%**	**79%**
ISU 2000	66	**29%**	**79%**

Quantitative Problem Solving: Are skills being sacrificed?

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%

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 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?

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 112: F98 **Six final exam questions**	*76*	77%
Physics 221: F97 & F98 **Subset of three questions**	*372*	59%
Physics 112: F98, F99, F00 **Subset of three questions**	*241*	78%

Outline

1. Physics Education as a Research Problem

    Methods of physics education research

2. Probing the Structure of Students' Knowledge

    Example: Students ideas' about equipotentials

3. Research-Based Instructional Methods

    Guiding student inquiry

4. Research-Based Curriculum Development

    A "model" problem: law of gravitation

Research-Based Curriculum Development

- Investigate student learning in actual classes; 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]

Addressing Learning Difficulties: A Model Problem

Student Concepts of Gravitation

[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.*

Addressing Learning Difficulties: A Model Problem

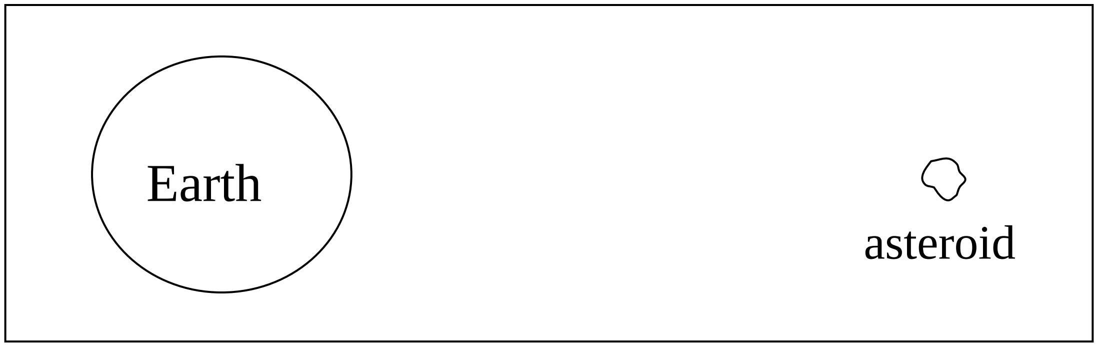
Student Concepts of Gravitation

[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.*

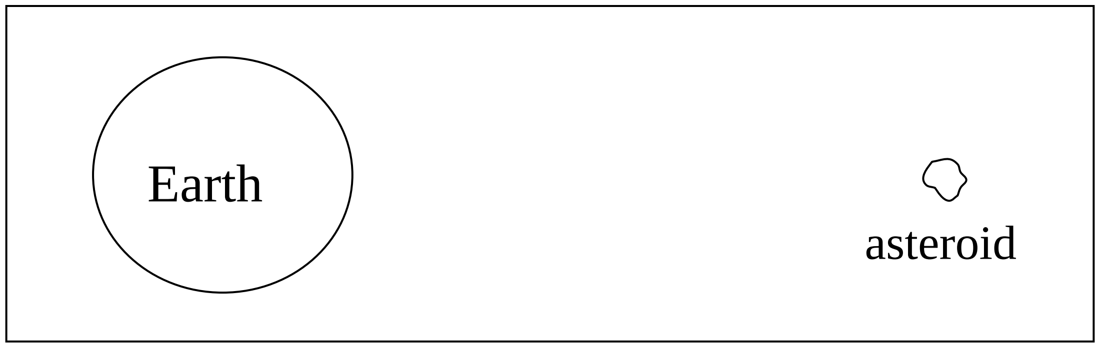
- Worksheets developed to address learning difficulties; tested in calculus-based physics course Fall 1999

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.*

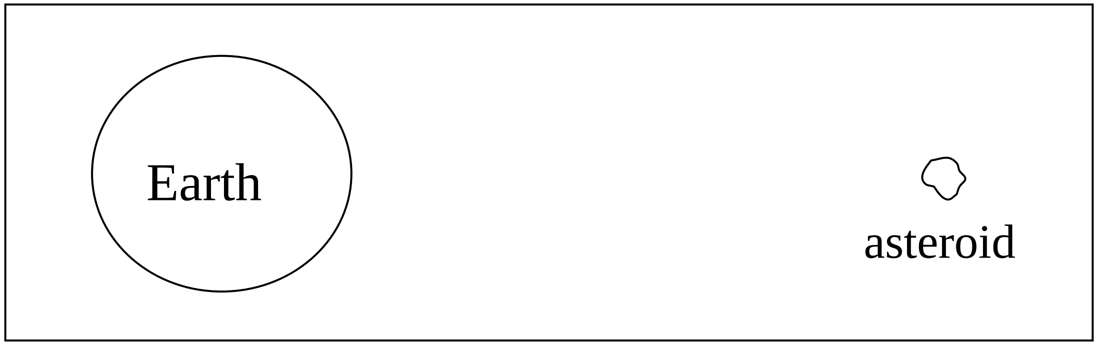
Example: Newton's Third Law in the Context of Gravity



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.*

[Presented during first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.]

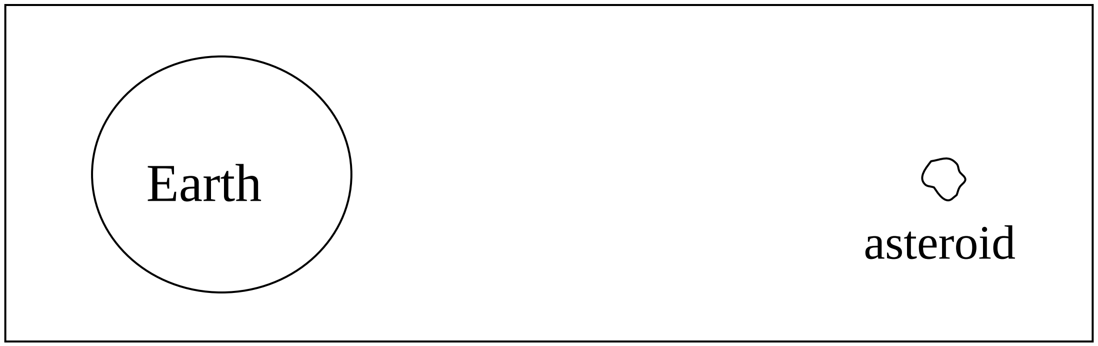
Example: Newton's Third Law in the Context of Gravity



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.*

[Presented during first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.]

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

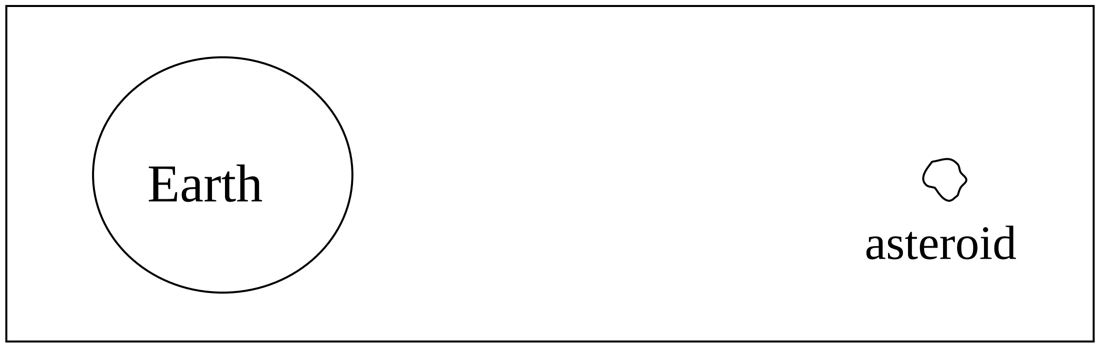


Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid*?*** *Explain the reasoning for your choice.*

[Presented during first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.]

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

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



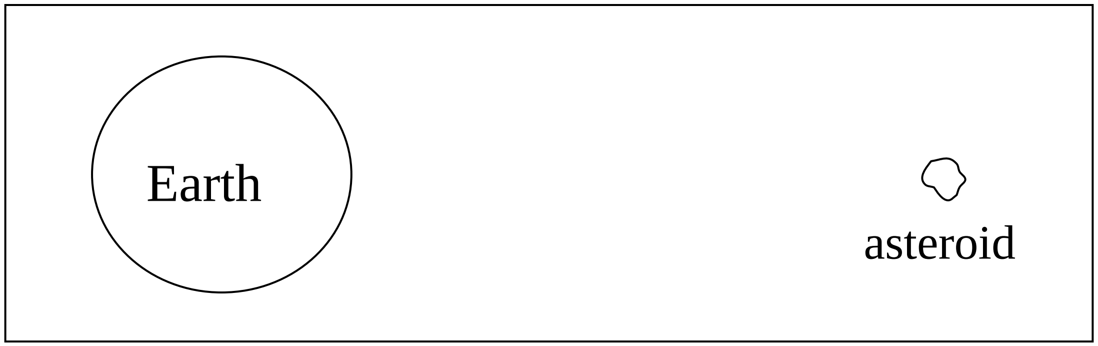
Is the magnitude of the force exerted **by the asteroid on the Earth** *larger than, smaller than, or the same as the magnitude of the force exerted* **by the Earth on the asteroid?** *Explain the reasoning for your choice.*

[Presented during first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.]

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

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

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.*

[Presented during first week of class to all students taking calculus-based introductory physics at ISU during Fall 1999.]

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

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

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

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

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*

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*

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)

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)

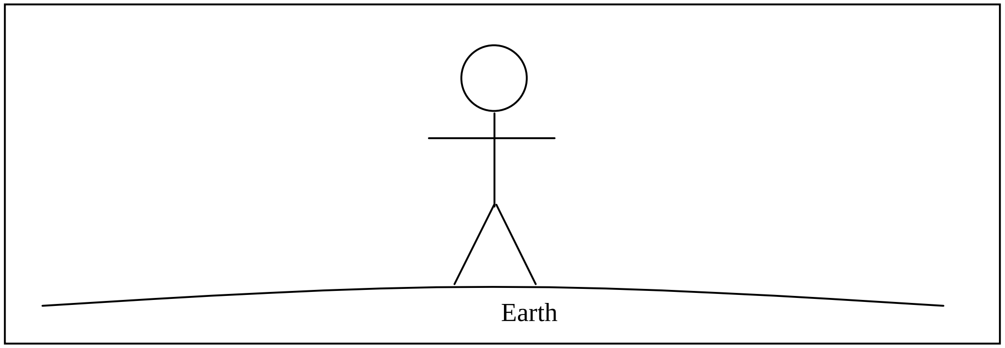
- Design based on research, as well as instructional experience

- Targeted at difficulties with Newton’s third law, and with use of proportional reasoning in inverse-square force law

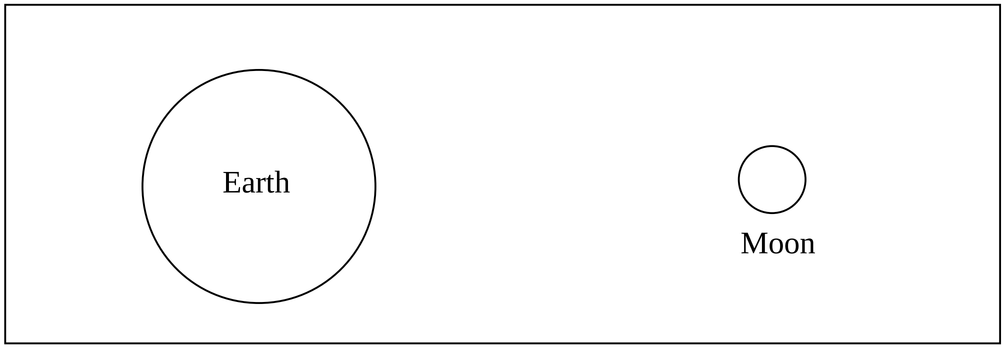
Name_______________________

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)**.



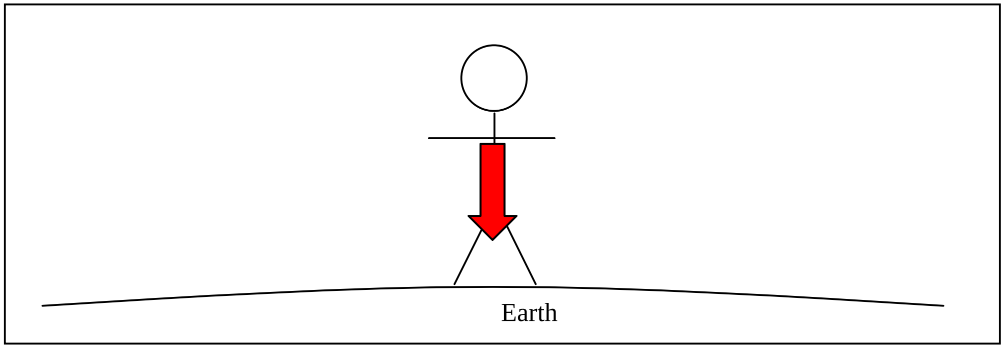
c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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

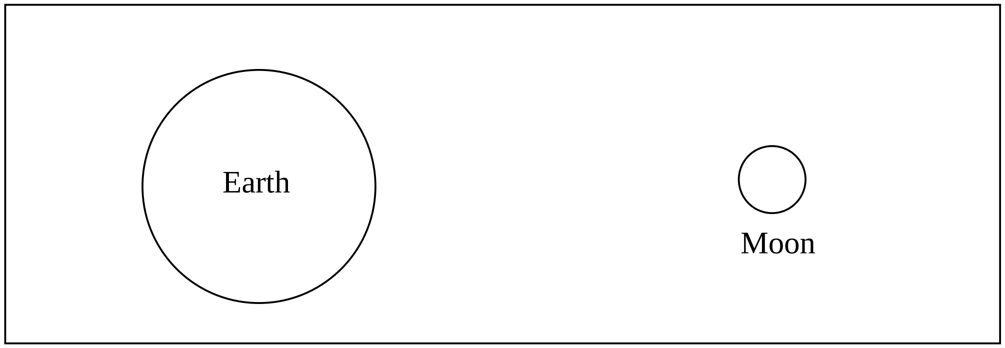
Name________________________

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)**.



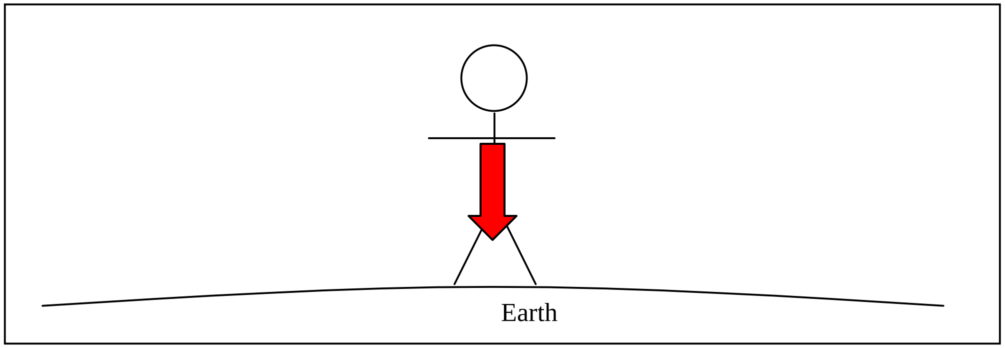
c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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

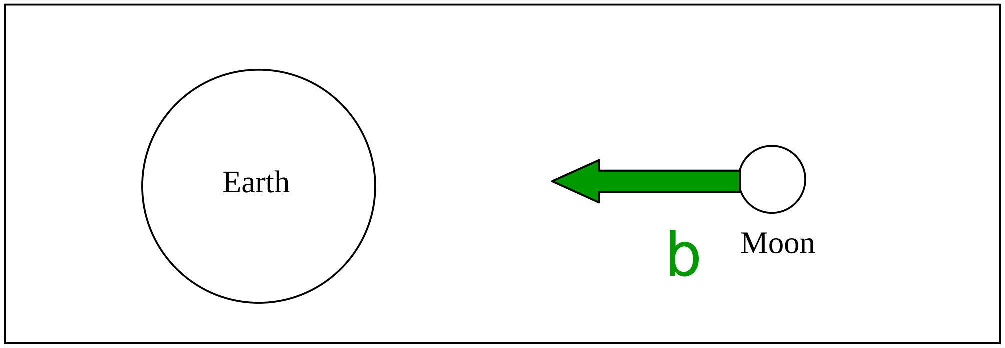
Name______________________

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)**.



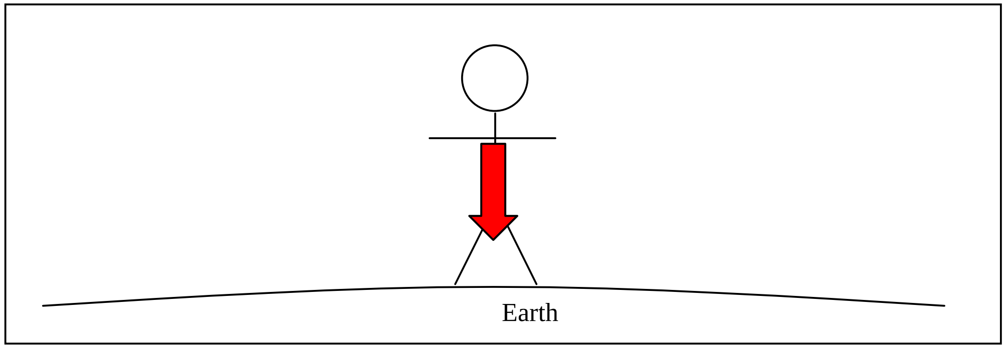
c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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

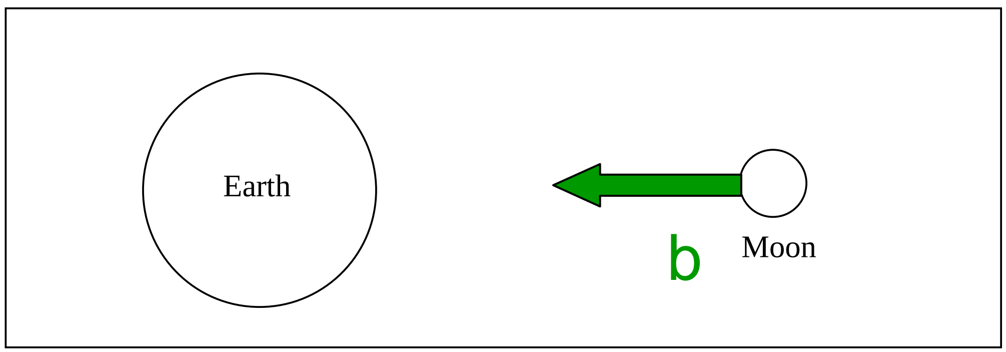
Name_______________________

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)**.



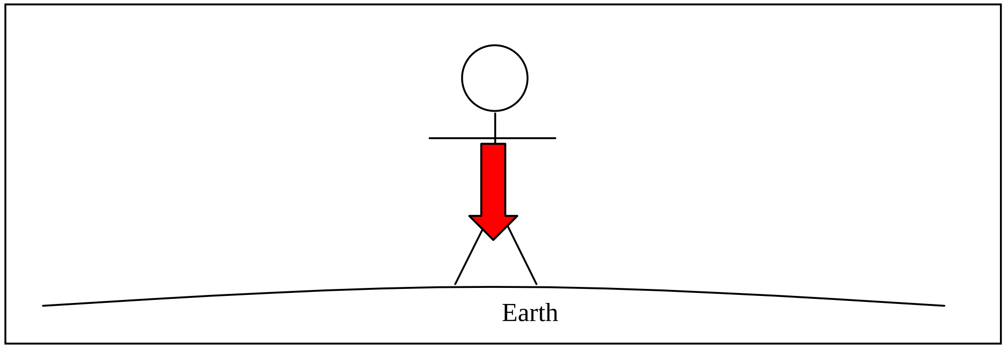
c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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

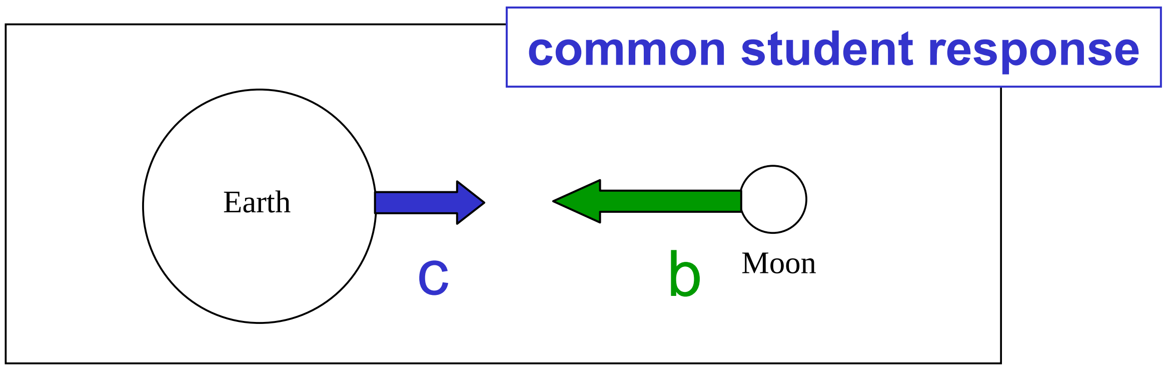
Name________________________

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.

e) Consider the magnitude of the gravitational force in (b). Write down an algebraic expression for the strength of the force. (Refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

f) Consider the magnitude of the gravitational force in (c). Write down an algebraic expression for the strength of the force. (Again, refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

g) Look at your answers for (e) and (f). Are they the same?

h) Check your answers to (b) and (c) to see if they are consistent with (e) and (f). If necessary, make changes to the arrows in (b) and (c).

e) Consider the magnitude of the gravitational force in (b). Write down an algebraic expression for the strength of the force. (Refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

$$\boxed{F_b = G\frac{M_e M_m}{r^2}}$$

f) Consider the magnitude of the gravitational force in (c). Write down an algebraic expression for the strength of the force. (Again, refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

g) Look at your answers for (e) and (f). Are they the same?

h) Check your answers to (b) and (c) to see if they are consistent with (e) and (f). If necessary, make changes to the arrows in (b) and (c).

e) Consider the magnitude of the gravitational force in (b). Write down an algebraic expression for the strength of the force. (Refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

$$\boxed{F_b = G\frac{M_e M_m}{r^2}}$$

f) Consider the magnitude of the gravitational force in (c). Write down an algebraic expression for the strength of the force. (Again, refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

$$\boxed{F_c = G\frac{M_e M_m}{r^2}}$$

g) Look at your answers for (e) and (f). Are they the same?

h) Check your answers to (b) and (c) to see if they are consistent with (e) and (f). If necessary, make changes to the arrows in (b) and (c).

e) Consider the magnitude of the gravitational force in (b). Write down an algebraic expression for the strength of the force. (Refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

$$\boxed{F_b = G\frac{M_e M_m}{r^2}}$$

f) Consider the magnitude of the gravitational force in (c). Write down an algebraic expression for the strength of the force. (Again, refer to Newton's Universal Law of Gravitation at the top of the previous page.) Use M_e for the mass of the Earth and M_m for the mass of the Moon.

$$\boxed{F_c = G\frac{M_e M_m}{r^2}}$$

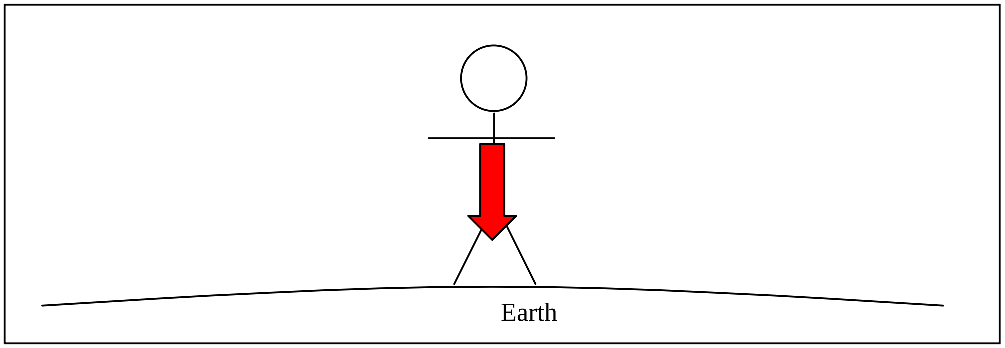
g) Look at your answers for (e) and (f). Are they the same?

h) **Check your answers to (b) and (c) to see if they are consistent with (e) and (f). If necessary, make changes to the arrows in (b) and (c).**

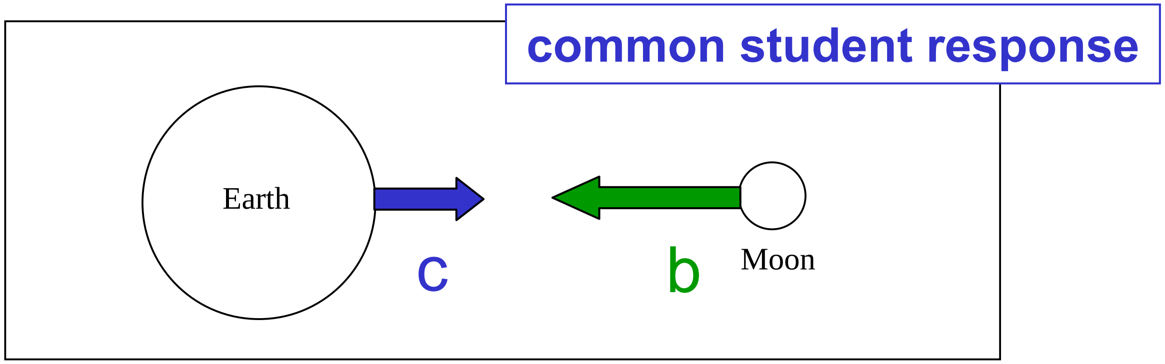
Name_______________________

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)**.



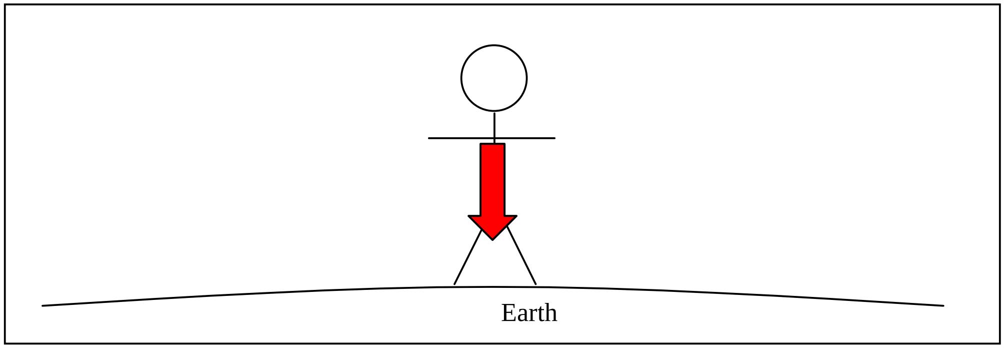
c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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

Name______________________

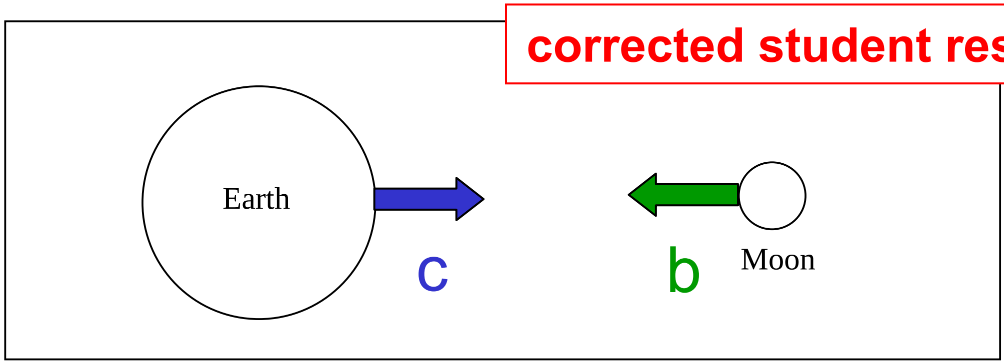
Gravitation Worksheet
Physics 221

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)**.

corrected student response

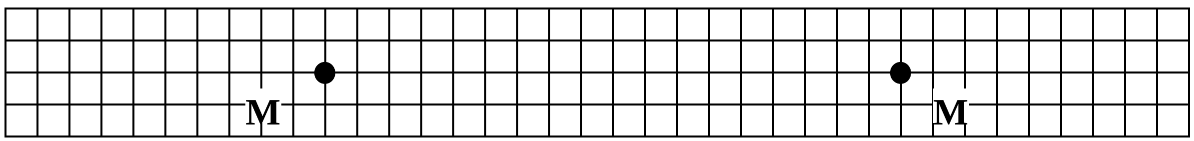


c) Now, in the same picture (above), draw an arrow which represents the force exerted ***by*** the Moon ***on*** the Earth. Label this arrow **(c)**. Remember to draw the arrow with the correct length and direction as compared to the arrow you drew in **(b)**.

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

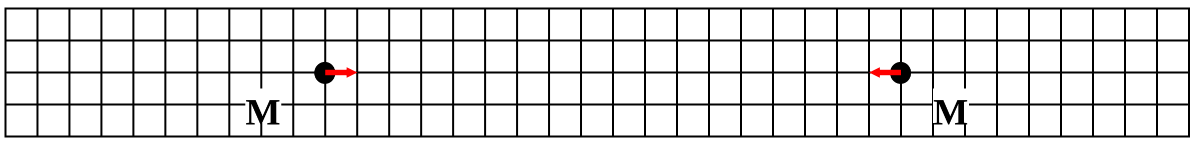
2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = “M”) are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.



2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = "M") are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.



2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = "M") are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.

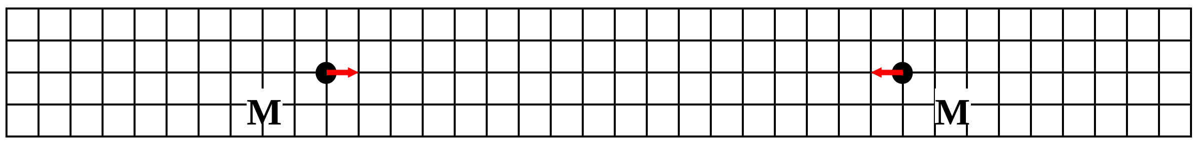
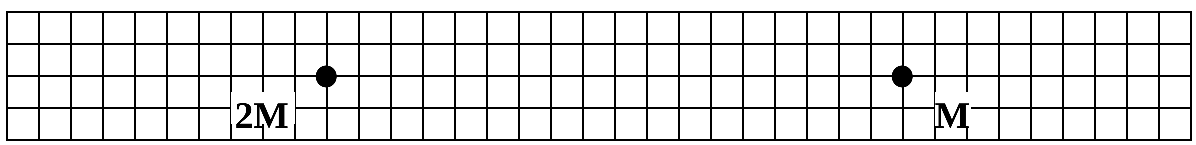


Diagram (ii): Now, one of the spheres is replaced with a sphere of mass 2M. Draw a new set of vectors representing the mutual gravitational forces in this case.



2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = "M") are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.

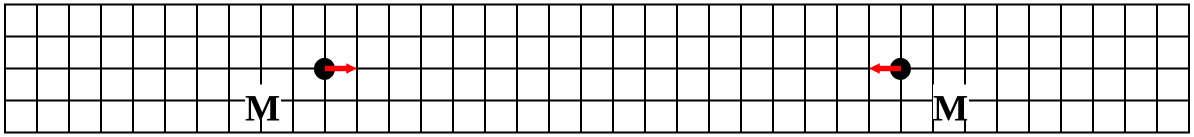
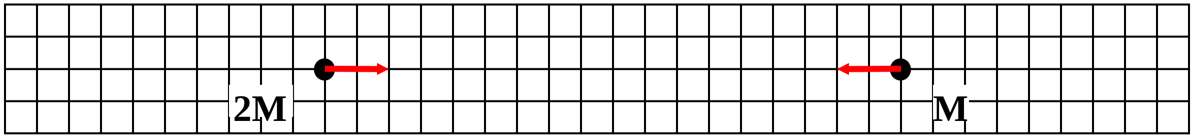


Diagram (ii): Now, one of the spheres is replaced with a sphere of mass 2M. Draw a new set of vectors representing the mutual gravitational forces in this case.



2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = "M") are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.

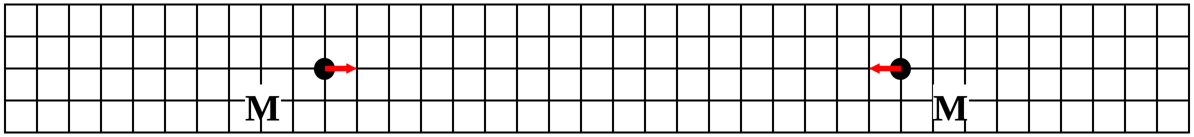


Diagram (ii): Now, one of the spheres is replaced with a sphere of mass 2M. Draw a new set of vectors representing the mutual gravitational forces in this case.

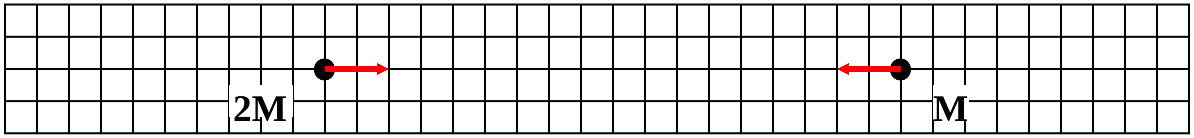
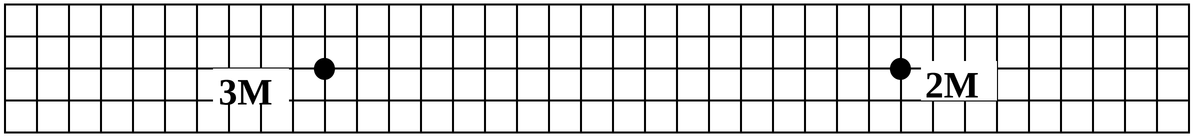


Diagram (iii): In this case, the spheres have masses 2M and 3M. Again, draw the vectors representing the mutual gravitational forces.



2) In the following diagrams, draw arrows representing force vectors, such that the length of the arrow is proportional to the magnitude of the force it represents.

Diagram (i): In this figure, two equal spherical masses (mass = "M") are shown. Draw the vectors representing the gravitational forces the masses exert on each other. Draw your *shortest* vector to have a length equal to *one* of the grid squares.

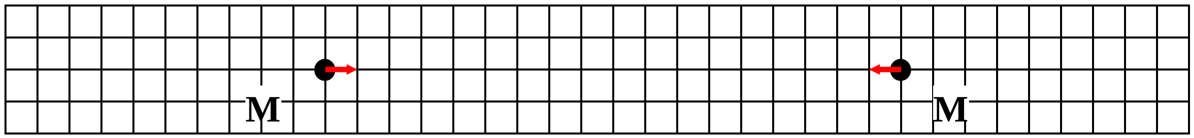


Diagram (ii): Now, one of the spheres is replaced with a sphere of mass 2M. Draw a new set of vectors representing the mutual gravitational forces in this case.

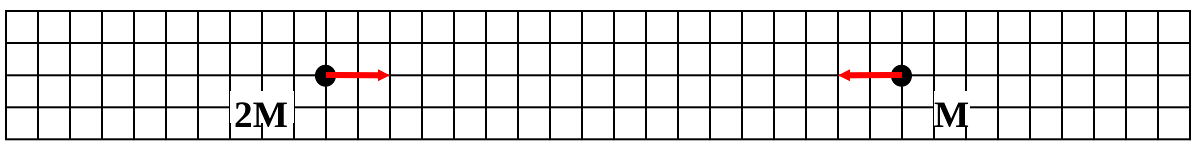
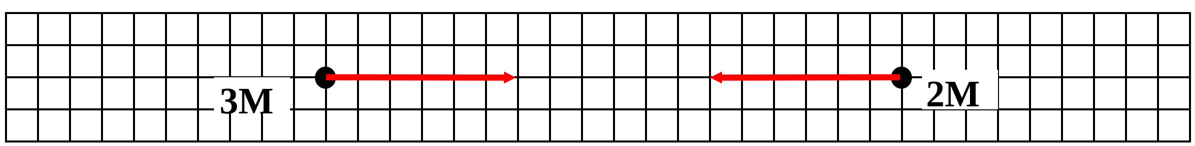


Diagram (iii): In this case, the spheres have masses 2M and 3M. Again, draw the vectors representing the mutual gravitational forces.



Final Exam Question #1

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.

Final Exam Question #1

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?

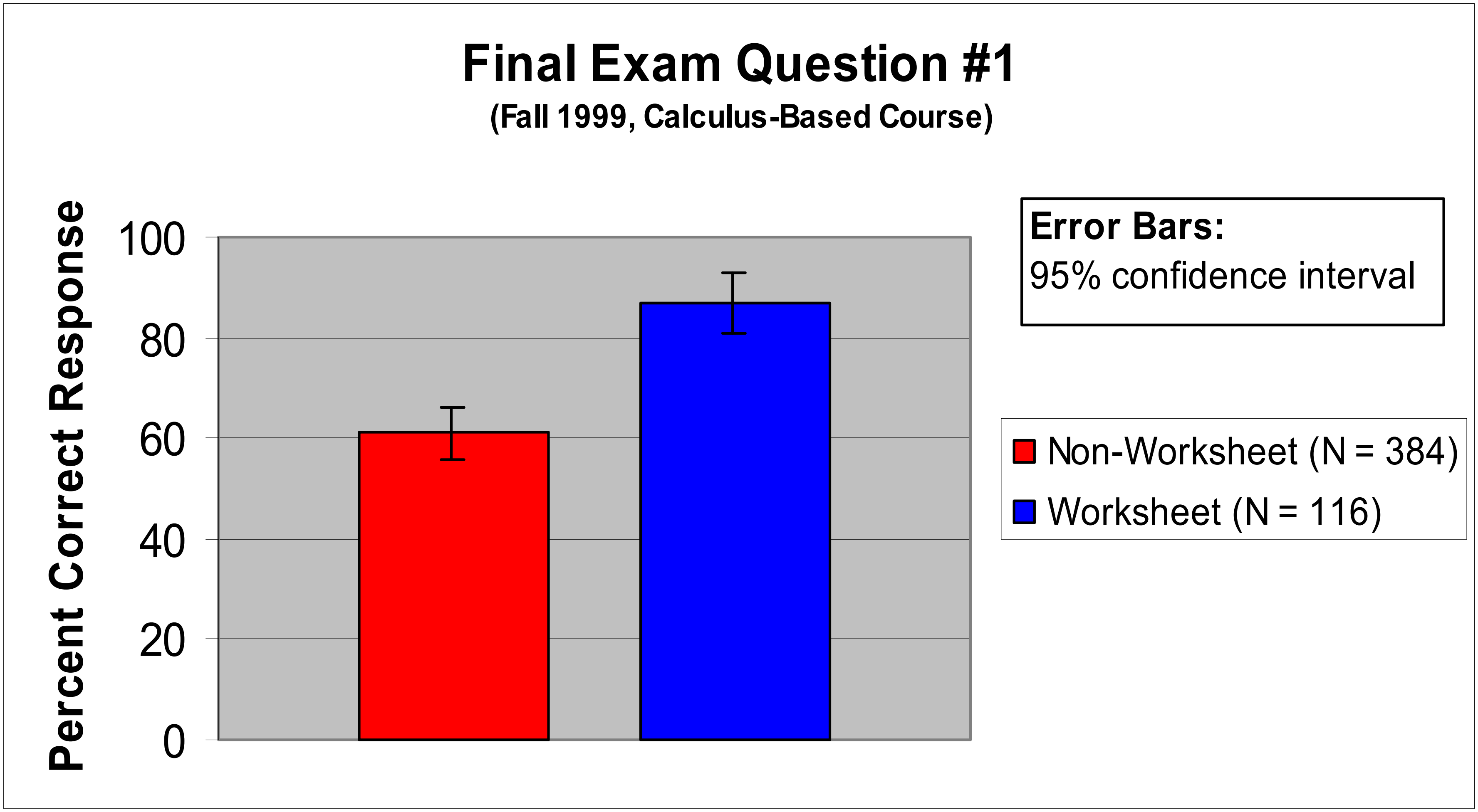
A. The gravitational force exerted by the chunk of ice on Saturn is **greater than** the gravitational force exerted by Saturn on the chunk of ice.

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.

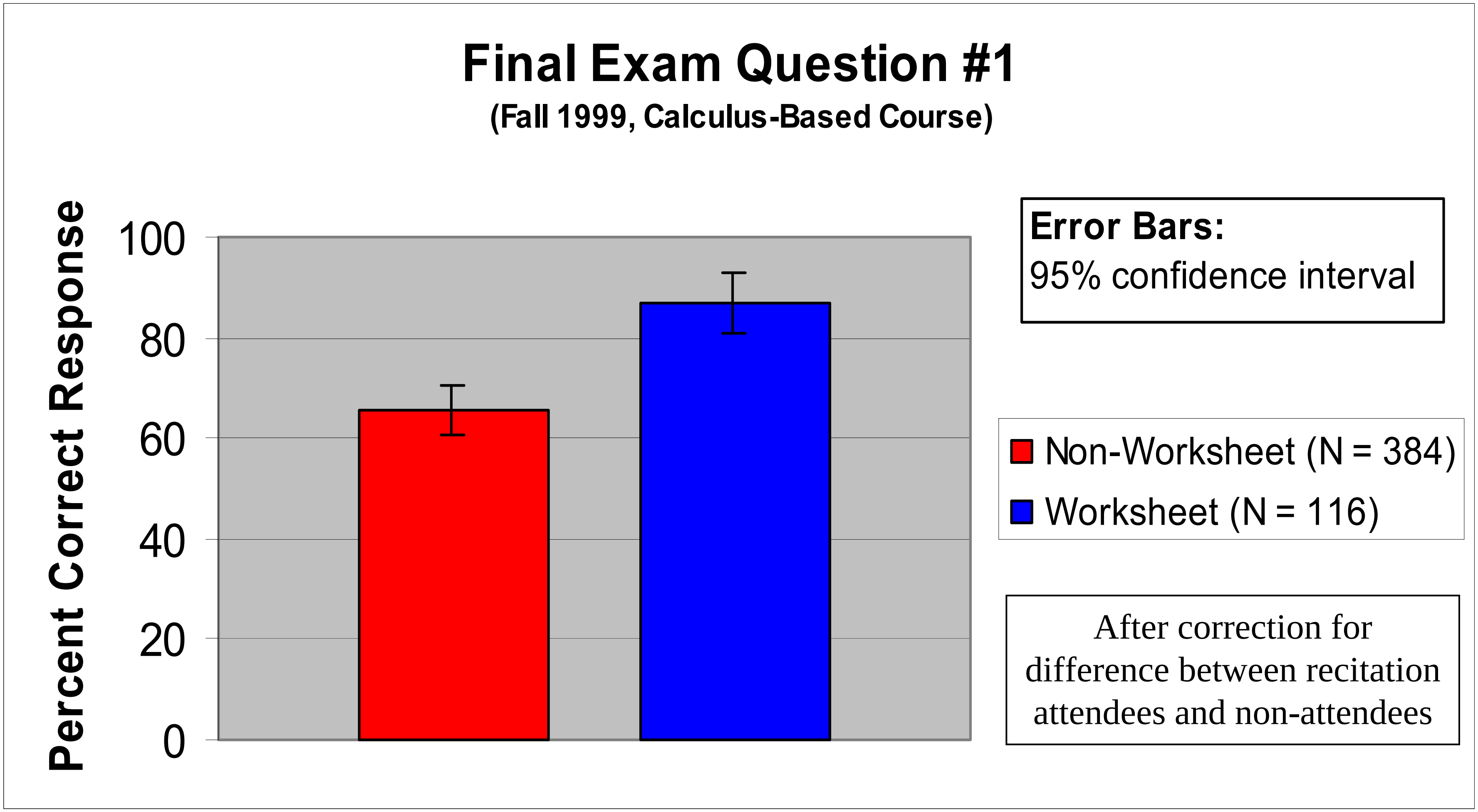
C. The gravitational force exerted by the chunk of ice on Saturn is **nonzero, and less than** the gravitational force exerted by Saturn on the chunk of ice.

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

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



Final Exam Question #1
(Fall 1999, Calculus-Based Course)
Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)


Final Exam Question #1
(Fall 1999, Calculus-Based Course)
Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)
After correction for difference between recitation attendees and non-attendees

Final Exam Question #2

Final Exam Question #2

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:

A. equal, and are equal to *F.*

B. equal, and are larger than *F.*

C. equal, and are smaller than *F.*

D. not equal, but one of them is larger than *F.*

E. not equal, but neither of them is larger than *F.*

Final Exam Question #2

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:

A. equal, and are equal to *F*.

B. equal, and are larger than *F*.

C. equal, and are smaller than *F*.

D. not equal, but one of them is larger than *F*.

E. not equal, but neither of them is larger than *F*.

Final Exam Question #2

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:

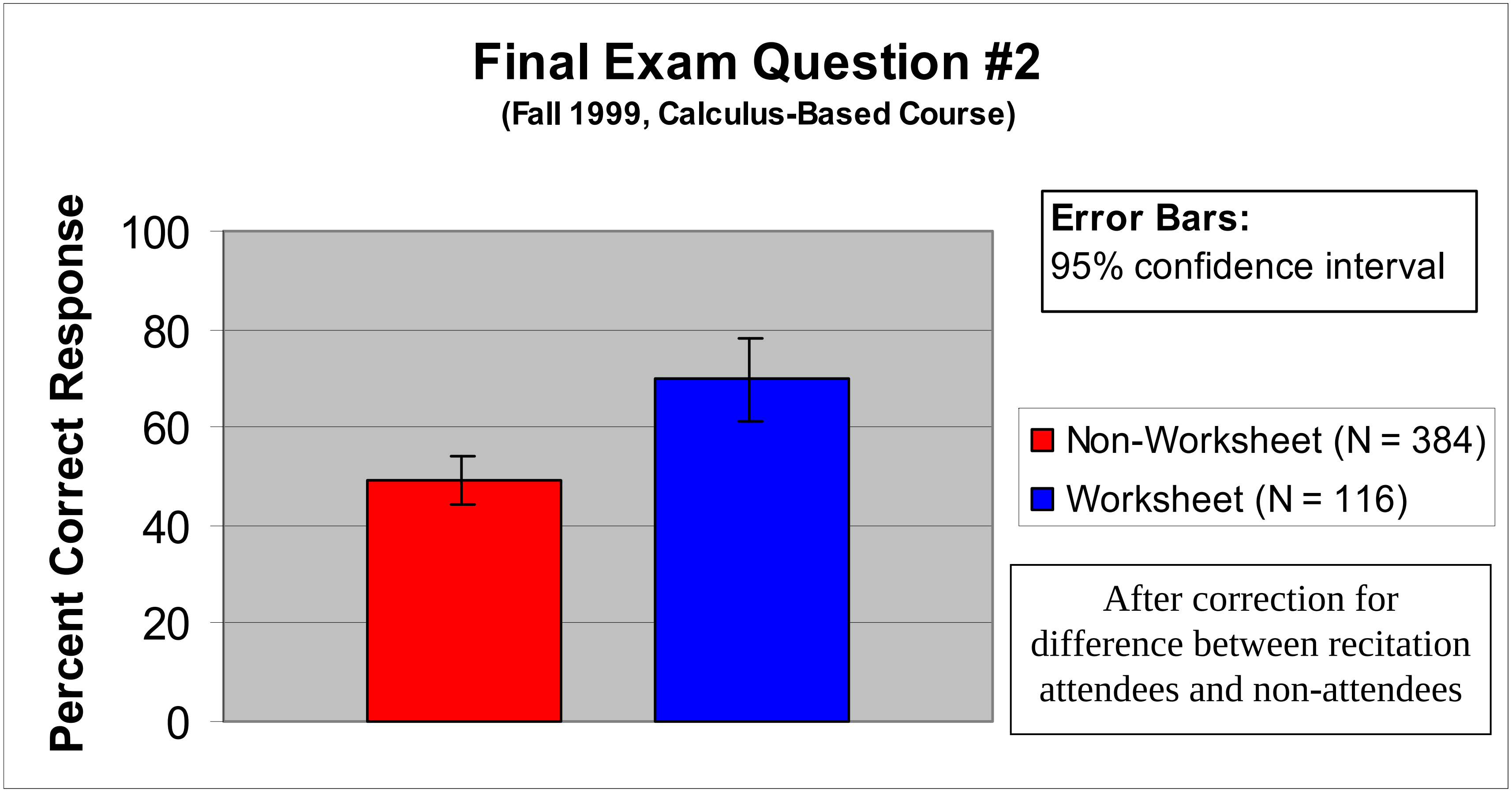
A. equal, and are equal to *F.*

B. equal, and are larger than *F.*

C. equal, and are smaller than *F.*

D. not equal, but one of them is larger than *F.*

E. not equal, but neither of them is larger than *F.*


Final Exam Question #2
(Fall 1999, Calculus-Based Course)
Percent Correct Response
100
80
60
40
20
0
Error Bars:
95% confidence interval
Non-Worksheet (N = 384)
Worksheet (N = 116)
After correction for
difference between recitation
attendees and non-attendees

Summary

Summary

- Research on student learning lays basis for development of improved instructional materials in science education.

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.

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.
- Treating science education as a research problem holds promise of cumulative progress, based on solid foundation of previous results.

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.

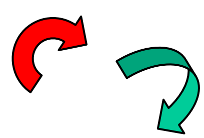
- Treating science education as a research problem holds promise of cumulative progress, based on solid foundation of previous results.

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.

- Treating science education as a research problem holds promise of cumulative progress, based on solid foundation of previous results.



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.

- Treating science education as a research problem holds promise of cumulative progress, based on solid foundation of previous results.