Frontiers and Challenges in Physics Education Research

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and the Iowa State University Center for Teaching Excellence

Outline

- Objectives and desired outcomes
- Assessments: what is necessary/desirable?
- Investigating student reasoning through detailed analysis of response patterns
- How do you hit a moving target? Addressing the dynamics of students' thinking
- Some sociological issues in PER

Reference: Heron and Meltzer, "Guest Editorial," AJP (May 2005)

Production Assistance: Warren Christensen

Objectives of the Endeavor: PER as an Applied Field

Goals for my research:

- Find ways to help students learn physics more effectively and efficiently
  - Develop deeper understanding of concepts, ability to solve unfamiliar problems
  - Appreciate overall structure of physical theory
- Help students develop improved problem-solving and reasoning abilities applicable in diverse contexts

Desired Outcomes

- **Cognitive:** ability to apply knowledge of physics to solve problems in unfamiliar contexts
- **Behavioral:** ability to understand, assess, and carry out (to some extent) investigations employing the methods and outlook of a physicist.

Specific desired outcomes are level-dependent, i.e., introductory course, upper-level course, graduate course, etc.

Desired Assessment Modes

Assessment of:

- knowledge
- behaviors

Determined:

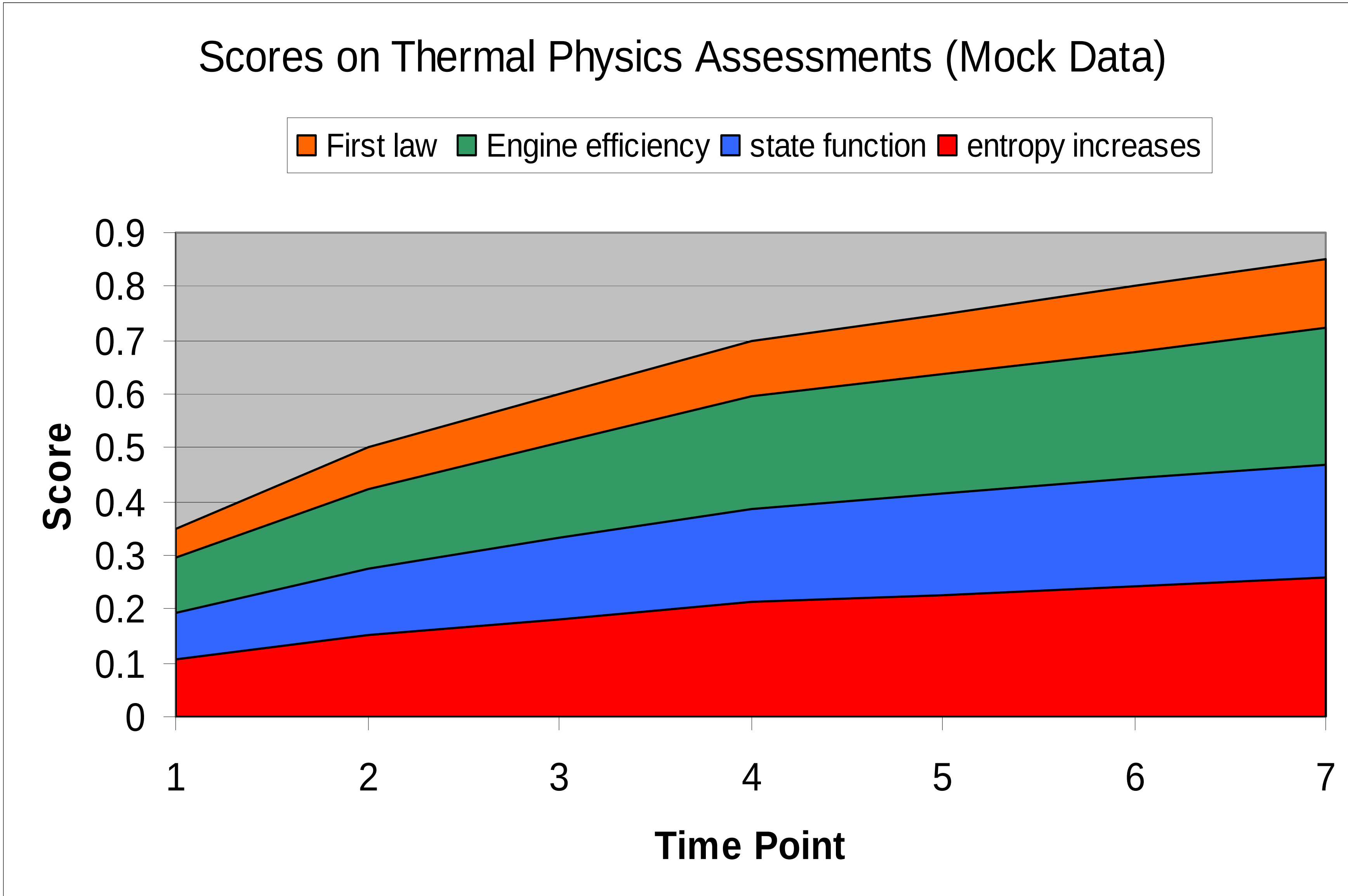
- in different contexts
- at different times

From the standpoint of:

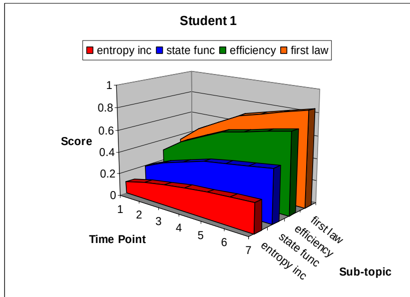
- absolute level
- consistency

For:

- individual students
- whole class



Scores on Thermal Physics Assessments (Mock Data)
First law
Engine efficiency
state function
entropy increases
Score
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
1
2
3
4
5
6
7
Time Point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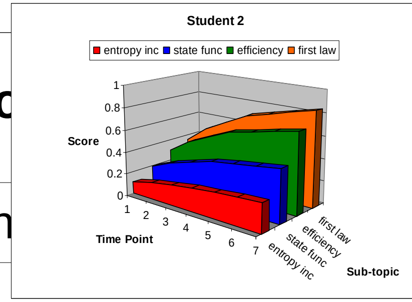
Score
Time Point
Sub-topic

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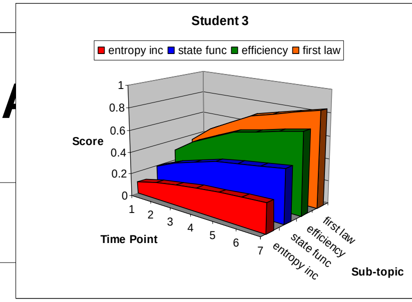
Score
Time Point
Sub-topic

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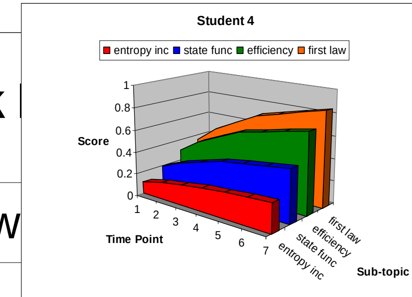
Score
Time Point
Sub-topic

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Score
Time Point
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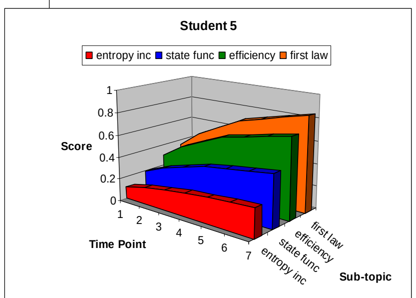
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Score
Time Point
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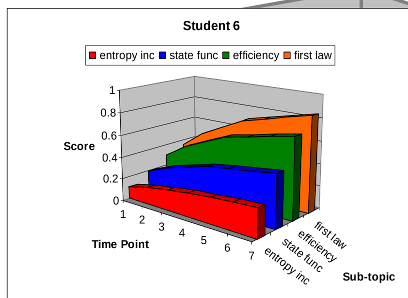
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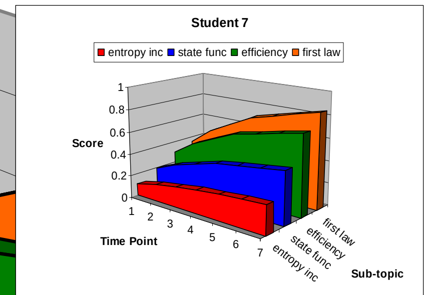
Score
Time Point
Sub-topic

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Score
Time Point
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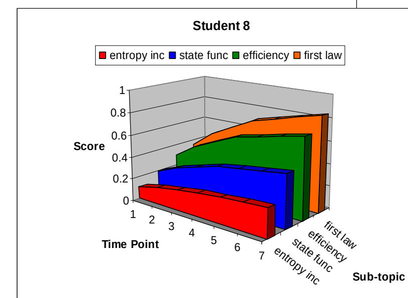
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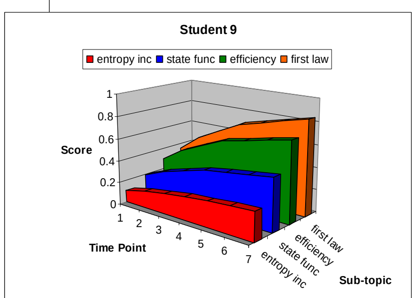
Score
Time Point
Sub-topic

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Score
Time Point
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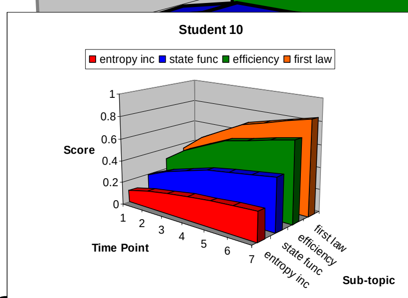
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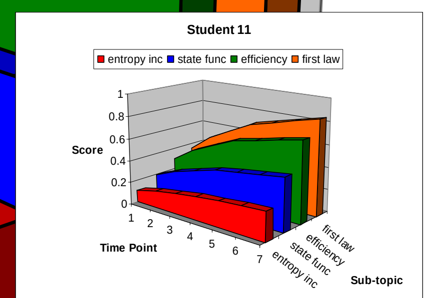
Score
Time Point
Sub-topic

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Score
Time Point
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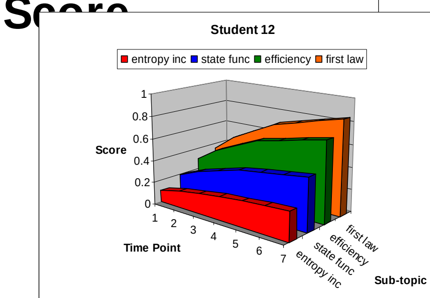
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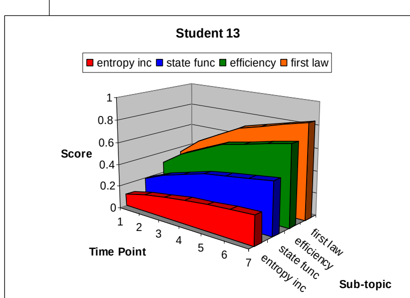
Score
Time Point
Sub-topic

Student 13
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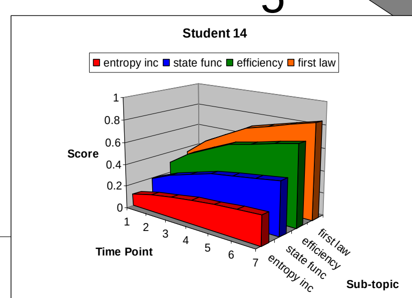
Score
Time Point
Sub-topic

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entropy inc state func efficiency first law
Score
Time Point
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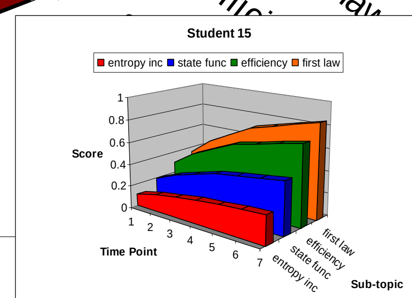
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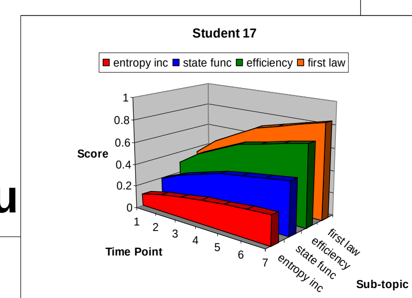
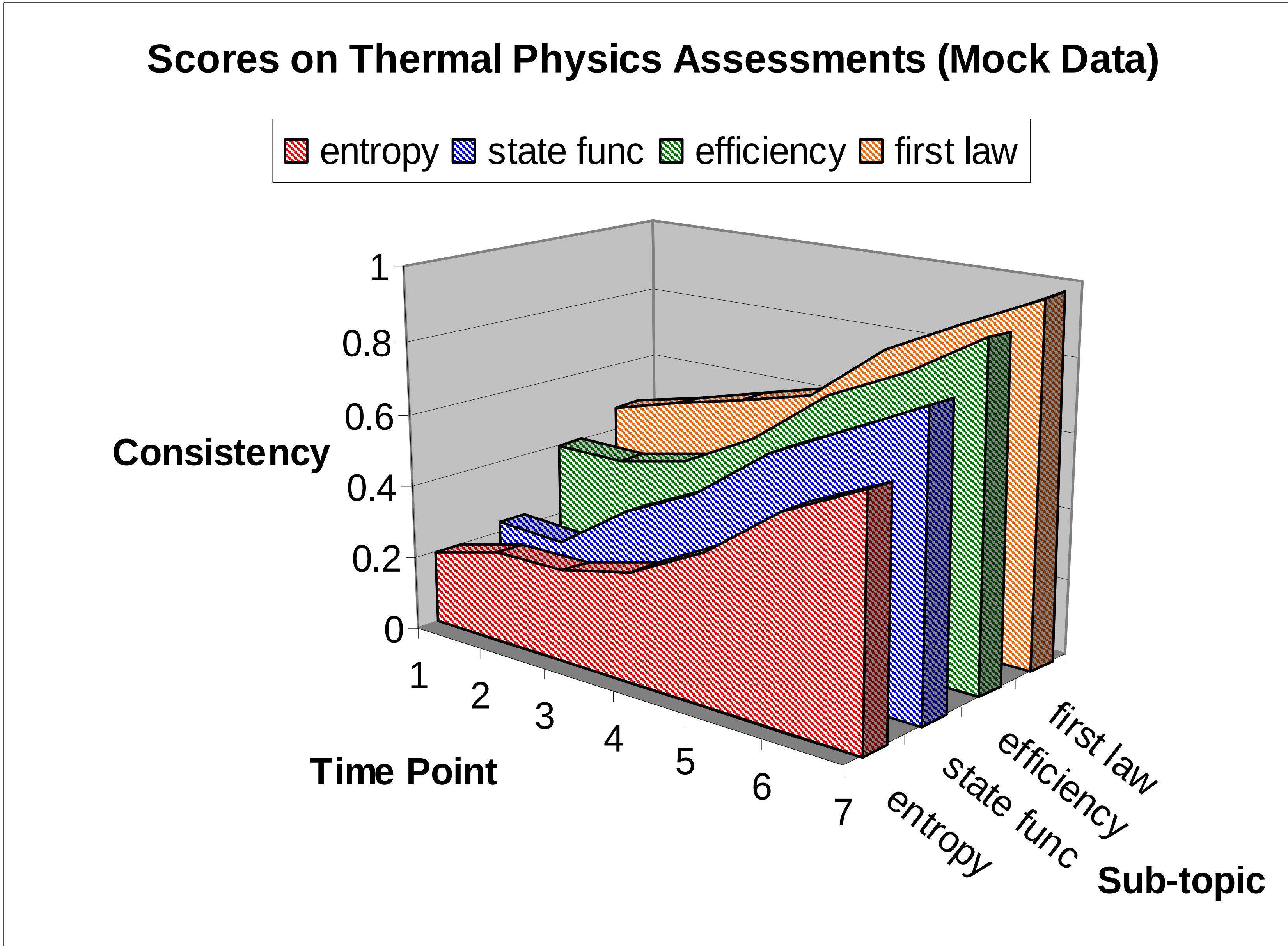
Score
Time Point
Sub-topic

Student 17
entropy inc state func efficiency first law
Score
Time Point
Sub-topic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entropy
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Consistency
1
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Time Point
1
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Sub-topic
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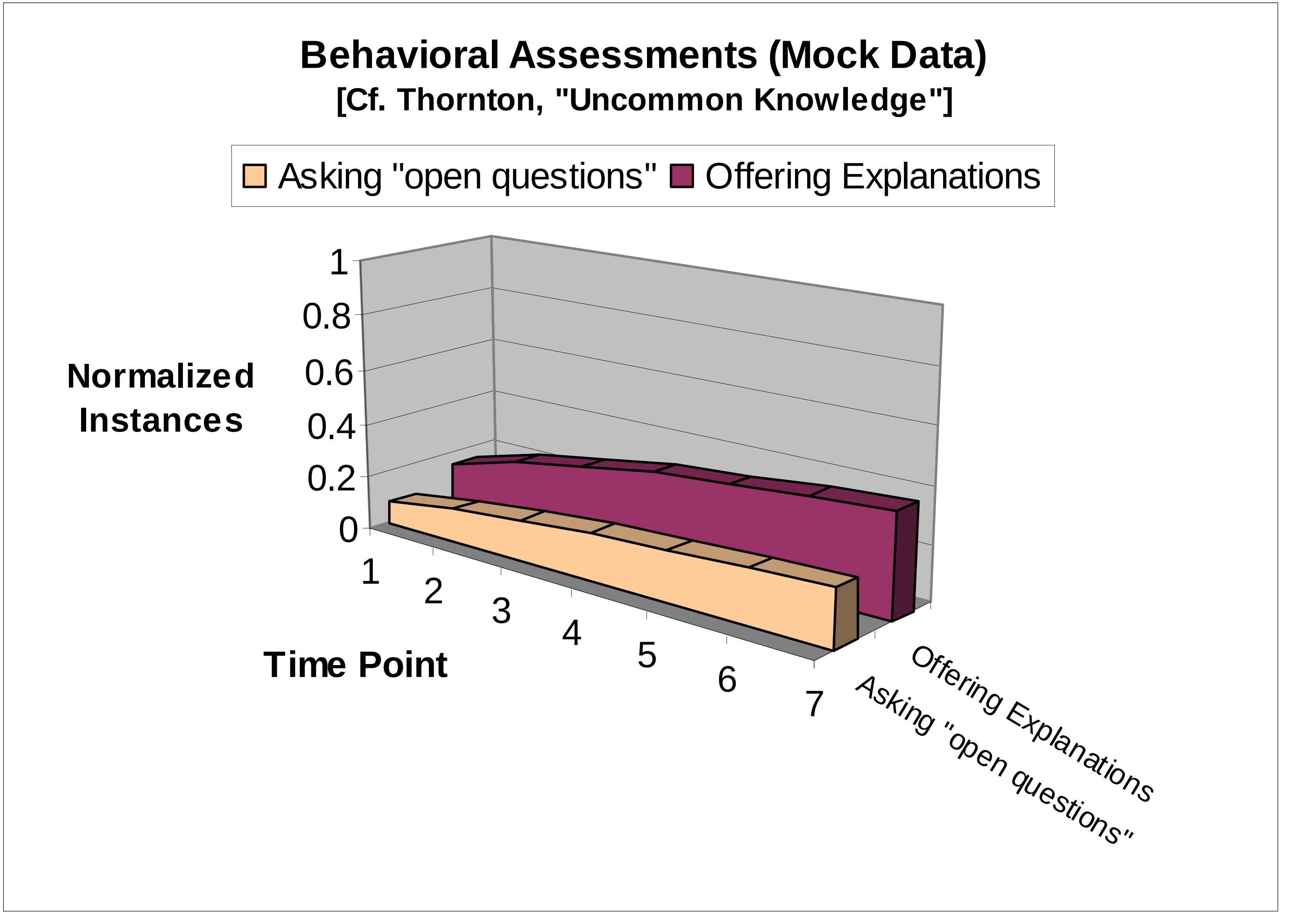
first law



Behavioral Assessments (Mock Data)
[Cf. Thornton, "Uncommon Knowledge"]
Asking "open questions"
Offering Explanations
Normalized Instances
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
Time Point
Offering Explanations
Asking "open questions"

Probing Knowledge State in Depth

- With multiple-choice data:
  - factor analysis
  - concentration analysis (Bao and Redish)
  - analysis of learning “hierarchies”
- With free-response data:
  - in principle, could generate information similar to that yielded by M-C methods
  - logistically more difficult, but perhaps greater reliability?
  - explored little or not at all, so far

Upper-Level Courses

- Vast territory, still little explored by PER
- Research will need to emphasize *development* of students' thinking
  - Need to locate students along learning trajectory from introductory through advanced courses will become unavoidable
- Potential exists to strike strong resonance with traditional physics faculty
  - through development of "helpful" teaching materials and strategies

Assessment of Problem-Solving Ability

- Very difficult to disentangle separate contributions of subject-matter knowledge, reasoning ability, and mathematical problem-solving skills
- Extensive work by many groups to develop rubrics for assessing general problem-solving ability
- Promising approach: analysis of students' varied "solution pathways"
  - In chemistry context, differences among demographic groups have apparently been demonstrated

Investigating Students' Reasoning Through Detailed Analysis of Response Patterns

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  - R. J. Dufresne, W. J. Leonard, and W. J. Gerace, 2002.
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- 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" (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.

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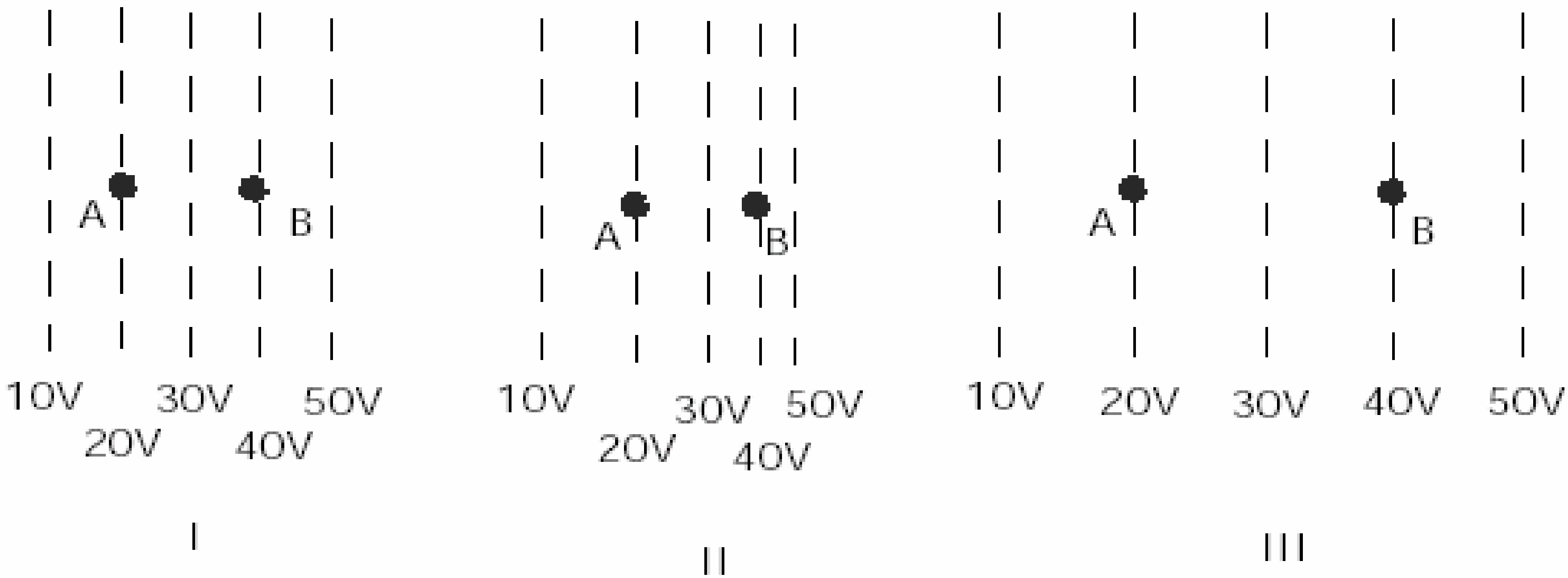
- Only about one third of students have had any previous exposure to electricity and/or magnetism concepts.

- *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.

#26-28

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.



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

#26

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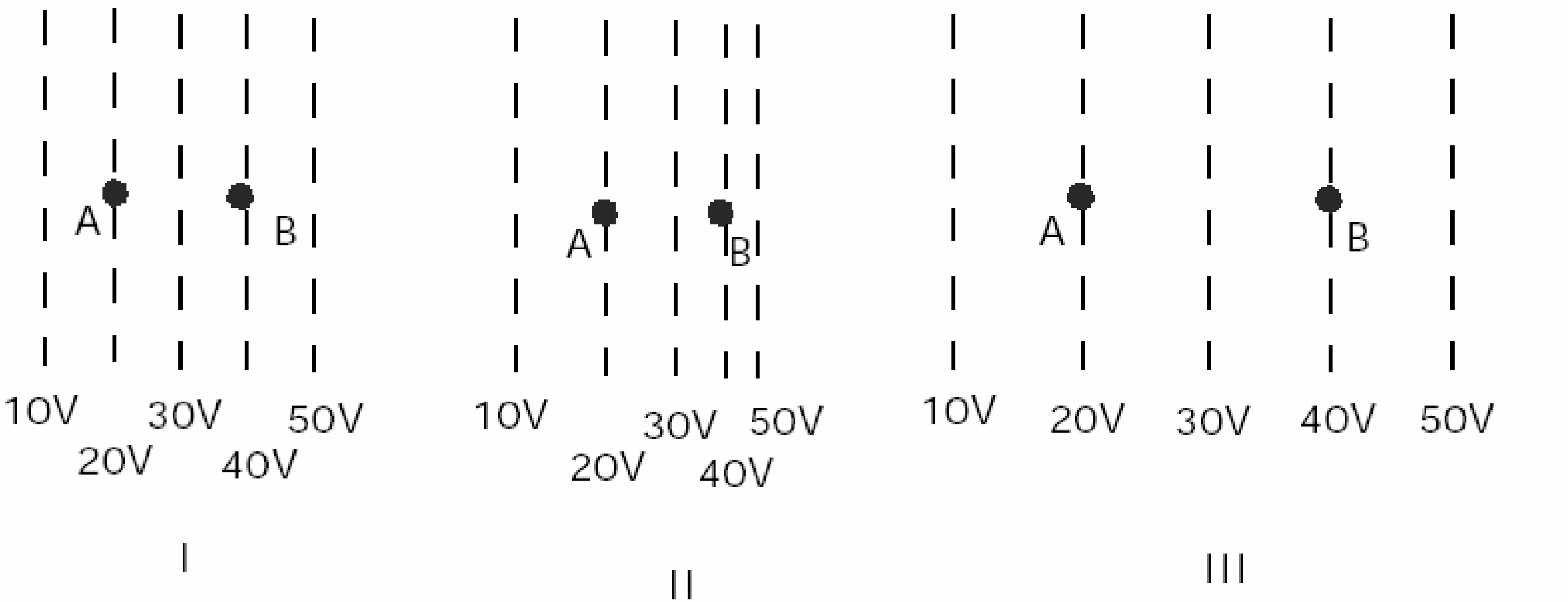

How does the amount of work needed to move this charge compare for these three cases?

(a) Most work required in I.
(b) Most work required in II.
(c) Most work required in III.
(d) I and II require the same amount of work but less than III.
(e) All three would require the same amount of work.

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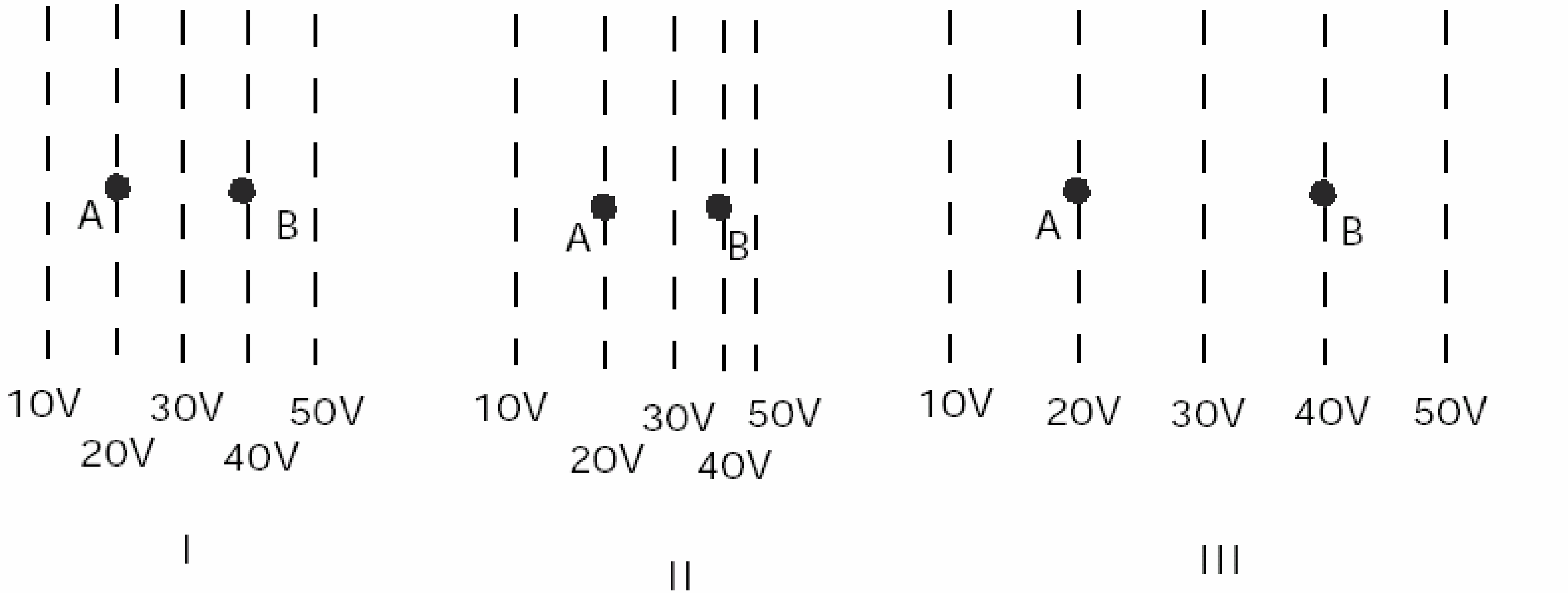

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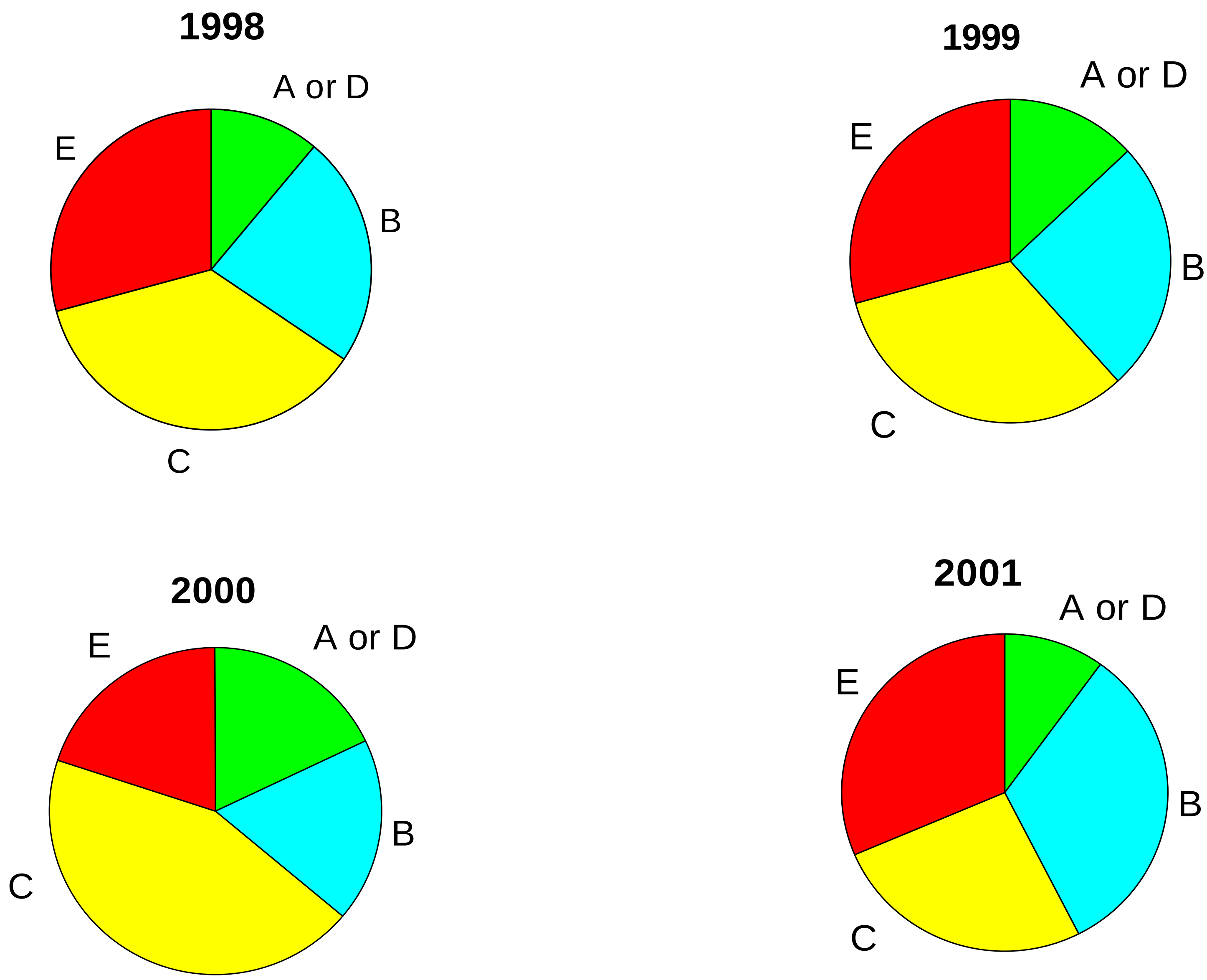
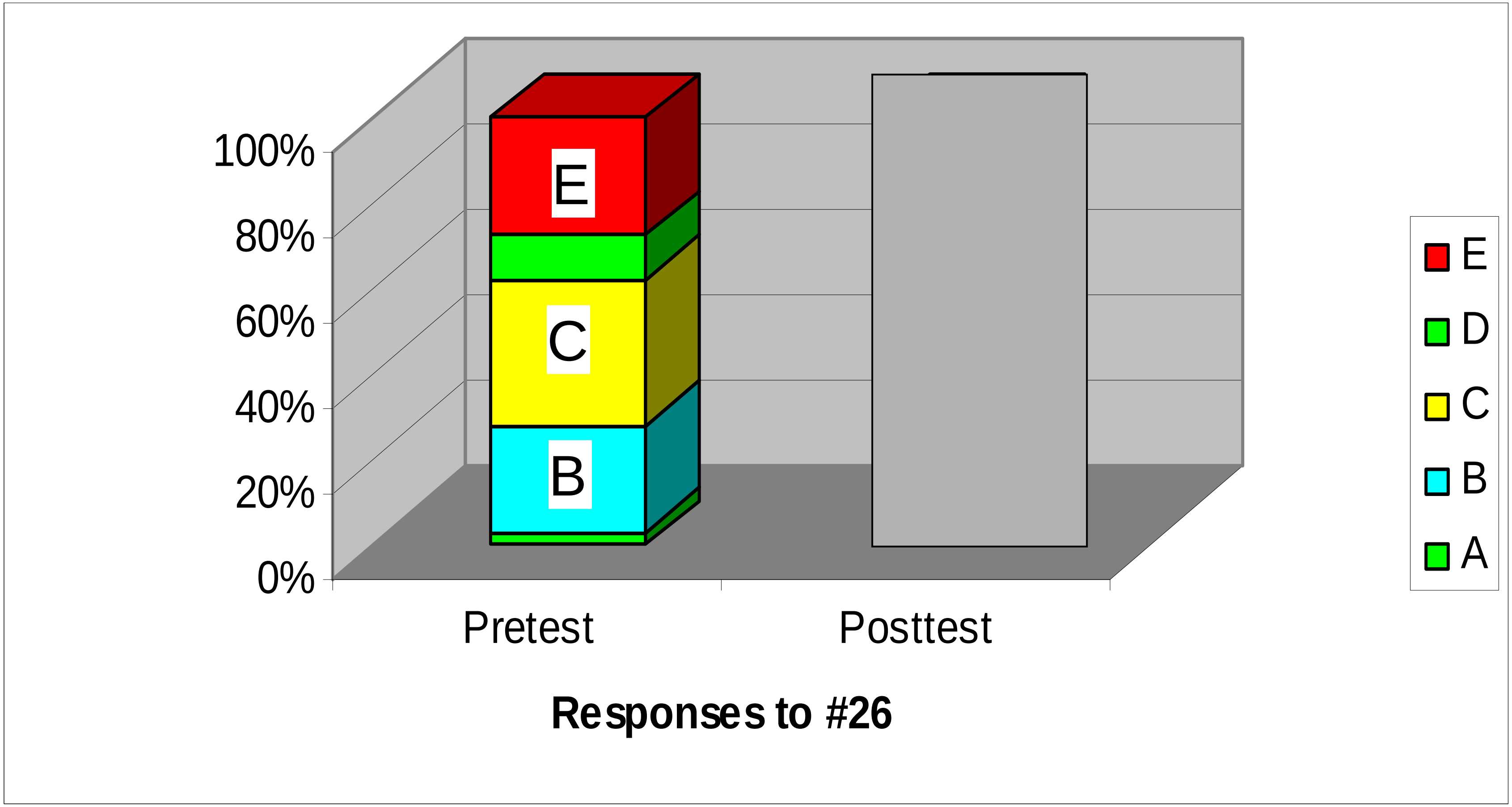
$W = q\Delta V$; equal in I, II, and III

Pre-Instruction Responses to Question #26





1998-2001

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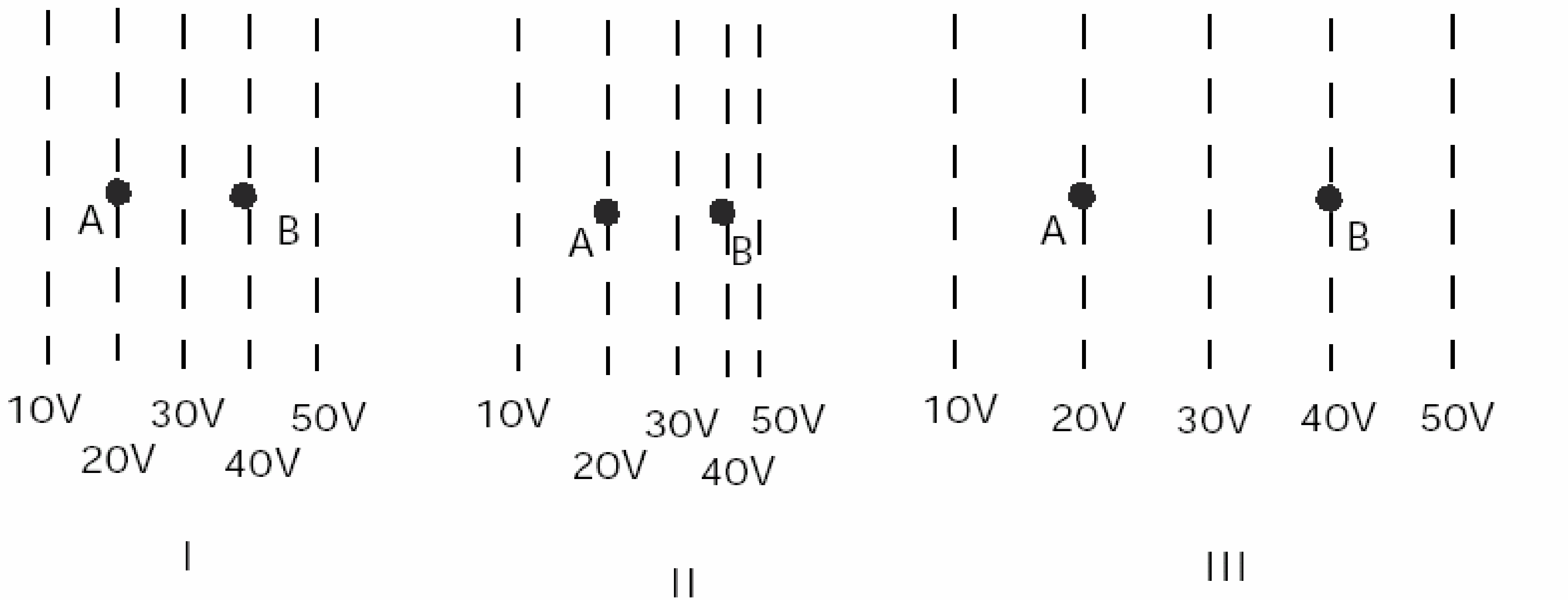

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Explanations for #26

(Pre-Instruction: 60-90% categorizable)

- Response “B”
  - “Because the fields increase in strength as the object is required to move through it”
  - “Because the equipotential lines are closest together”

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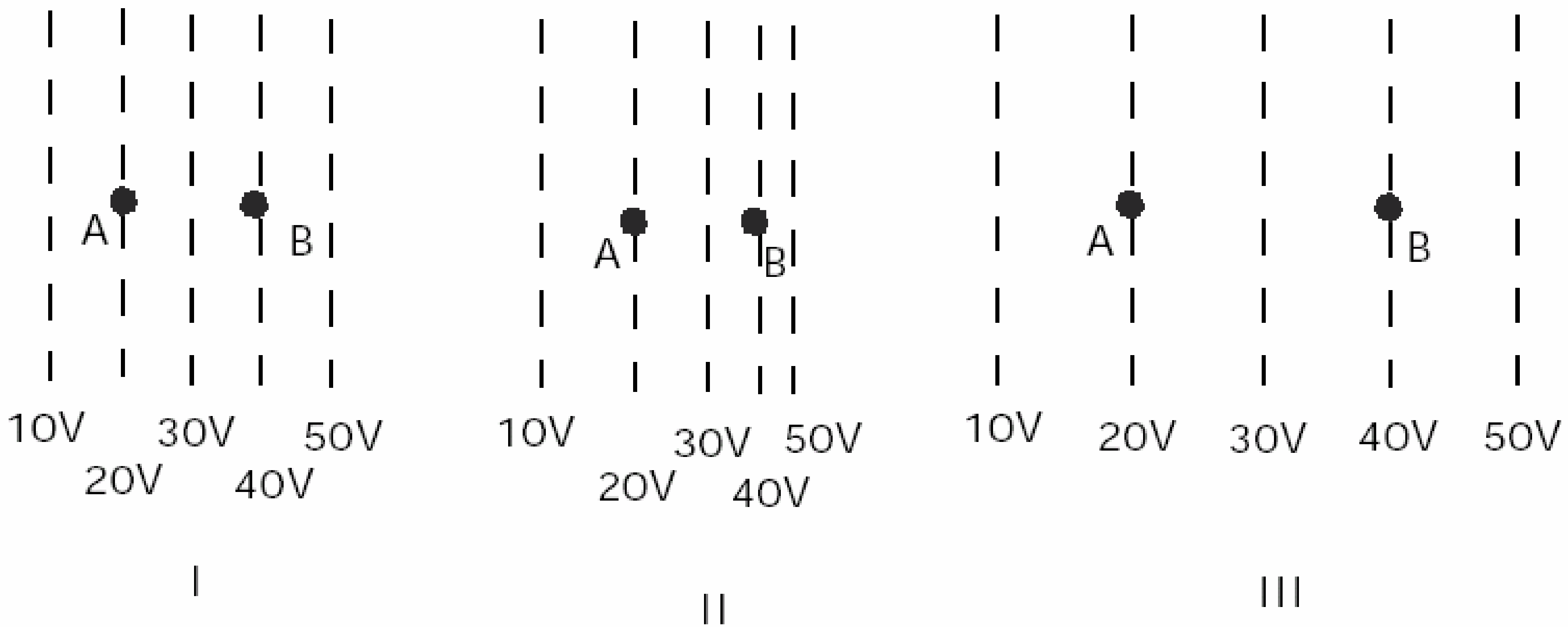

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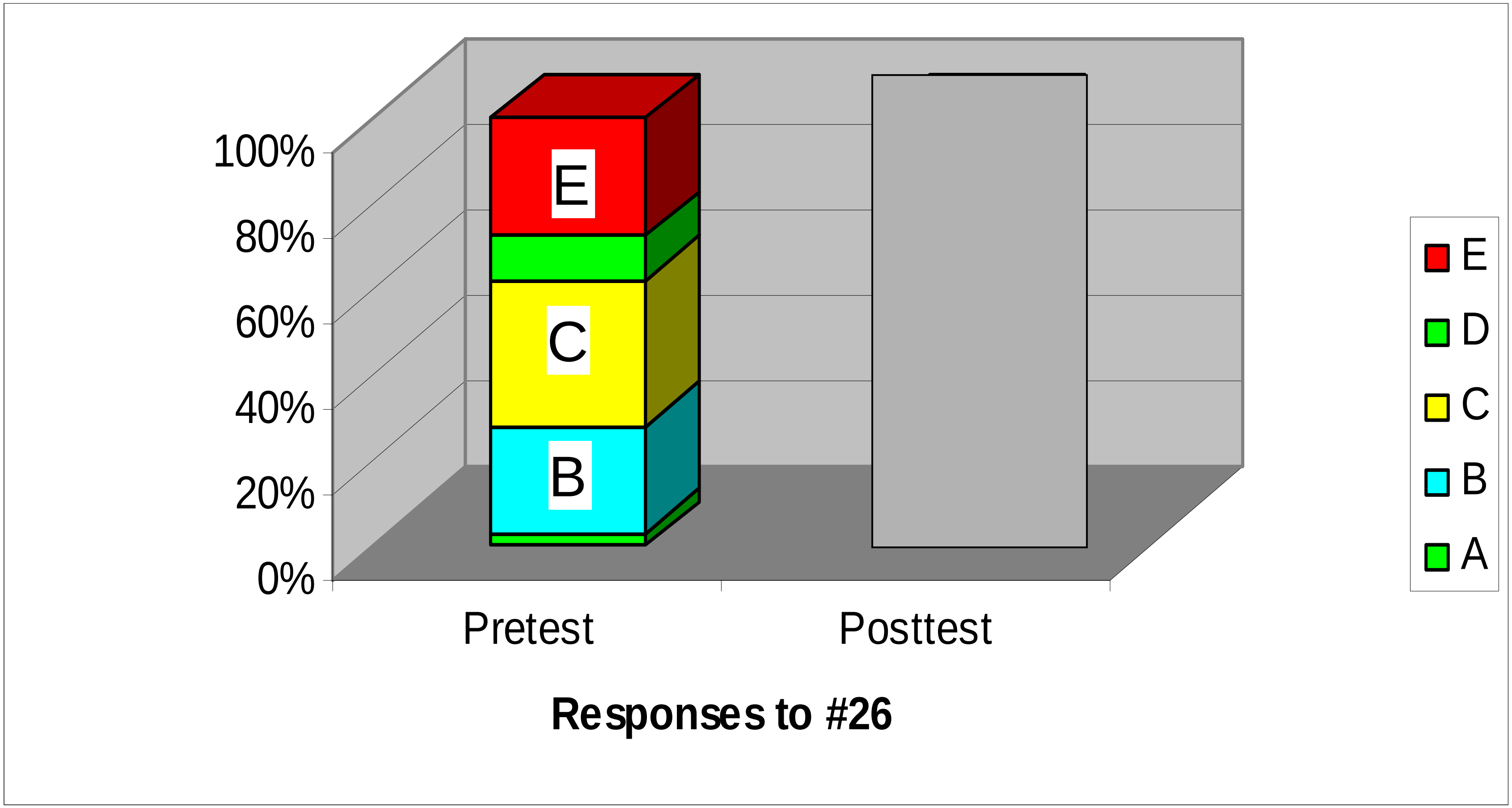
- Response “E” [*correct*]
  - “The electric potential difference is the same in all three cases”



1998-2001

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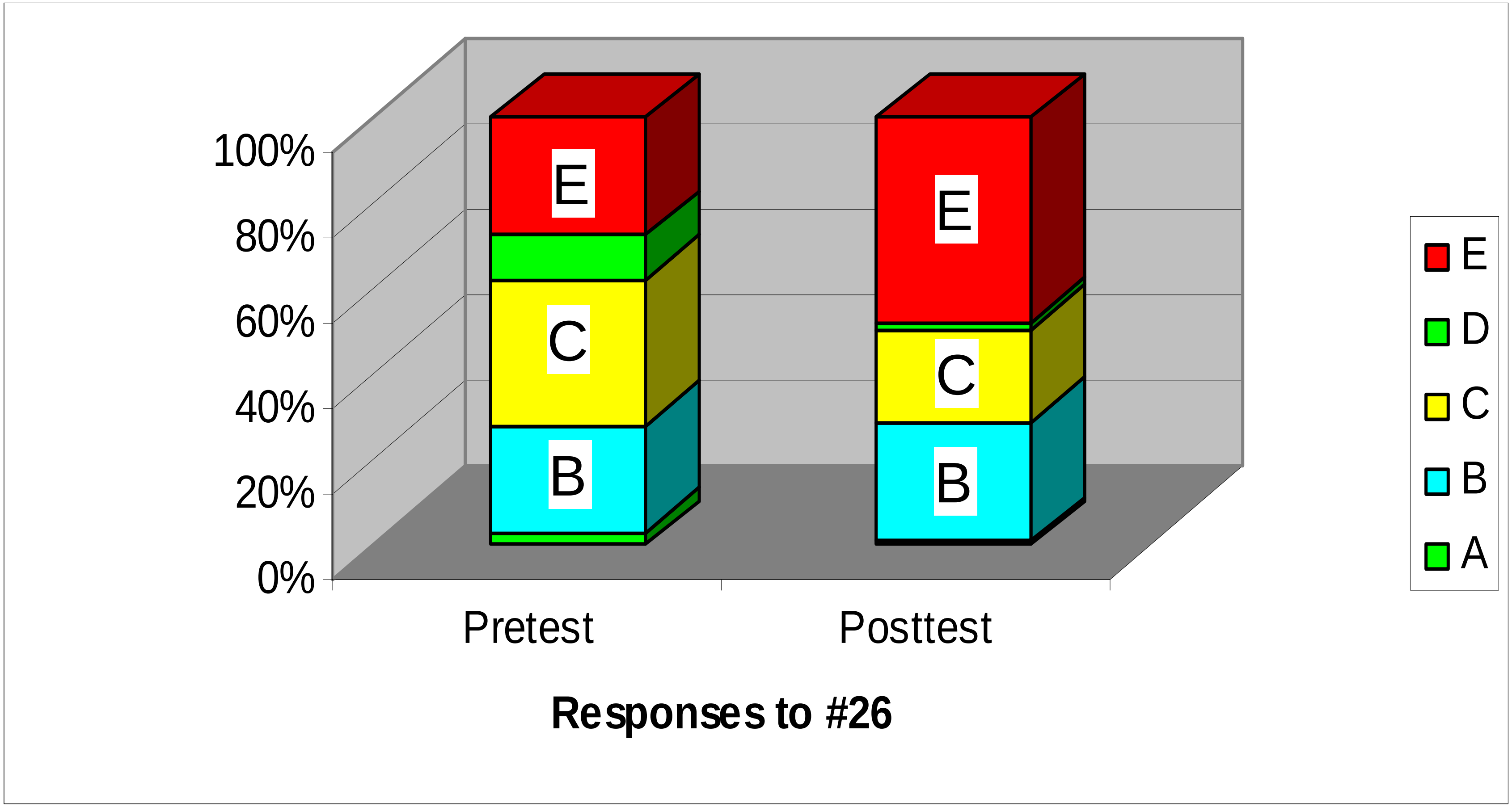

1998-2001
N = 299

Explanations for #26

(Post-Instruction: 70-100% categorizable)

- Proportion giving response “B” almost unchanged
  - “Because equipotential lines in II are closer together, the magnitude of the electric force is greater and would need the most work to move the charges”

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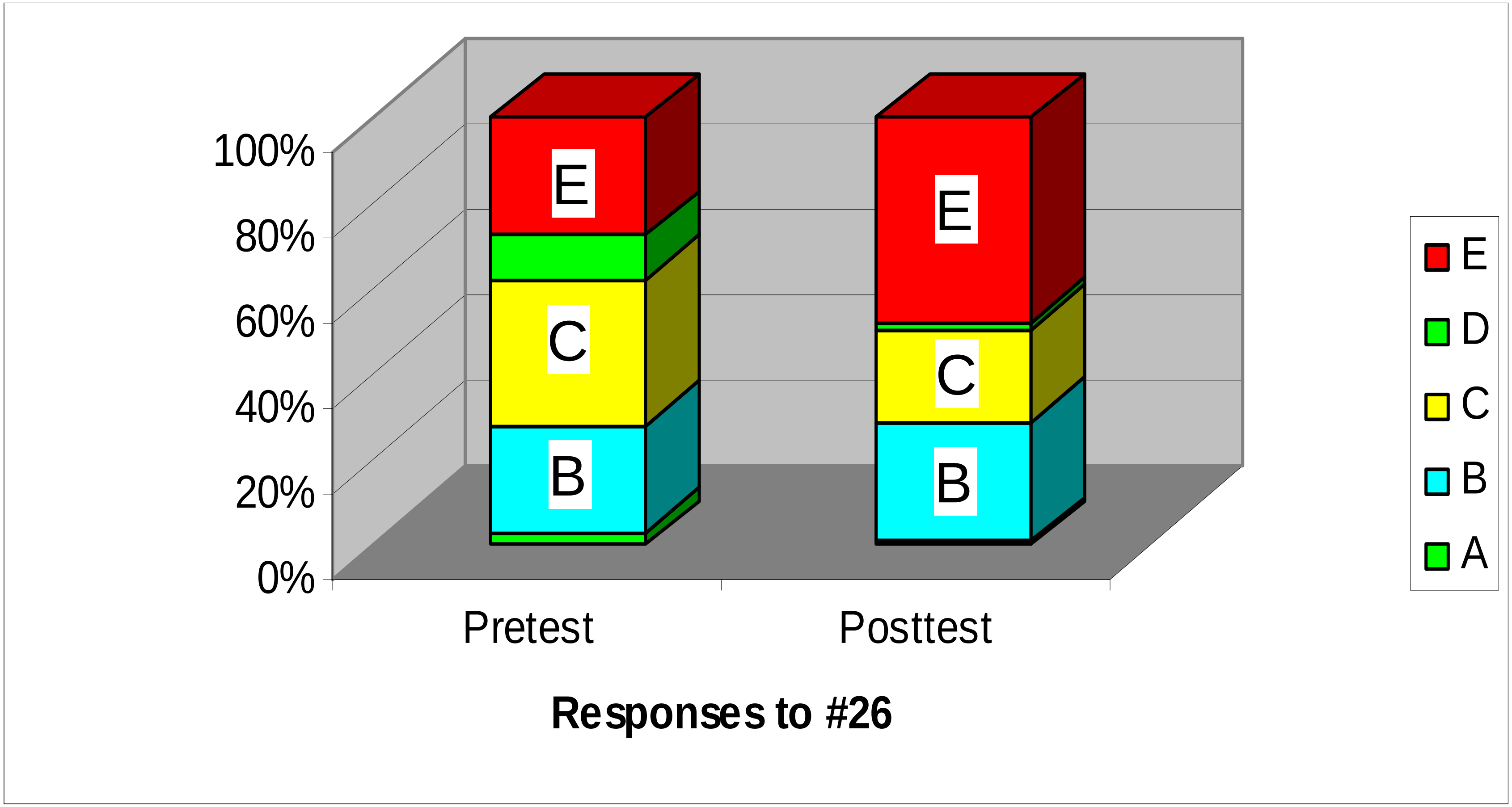
- Proportion giving response “C” decreases
  - “When the equipotential lines are farther apart it takes more work to move the charge”
- Proportion giving correct response “E” increases
  - “Because the charge is moved across the same amount of potential in each case”



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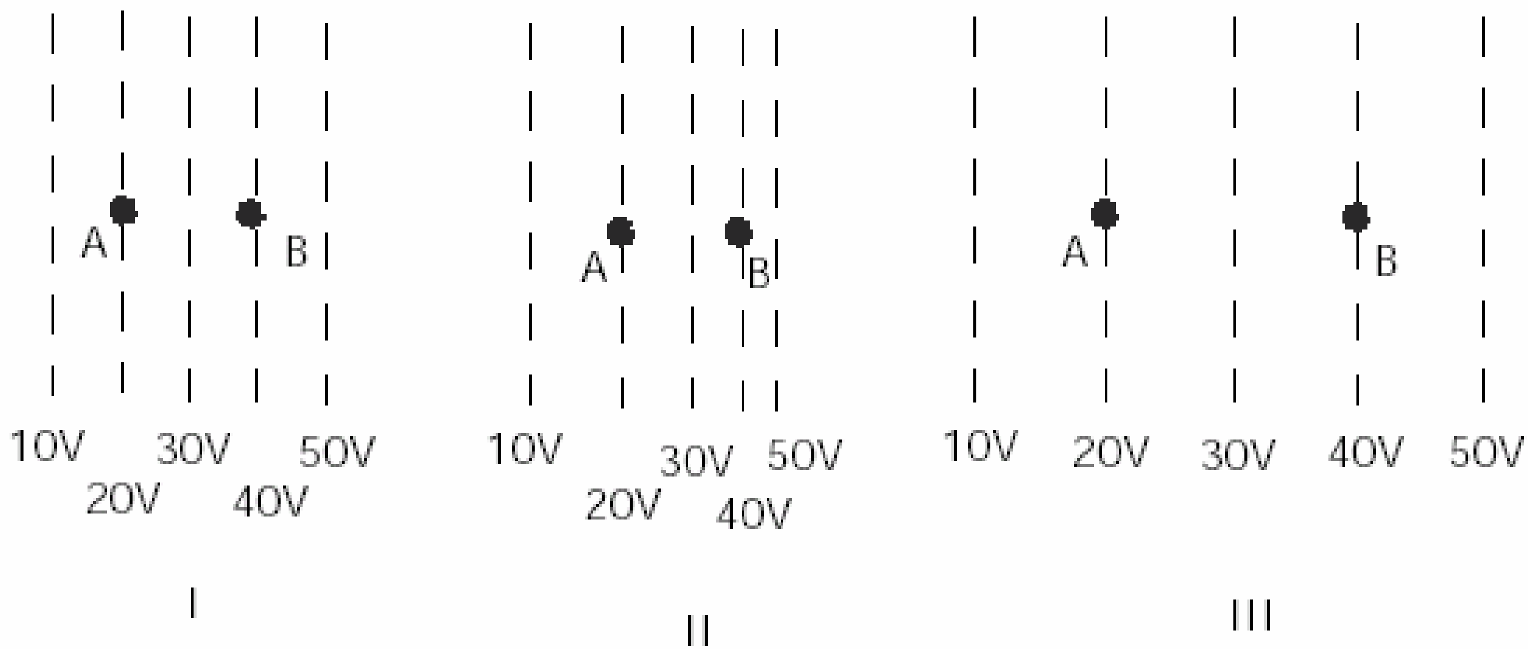

How does the magnitude of the electric field at B compare for these three cases?

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

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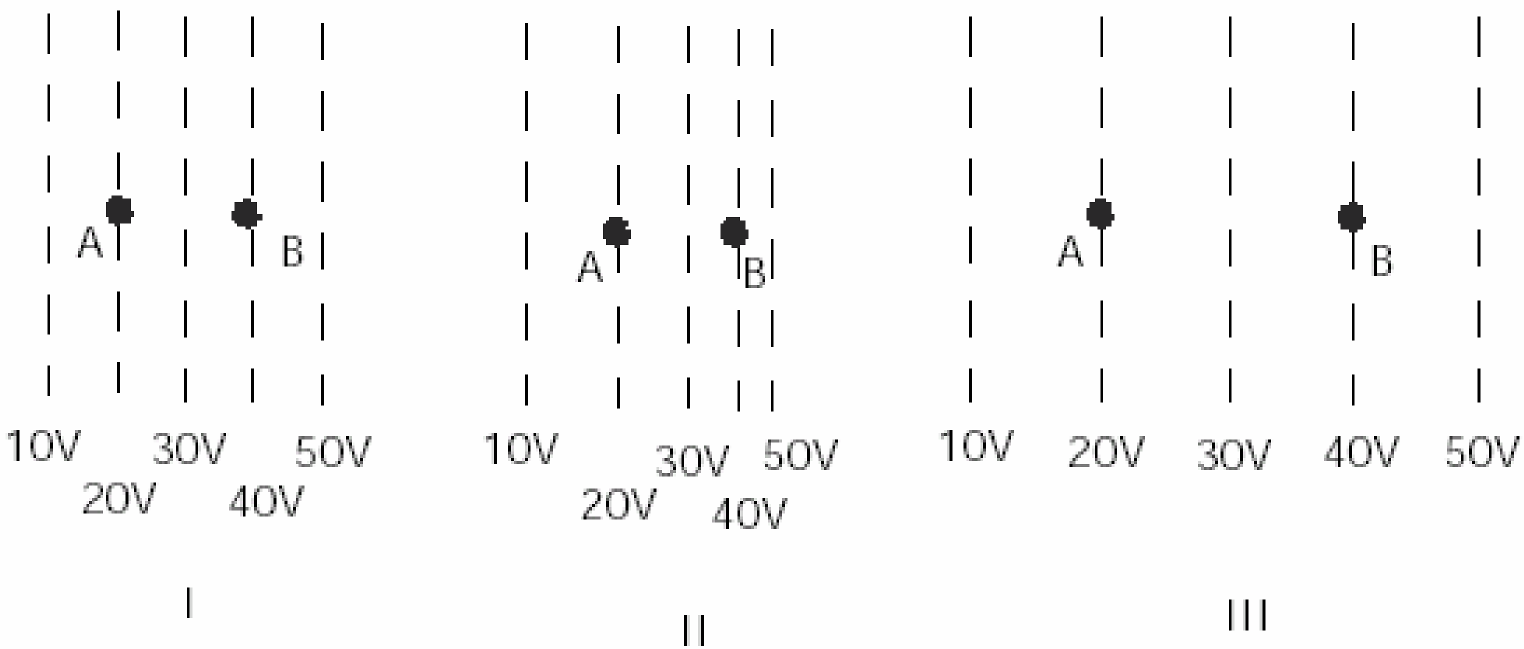


How does the magnitude of the electric field at B compare for these three cases?

(a) I > III > II

(b) I > II > III

(c) III > I > II

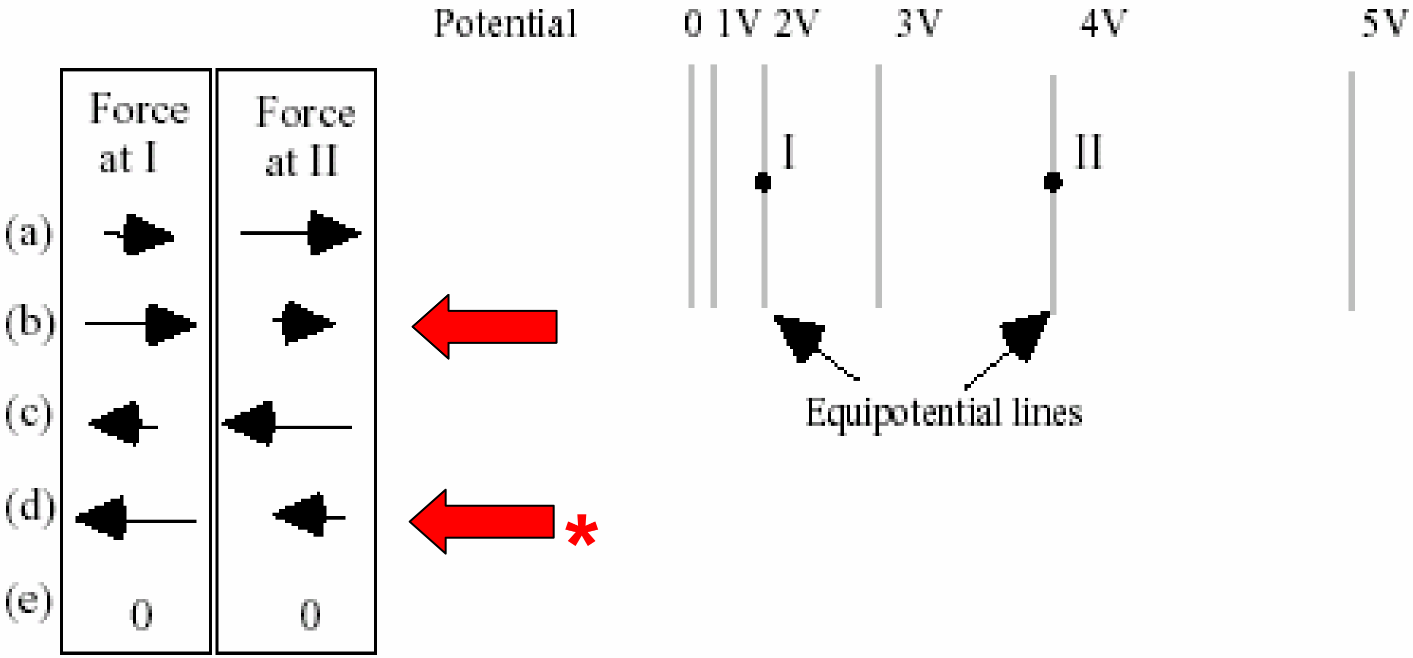
(d) II > I > III **[correct]**

(e) I = II = III

closer spacing of equipotential lines ⇒ larger magnitude field

#30

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 #27

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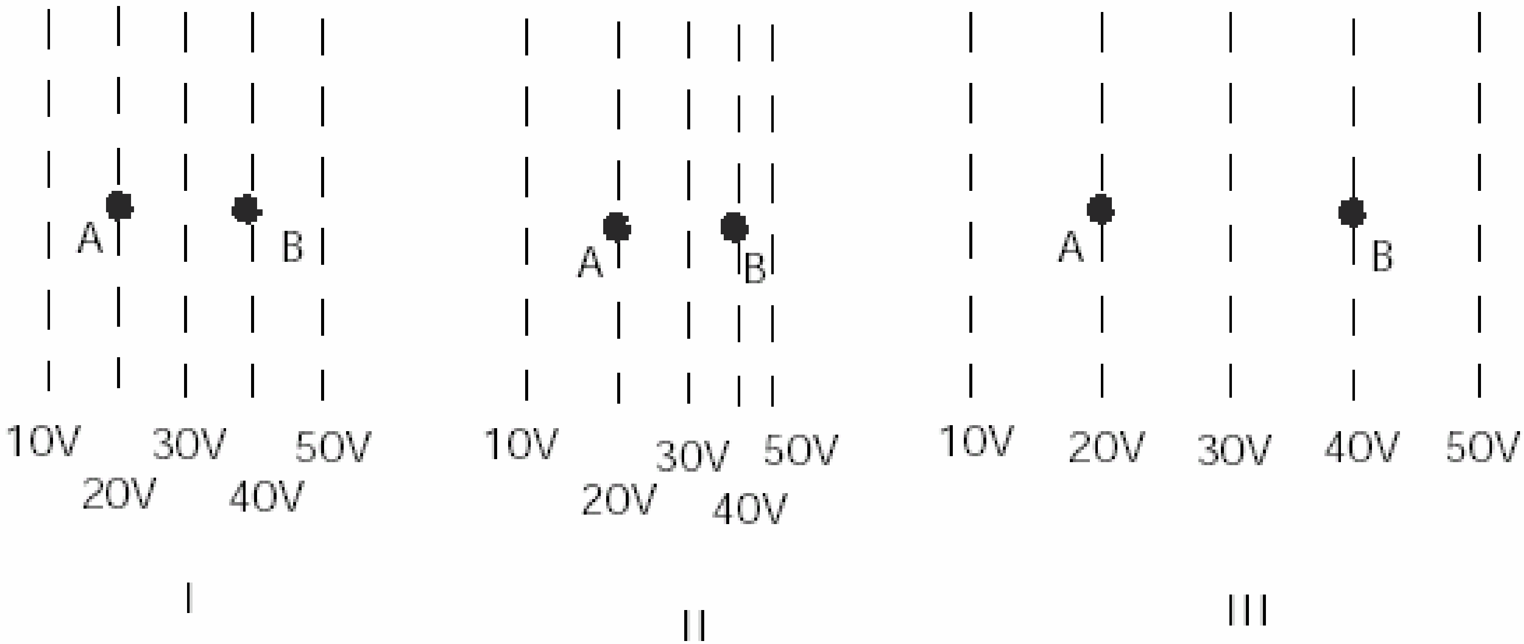

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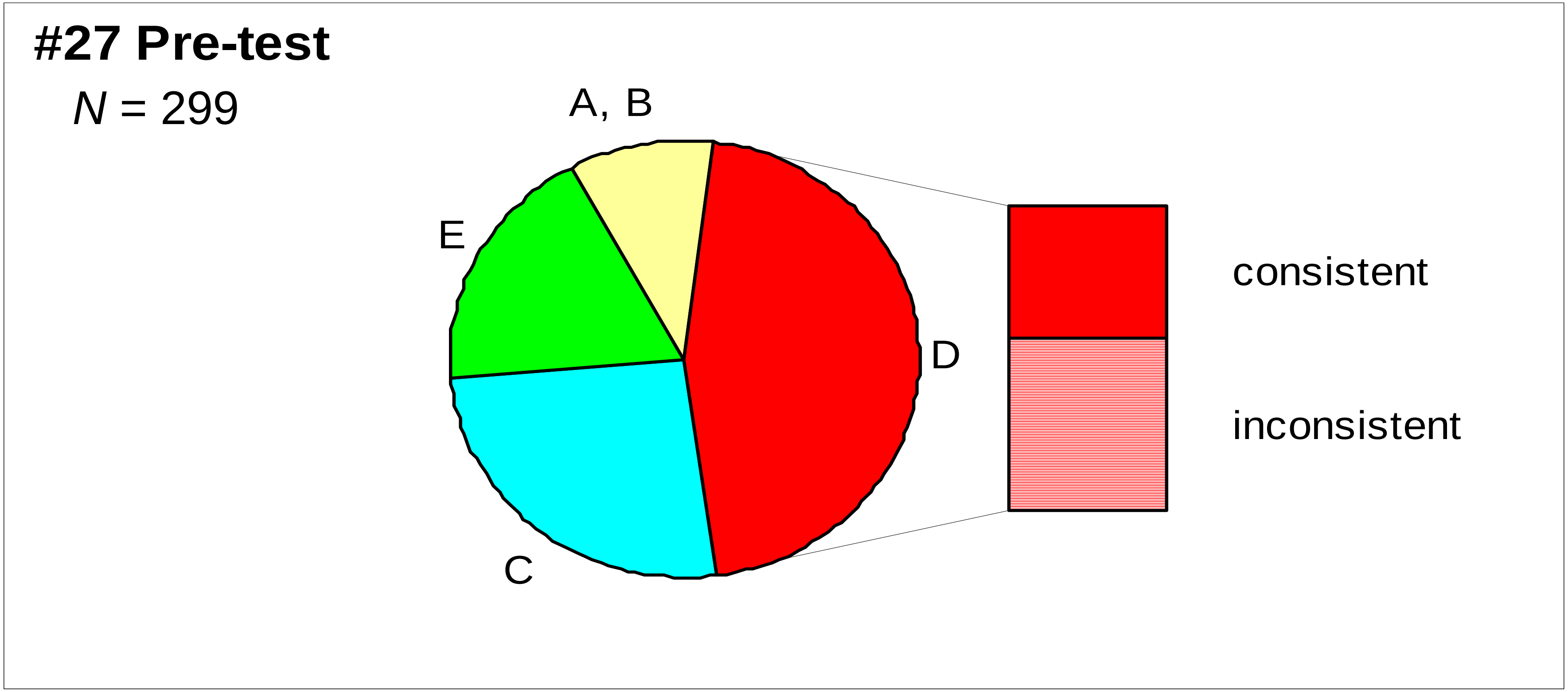
closer spacing of equipotential lines ⇒ larger magnitude field

Pre-Instruction



“D”: *closer spacing of equipotential lines ⇒ stronger field*

“consistent”: *consistent with answer on #30* *(but some guesses)*

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

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- 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”

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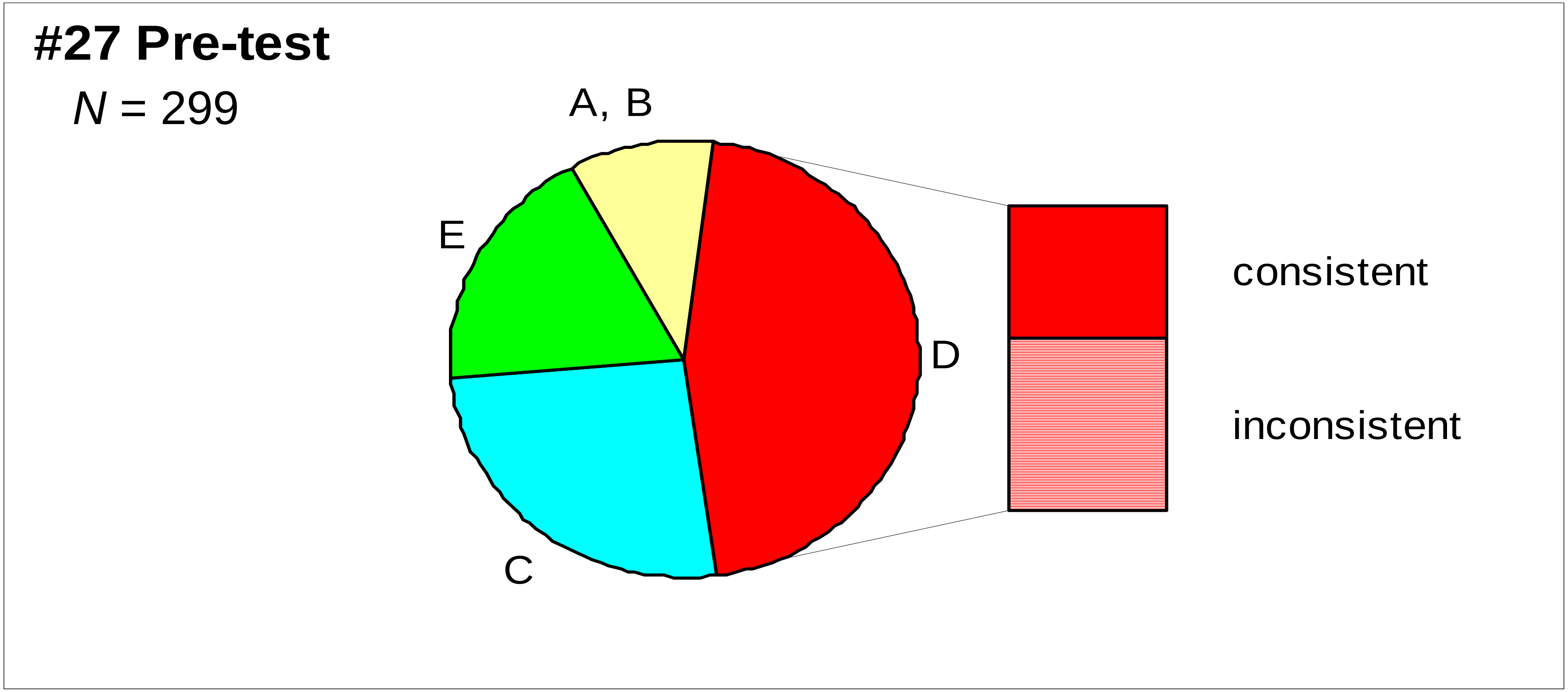
students' initial "intuitions" may influence their learning

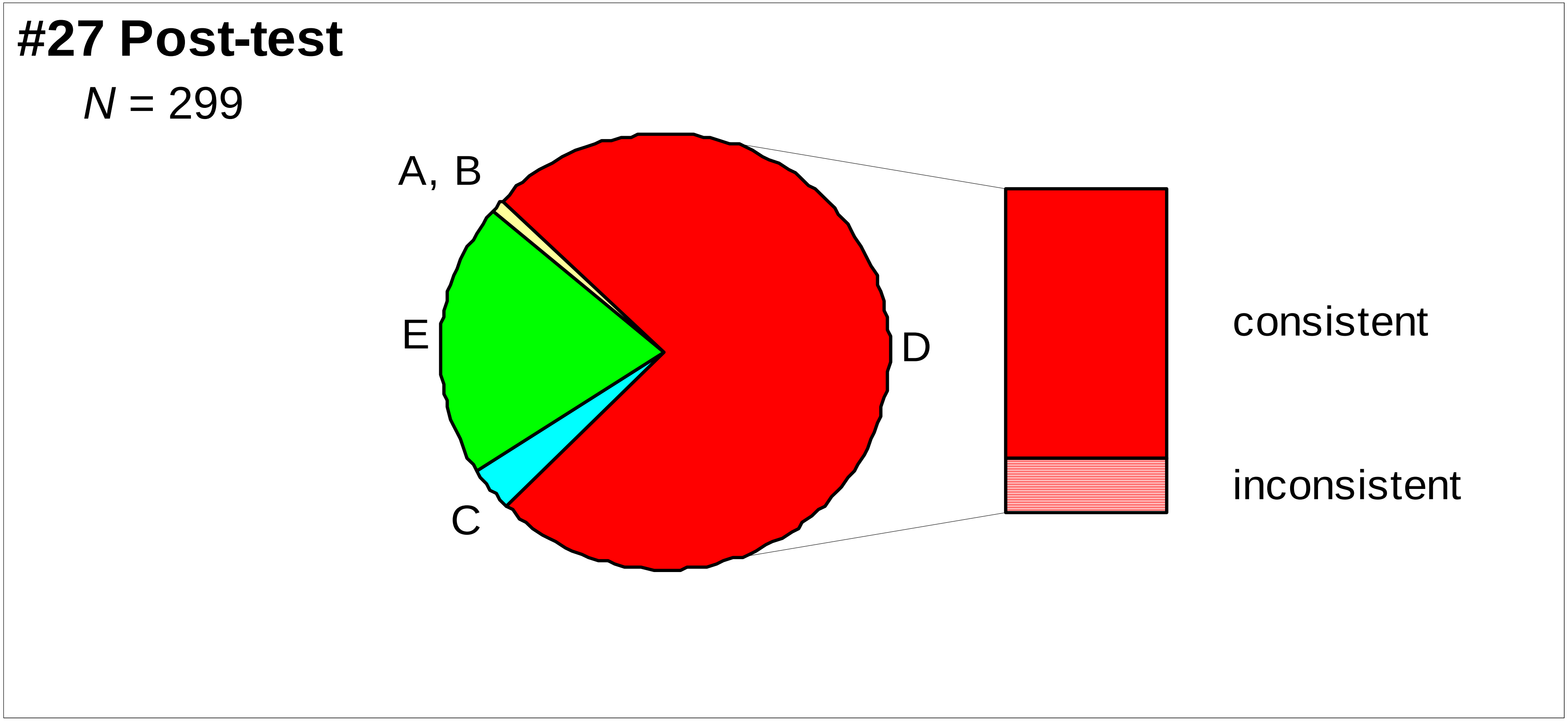
Pre-Instruction



“D”: ***closer spacing of equipotential lines ⇒ stronger field***

“consistent”: ***consistent with answer on #30*** ***(but some guesses)***

Post-Instruction



- **Sharp increase in correct responses**
- **Correct responses *more consistent* with other answers**

(and most explanations actually* are *consistent)

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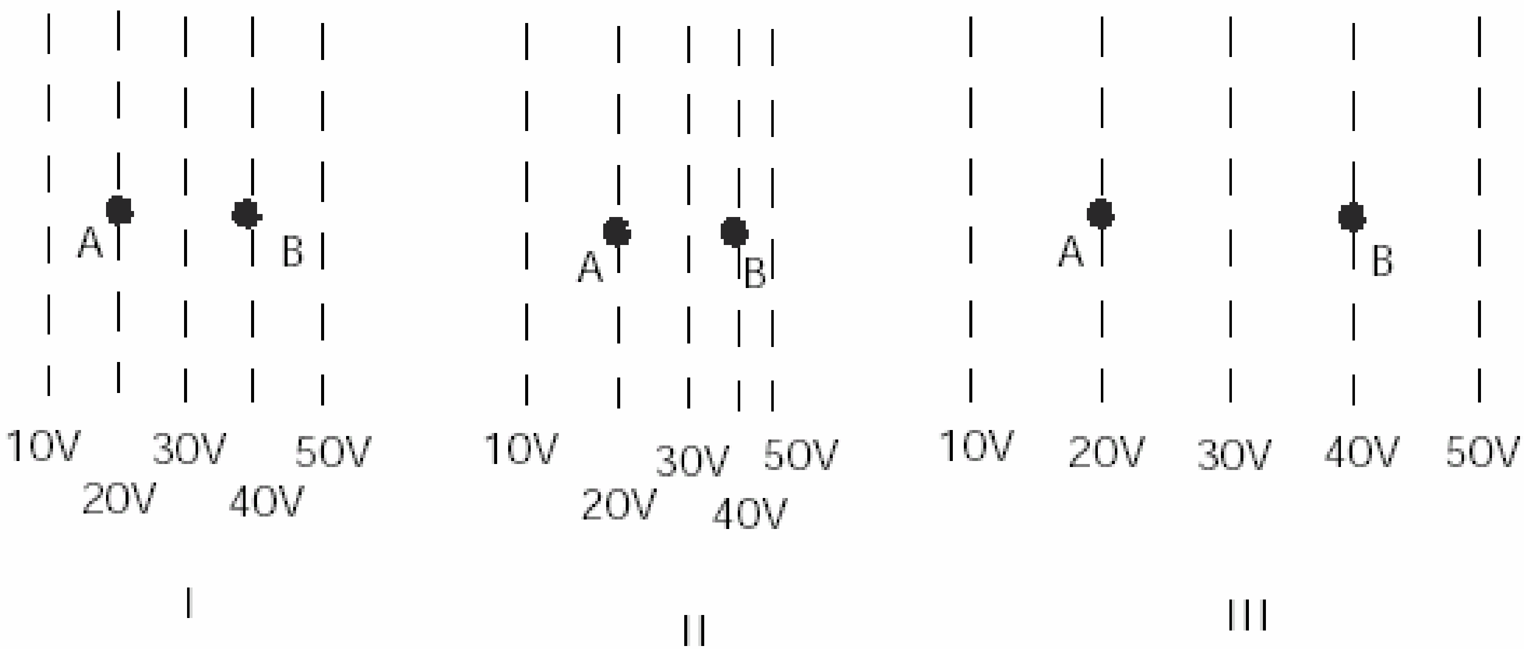


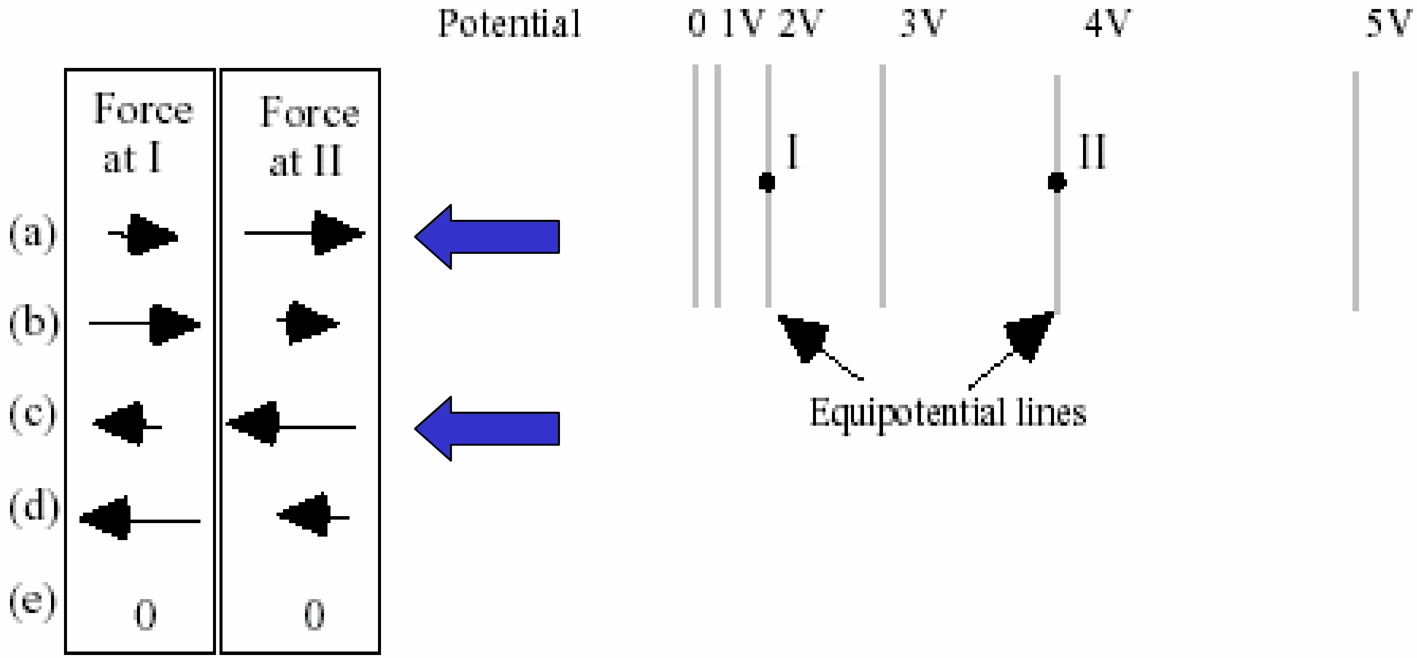
How does the magnitude of the electric field at B compare for these three cases?

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

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

#30

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 “C” response on #27

#27

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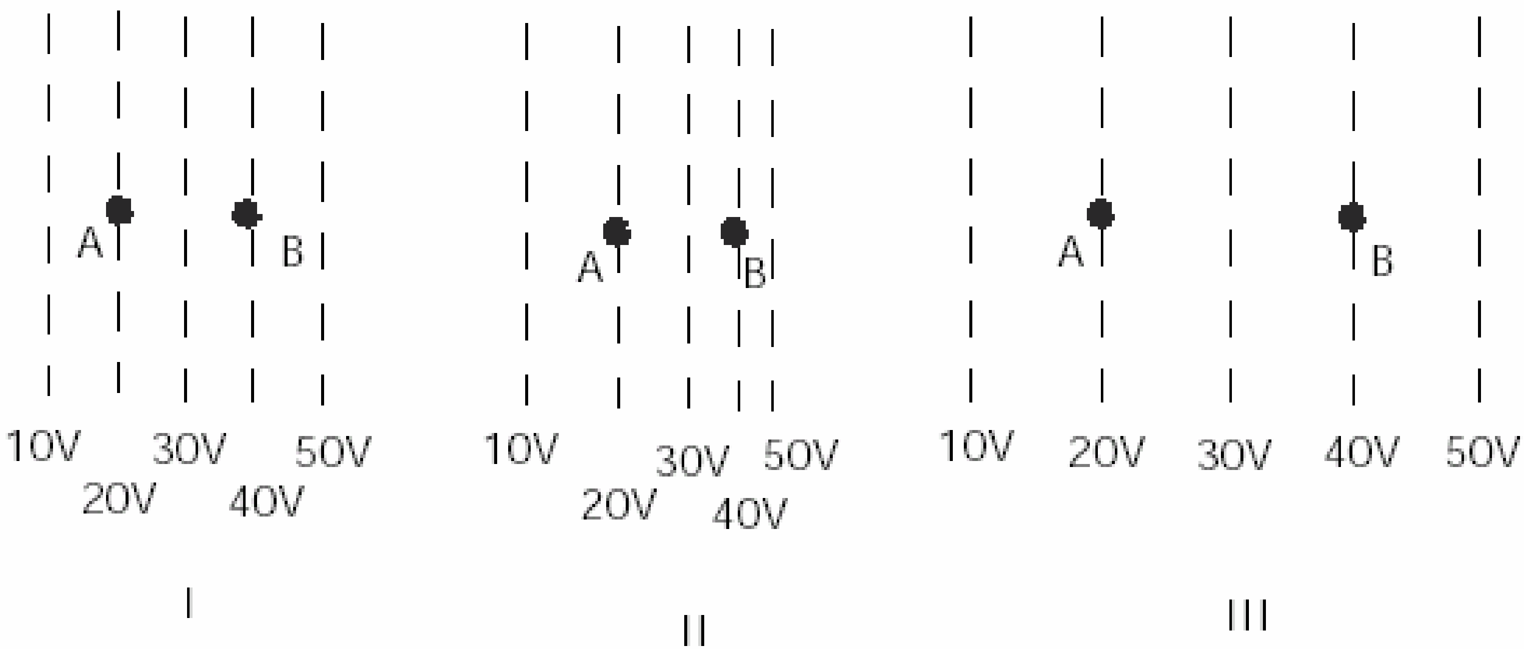

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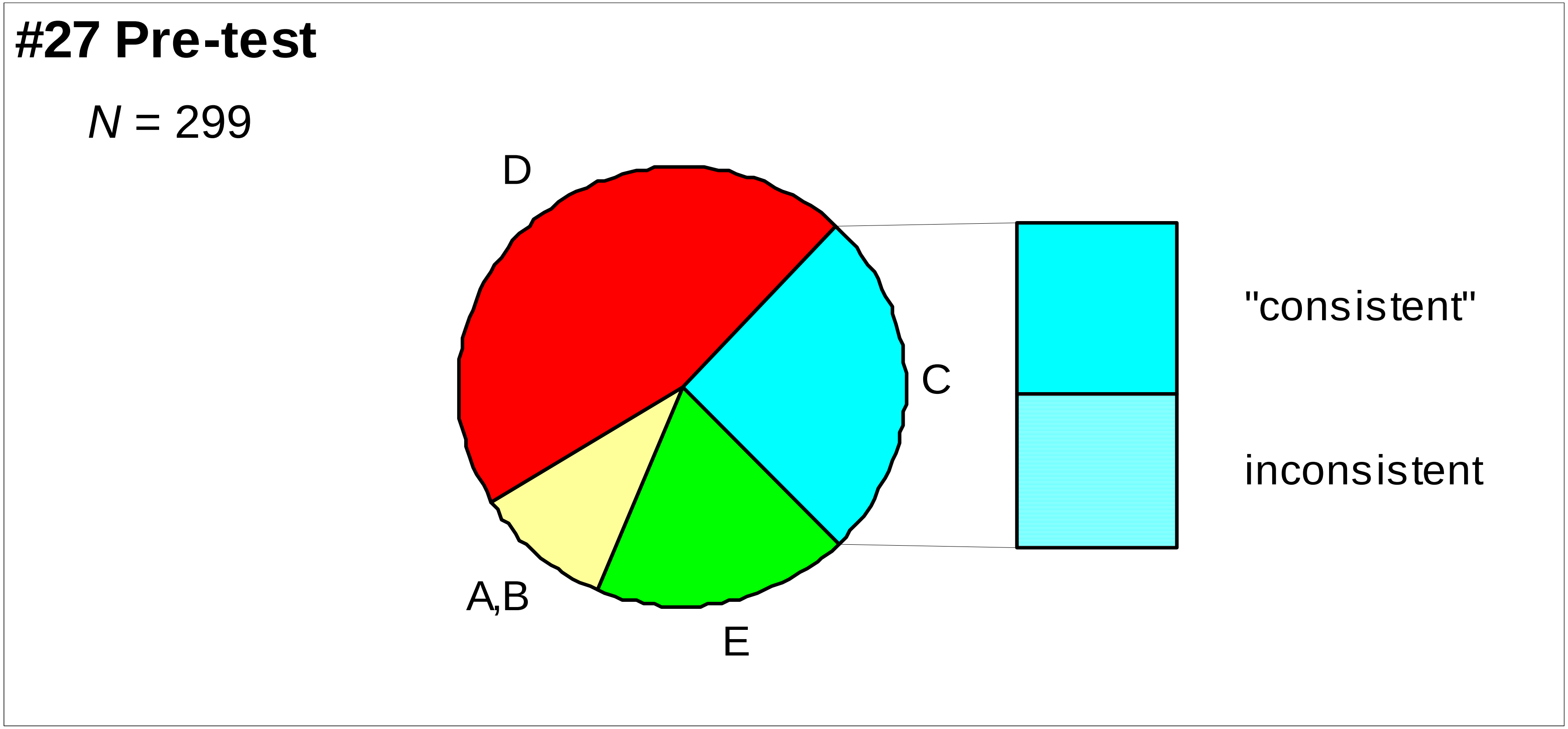
"C": wider spacing of equipotential lines ⇒ stronger field

Pre-Instruction



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

"consistent": <u>apparently</u> *consistent with answer on #30*

(but many inconsistent explanations)

Students' Explanations for Response "C" (Pre-Instruction)

- "III is the farthest apart, then I and then 2."

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- "The equipotential lines are farther apart so a greater magnitude is needed to maintain an electrical field."

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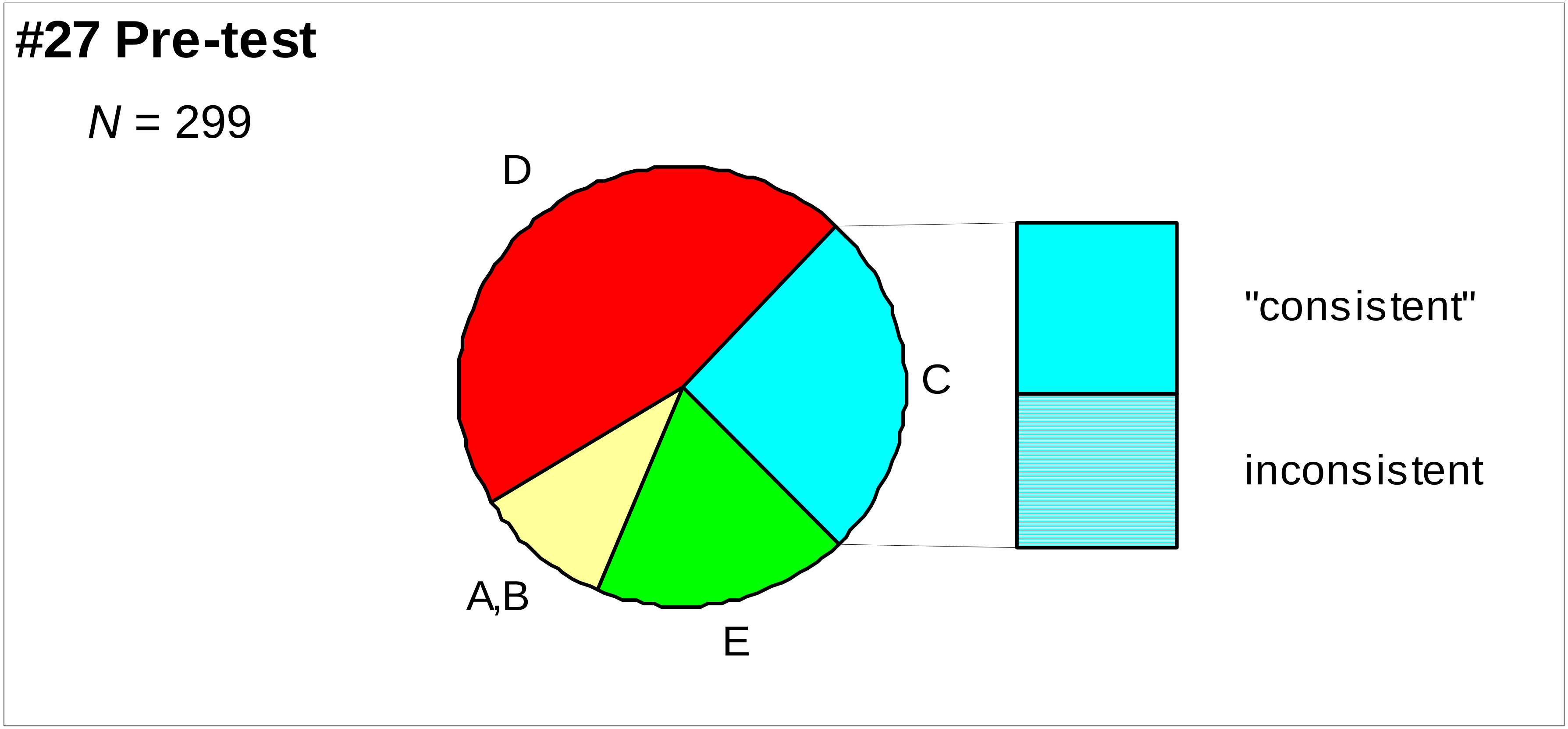
- "III is the farthest apart, then I and then 2."
- "The equipotential lines are farther apart so a greater magnitude is needed to maintain an electrical field."
- "I guessed."

Pre-Instruction

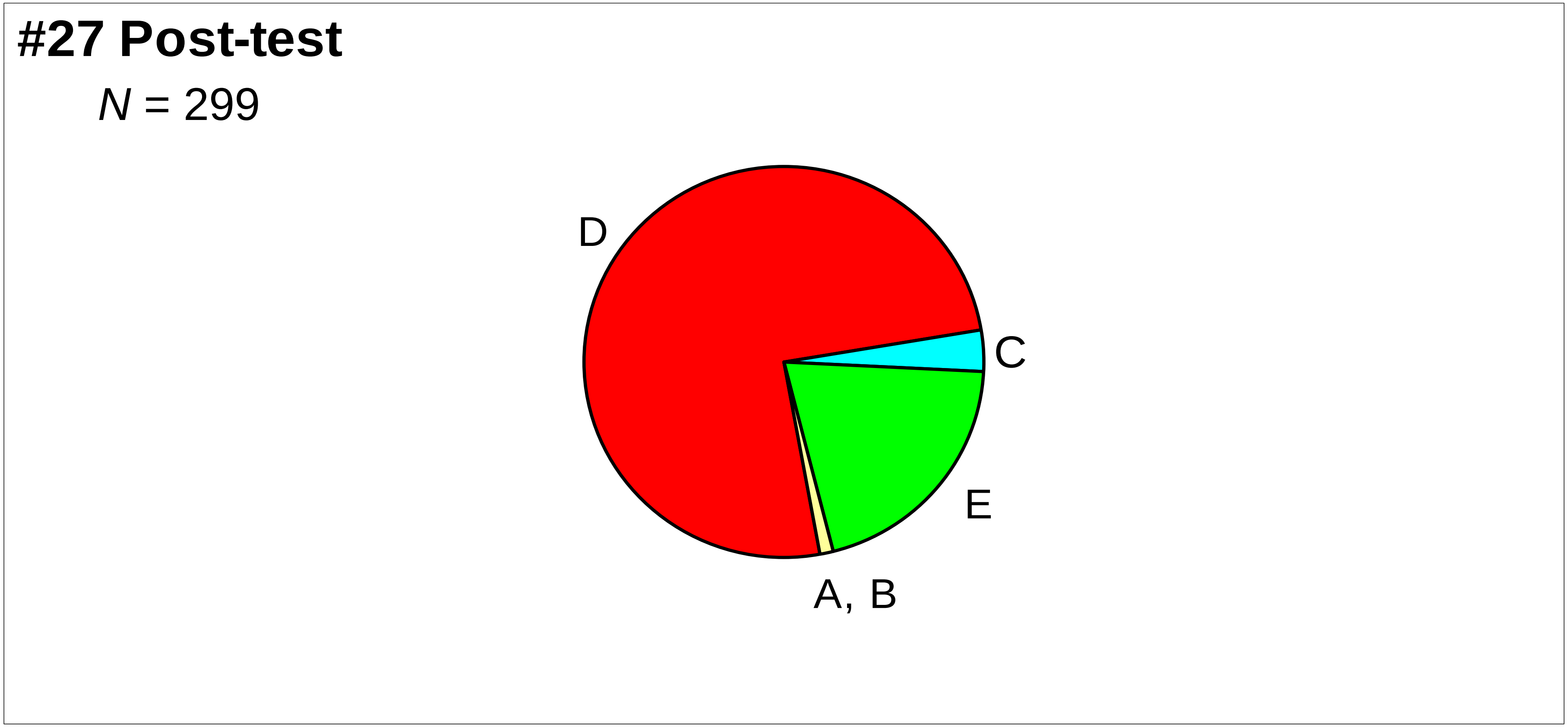


"C": wider spacing of equipotential lines ⇒ stronger field

"consistent": <u>apparently</u> *consistent with answer on #30*

(but many inconsistent explanations)

Post-Instruction



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

#27

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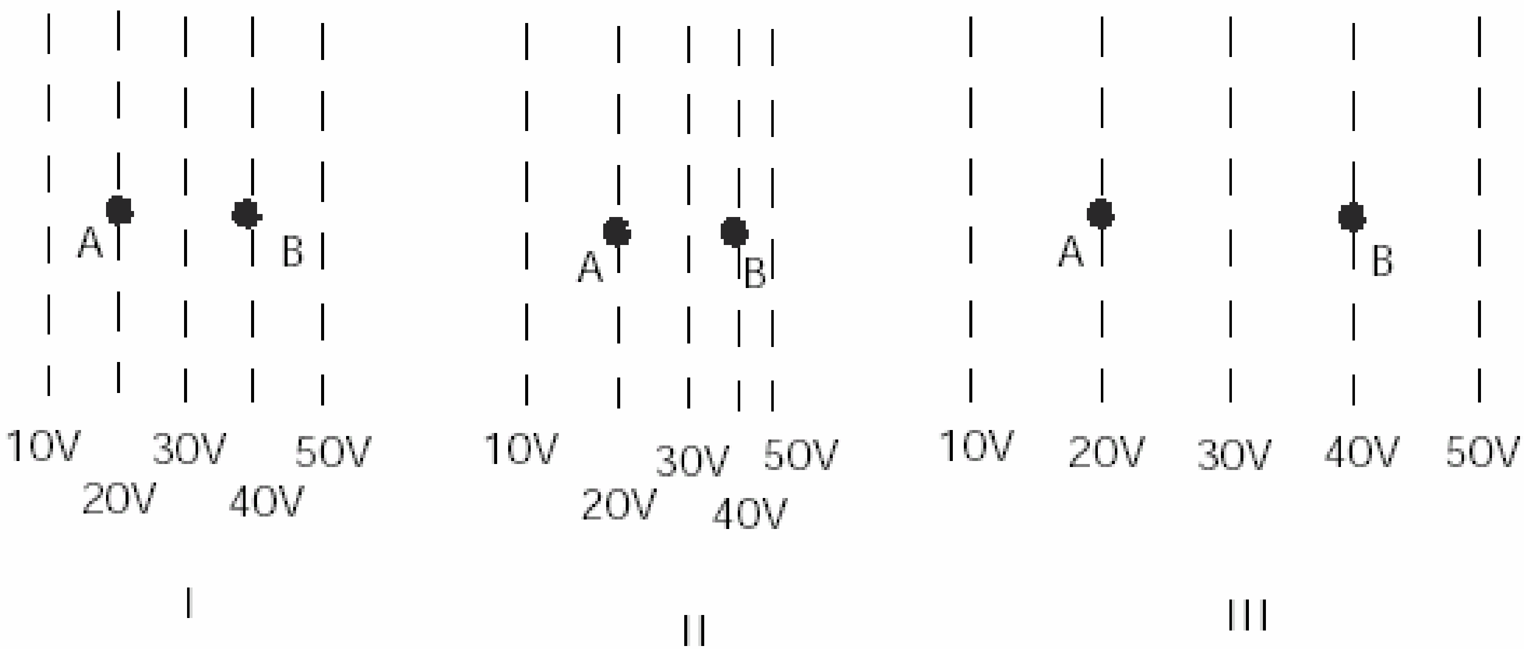

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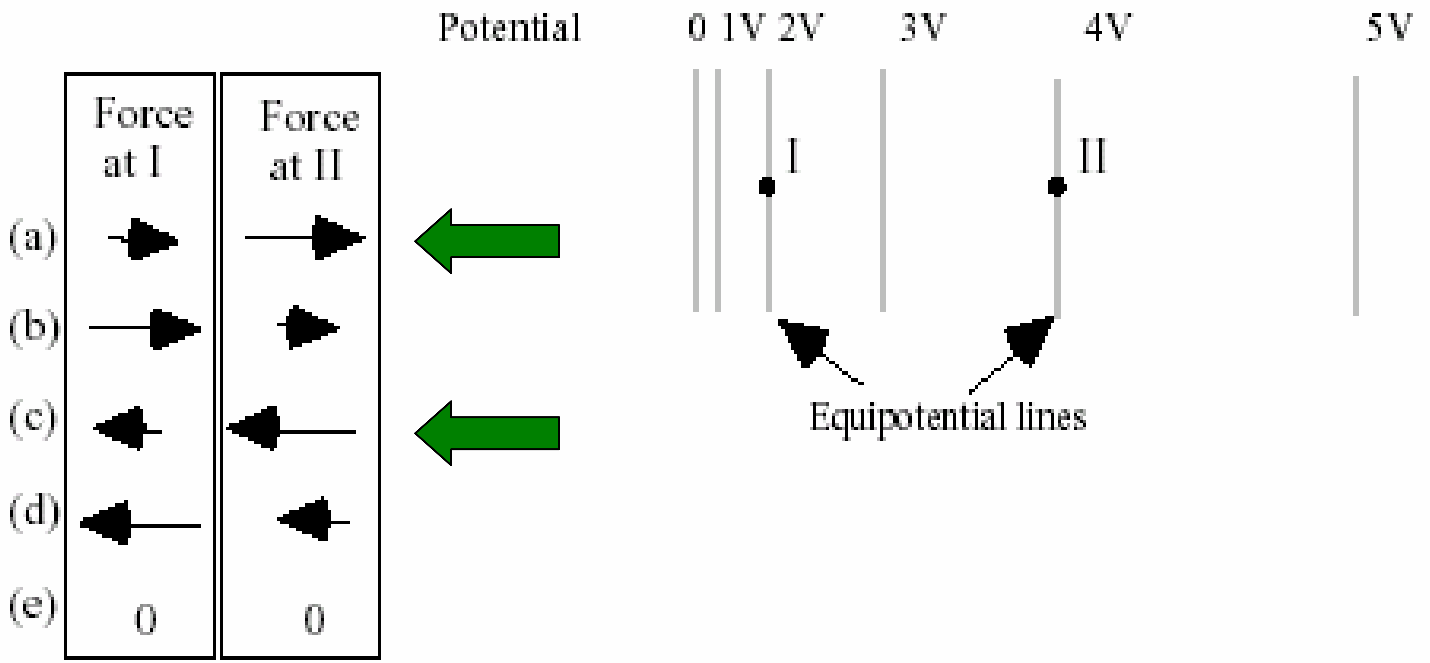
"E": magnitude of field scales with value of potential at given point

#30

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 #27

#27

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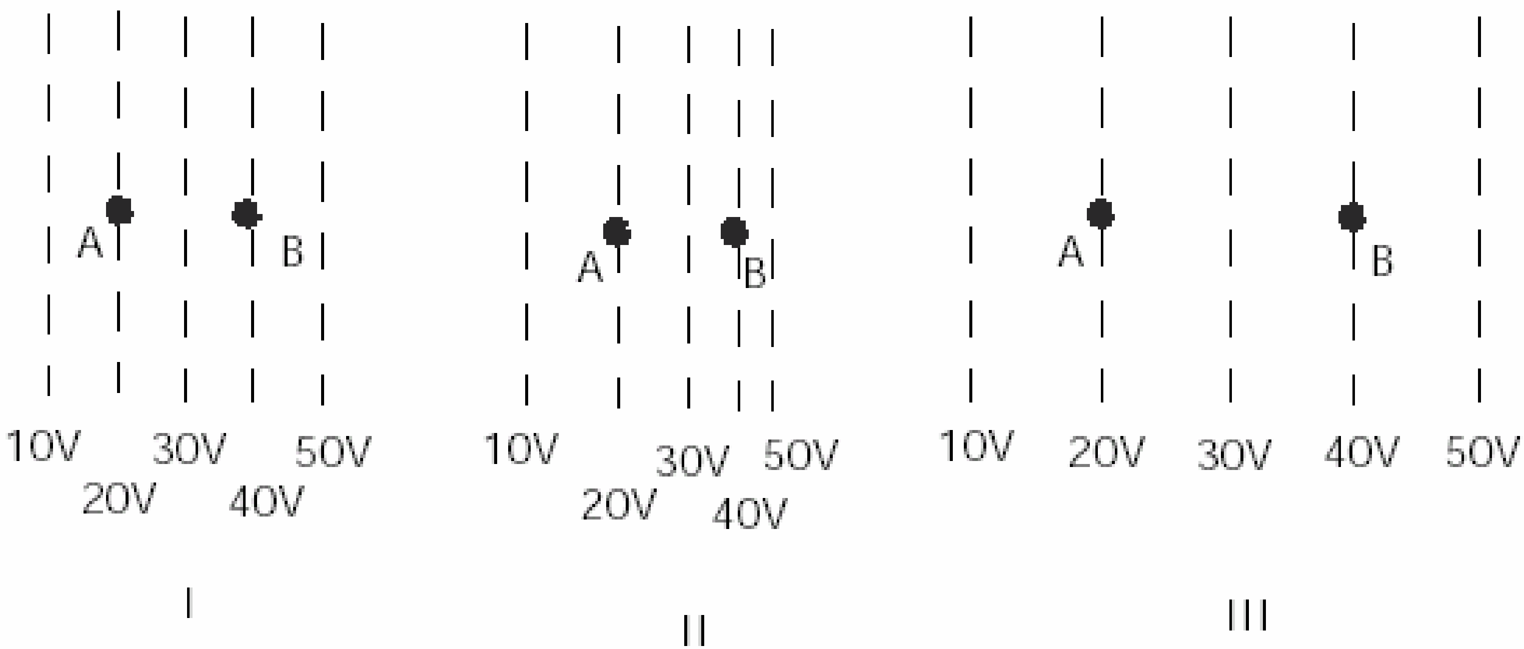

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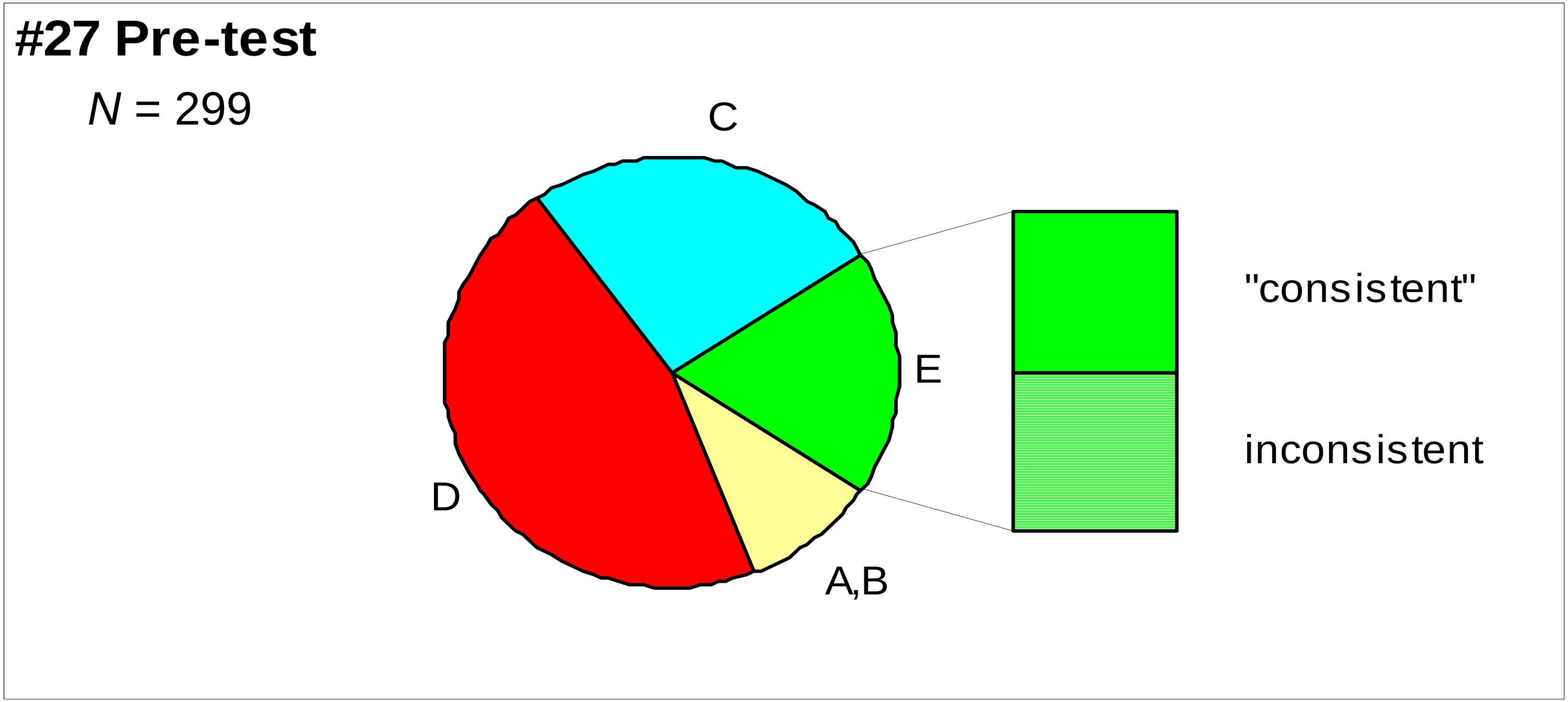
"E": magnitude of field scales with value of potential at given point

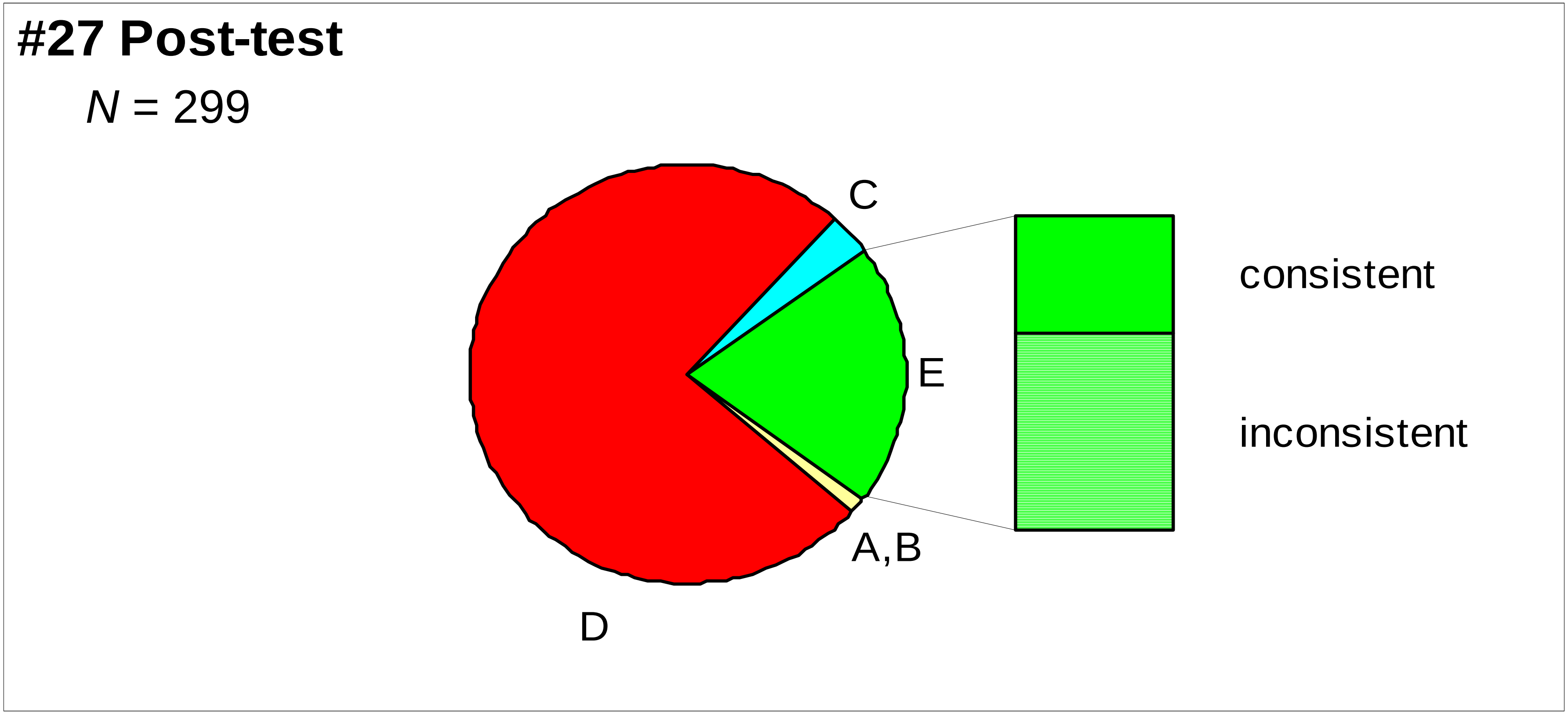
Pre-Instruction



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

"consistent": *consistent with answer on #30* *(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 $E_{B,\mathrm{I}} = E_{B,\mathrm{II}} = E_{B,\mathrm{III}}$]:

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- Examples of pre-instruction explanations:
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  - "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"

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  - "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"

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  - 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 ≈ 20%
    - *But less consistently applied after instruction: for students with "E" on #27, more discrepancies between responses to #27 and #30* ***<u>after</u>*** *instruction*

Important Lessons:

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- 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.

How do you hit a moving target?

Addressing the dynamics of students' thinking

Characterizing the Learning Process

- To be able to influence effectively the process of student learning, we need to assess and characterize it as an actual time-dependent *process*.
- Students' knowledge state is a generally increasing function of time, but in the details of variation may lie important clues to improving instruction.
- Characterization of a time-dependent process requires a bare minimum of two probes at different time points, while a varying rate requires three such probes.

Assessing Students' Mental State at a Particular Time

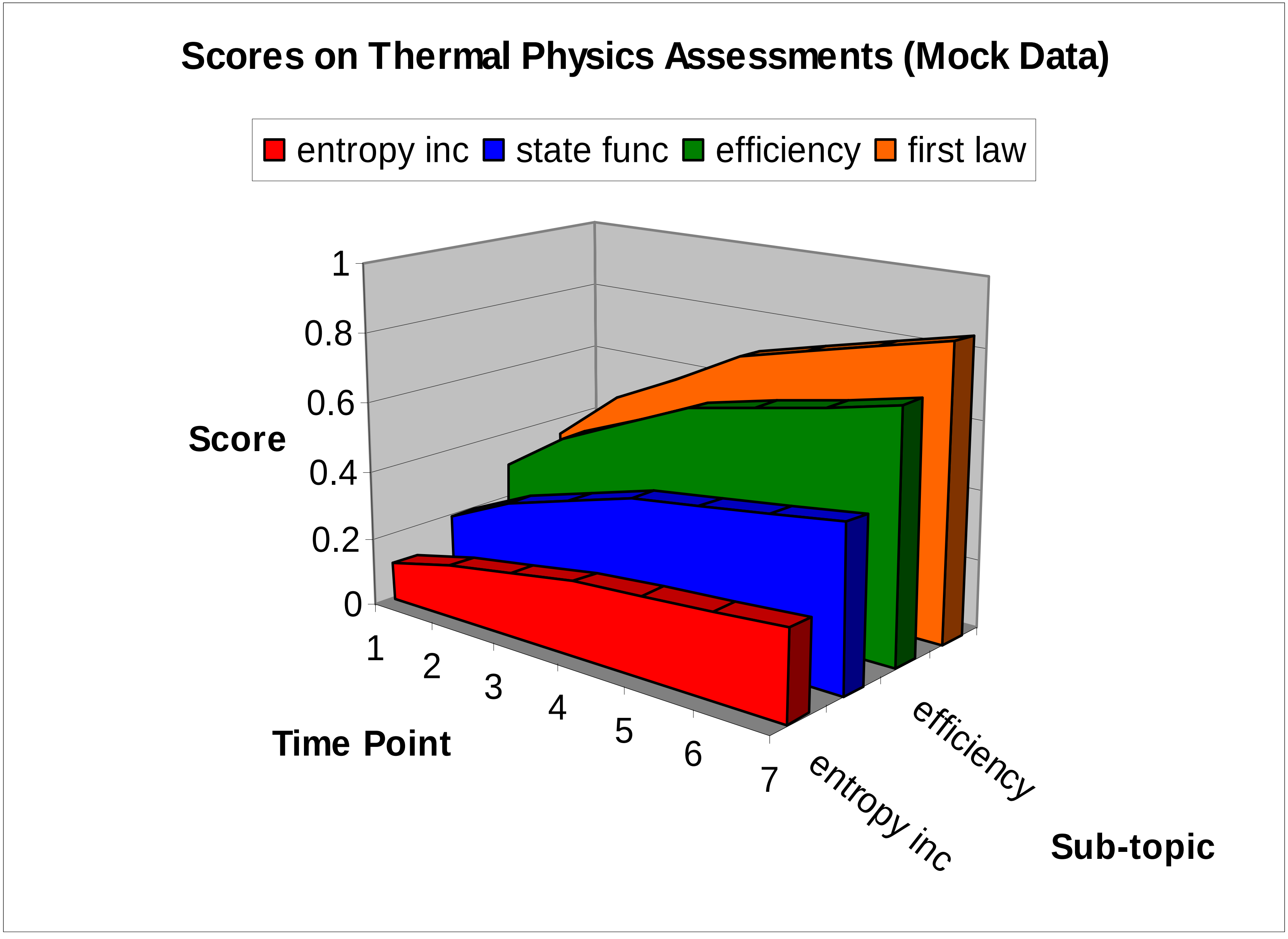
- Students' "knowledge state":
  - Context-dependent ideas related to specific concepts and interconnections among concepts
  - Assess with questions involving diverse contexts and representations
  - Determine individual "distribution function" of ideas ["mental model"]
- Students' "learning state":
  - Ideas and practices related to study methods
  - Attitudes and motivation
  - Response characteristics to instructional interventions
  - Assess with observations of learning practices (Thornton 2004), attitudinal surveys (Redish et al., Elby), "Dynamic Assessment" (Lidz), "teaching experiments" (Engelhardt et al.)

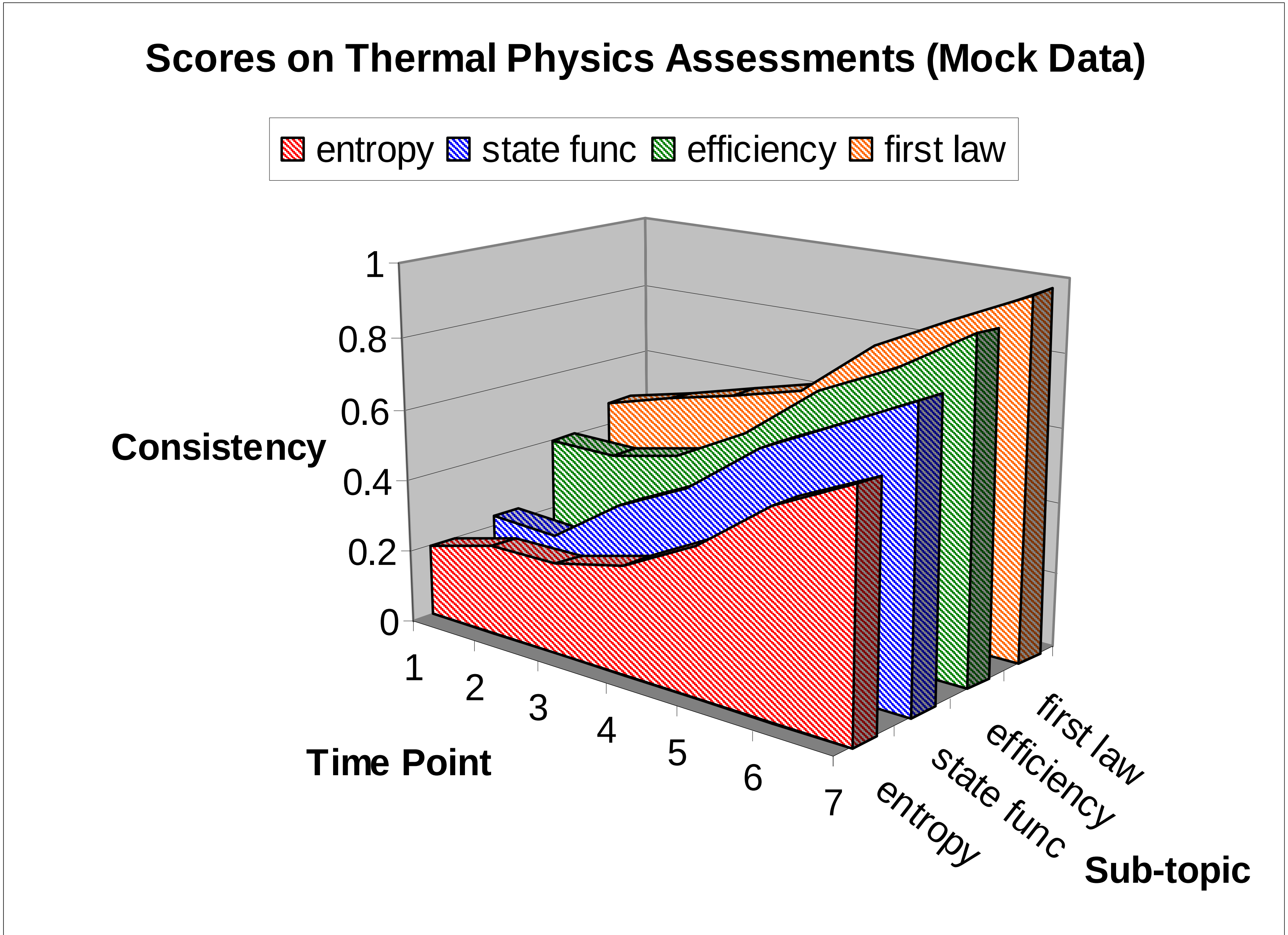
Characterizing the Process:
Qualitative Parameters

- The *sequence of ideas* and of *sets* of ideas [“mental models”] developed by a student during the process of learning a set of related concepts
- The *sequence of difficulties* encountered by a student during that process (related to “*ideas*,” but not necessarily the same)
- The *sequence of knowledge resources and study methods* employed by the student during that process
- The *sequence of attitudes and behaviors* developed by a student during that process

Characterizing the Process:
Quantitative Parameters

- The progression in *depth of knowledge* as measured by probability of correct response on a set of related questions (e.g., score *S*, range [0.00,1.00])
- The *average rate of learning R* of a set of related concepts (e.g., $R = g/\Delta t$ where *g* = normalized gain calculated using $S_{pretest}$ *and* $S_{posttest}$)
- The *time-dependent distribution function* characterizing the idea set of a student population


Scores on Thermal Physics Assessments (Mock Data)
entropy inc
state func
efficiency
first law
Score
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
Time Point
entropy inc
efficiency
Sub-topic



Scores on Thermal Physics Assessments (Mock Data)
entropy
state func
efficiency
first law
Consistency
1
0.8
0.6
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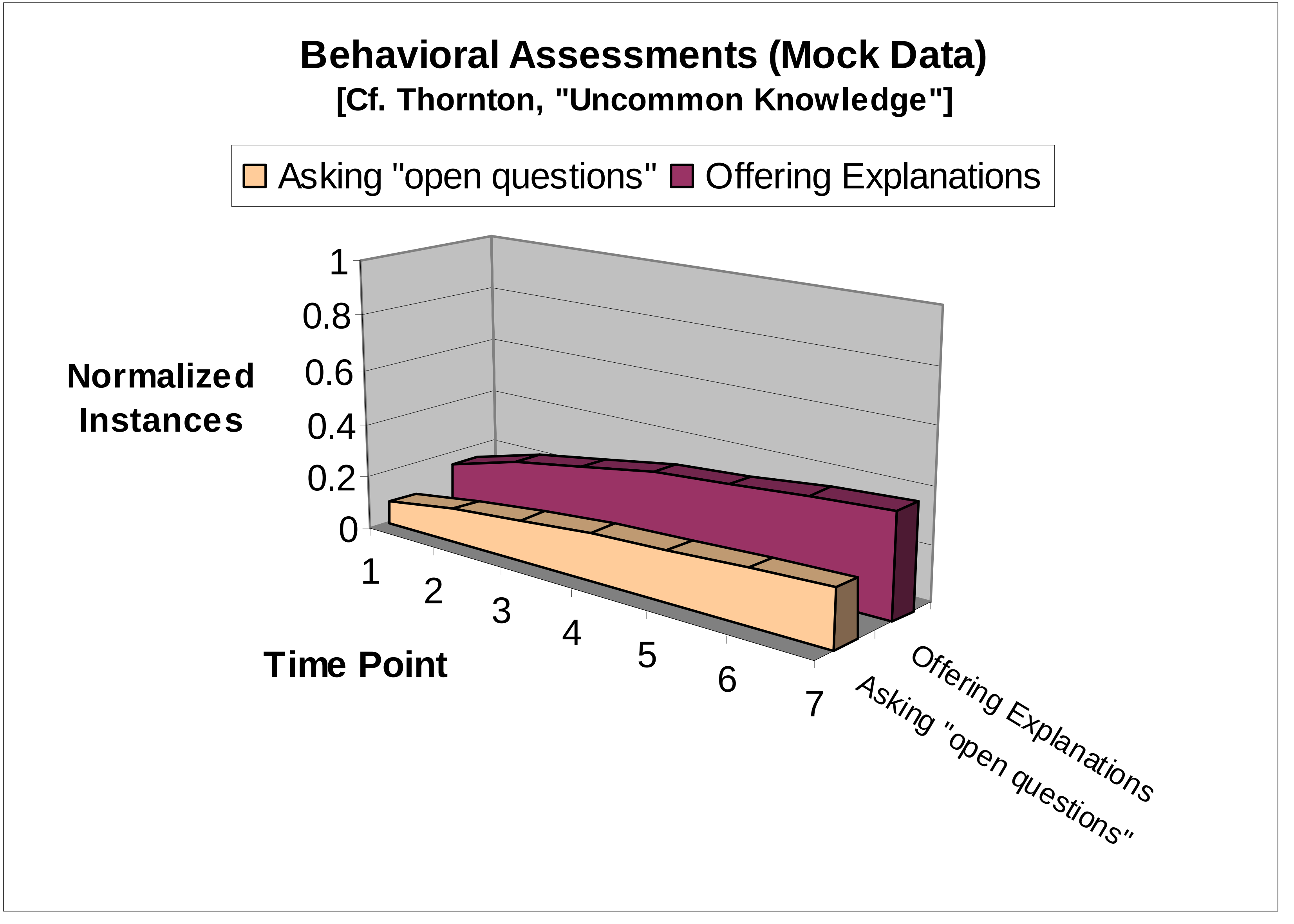

Behavioral Assessments (Mock Data)
[Cf. Thornton, "Uncommon Knowledge"]
Asking "open questions"
Offering Explanations
Normalized Instances
1
0.8
0.6
0.4
0.2
0
1
2
3
4
5
6
7
Time Point
Offering Explanations
Asking "open questions"

Phase I: “Kinematics” of Students’ Thinking

How can we characterize the pattern of students’ thinking as it ***evolves*** *during the learning process?*

- What is the complete set of students’ ideas and the interconnections among those ideas?
- What is the *normal course of evolution* of those ideas and of the interconnections among them?

Phase II: “Dynamics” of Students’ Thinking

*What are the factors that **influence** the evolutionary pattern of students’ thinking during the learning process (“learning trajectory”) ?*

- What is the *relative* influence of (a) individual student characteristics (preparation, etc.) and (b) instructional method, on the observed sequences of ideas, difficulties, attitudes, etc.?
- To what extent can the observed sequences be altered due to efforts of the instructor and/or student?

Phase II: “Dynamics” of Students’ Thinking

*What are the factors that **influence** the evolutionary pattern of students’ thinking during the learning process (“learning trajectory”) ?*

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Previous Work

- Sequence of ideas
  - Thornton 1997 (identification of “transitional” states)
  - Dykstra 2002
  - Hrepic et al. 2003
  - Itza-Ortiz et al. 2004
- Sequence of Attitudes
  - Redish, Saul, and Steinberg 1998 [MPEX]
  - Elby 2001 [EBAPS]
- Progression in Knowledge Depth
  - Bao and Redish 2001; Bao et al. 2002
  - Savinainen 2004
  - Meltzer 2003

Generalizability of Sequences

- Sequence of ideas: Some workers (e.g., Thornton 1997, Dysktra 2002) have postulated the existence of "transitional states," which are well-defined sets of ideas occurring during the transition from novice to expert thinking; others have described shifts in mental models (Bao and Redish 2001; Bao et al. 2002).
- Sequence of difficulties: Generalizability of *patterns* of difficulties is well established, but that of difficulty *sequences* has not been thoroughly investigated.
- Sequence of attitudes: There is evidence of regularities in attitude changes during instruction (Redish et al. 1998), but also evidence that these regularities are dependent on instructional context (Elby 2001).

Dynamic Assessment

- As an alternative to assessment of student thinking at a single instant (quiz, exam, etc.), a pre-planned sequence of questions, hints, and answers may be provided and the students' responses observed throughout the interval. Depth and rapidity of responses are a key assessment criterion. (Lidz, 1991)
- A similar method is the "teaching experiment," in which a mock instructional setting is used as a means to probe students' responses to various instructional interventions. (Engelhardt, et al. 2003)

Questions for Future Work (I)

- Can the existence of *well-defined* “transitional mental states” be confirmed?
- Are there common patterns of variation in learning rates? (E.g., monotonically increasing or decreasing.)
- Is magnitude of learning rate at an early phase of the process correlated with long-term learning rate?
- How does the individual “mental model” distribution function evolve in general? Is the evolution pattern correlated with individual characteristics?
- How does the population “mental model” distribution function evolve in general? Is the evolution pattern correlated with population demographics?

Questions for Future Work (II)

- Do transitional states [if they exist] vary among individuals according to differences in their background and preparation?
- Are different transitional states observed in traditional and reformed instruction?
- Are learning-rate variations influenced by individual background and/or instructional mode?
- Are the sequences of individual and population “idea distribution functions” [mental models] influenced by individual background and/or instructional mode?
- Can a more complete and accurate picture of a student’s learning trajectory be provided by “dynamic assessment” (or teaching experiments) over a brief time interval?

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And now for something completely different…

Some Sociological Issues: An Investigation

- Anecdotal, informal, 3-year multi-institutional study
- Ph.D.-granting physics departments ($N \approx 6$) that were considering making a permanent commitment to PER
- Unstructured interviews with faculty ($N \approx 40$)

Characterization of Faculty Attitudes

- Can categorize faculty into three populations:
    1) enthusiastic about and/or very sympathetic to PER
    2) openly hostile or unsympathetic to PER
    3) ostensibly neutral or noncommittal regarding PER

- Relative proportions of populations are highly locally determined

Transition Points

- Attitudes of Category (2) [“noncommittal”] faculty often undergo an apparent phase transition at critical points involving decisions regarding permanent departmental commitments
  - *Previously latent opposition becomes manifest*
- Variations in Category (2) attitudes often come as a dramatic surprise even to otherwise savvy departmental veterans (typically those in Category (1) [enthusiastic])

Key Factors

- Extra-department pressures (administrators, recently acquired funding, etc.) frequently add to pre-decision momentum in favor of PER
- Desires to acquire PER group almost invariably accompanied by implicit or explicit expectations for extraordinary local instructional support by PER personnel.
- Faculty alternative conceptions regarding PER funding mechanisms, publication rates, and citation rates are pervasive, and extraordinarily hard to dislodge.

A final thought…

Discipline-based Education Research

- Goals and methods of PER and AER very similar to those in Chemical Education Research, and many commonalities exist with education researchers in mathematics, engineering, and geoscience at the undergraduate level
- Methodological, political, and funding challenges similar as well
- Urgent need to join forces with other DBER in some fashion, on continuing basis