Physics Education Research: The Why and the How

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Outline

- Putting Physics into Educational Research
- A little theory
- How we take measurements
- How we develop curriculum
- An example from start to *middle* finish
- Conclusions

Traditional Education Research

- Traditional Educational Research
  - I noticed something in my class.
  - I made an adjustment to address the problem.
  - The students seem to like it.
- An instructor’s perception of a class environment is not bullet-proof fact, and proper assessment of student learning
- Traditional feedback for assessing student learning
  - average score on exams, homework, and labs
  - students’ class evaluations

Physics Education Research

Physics Education Research (PER) attempts to treat learning as rigorously as physicists treat experiments concerning physical phenomena.

Is PER physics research?

- How does a physicist do research?
  - Careful, controlled experiments on specific features of a system.
  - A system has particular properties and a measuring device is used to measure those particular properties.
  - Ample sample size; ensemble of comparable systems
  - Research is often grounded in mathematically descriptive theory that provides predictive power
- How does a PER'er do research?
  - Careful, controlled experiments on specific features of a system.

    My system is a group of students in a particular class.
  - A system has particular properties and a measuring device is used to measure those particular properties. **I'm trying to measure knowledge and my measuring device is a set of questions.**
  - Do I have an ensemble of students?… Do we have a theory?

What am I actually measuring?

- Student answers to questions…

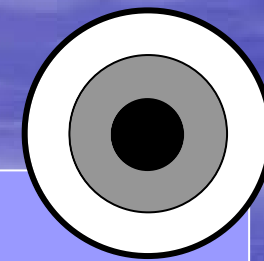
…which I assume is an indication of their knowledge

  - Physicists do not have an entropy meter!

- What is knowledge and how is it organized?

A Model for Students' Knowledge Structure

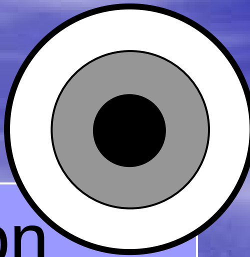
[Redish, *AJP* (1994), *Teaching Physics* (2003)]



Archery Target: three concentric rings

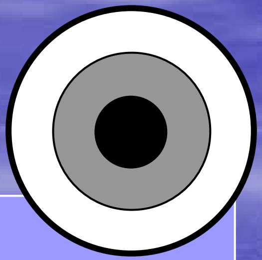
- Central black bull's-eye: what students know well
  - *tightly linked network of well-understood concepts*
- Middle gray ring: students' partial and imperfect knowledge [Vygotsky: "Zone of Proximal Development"]
  - *knowledge in development: some concepts and links strong, others weak*
- Outer white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

Response Characteristics Corresponding to Knowledge Structure



- When questions are posed related to **black**-region knowledge, students answer rapidly, confidently, and correctly – independent of context
- Questions related to **gray** region yield correct answers in some contexts and not in others; explanations may be incomplete or partially flawed
- Questions related to **white** region yield mostly noise: highly context-dependent, inconsistent, and unreliable responses, deeply flawed or totally incorrect explanations.

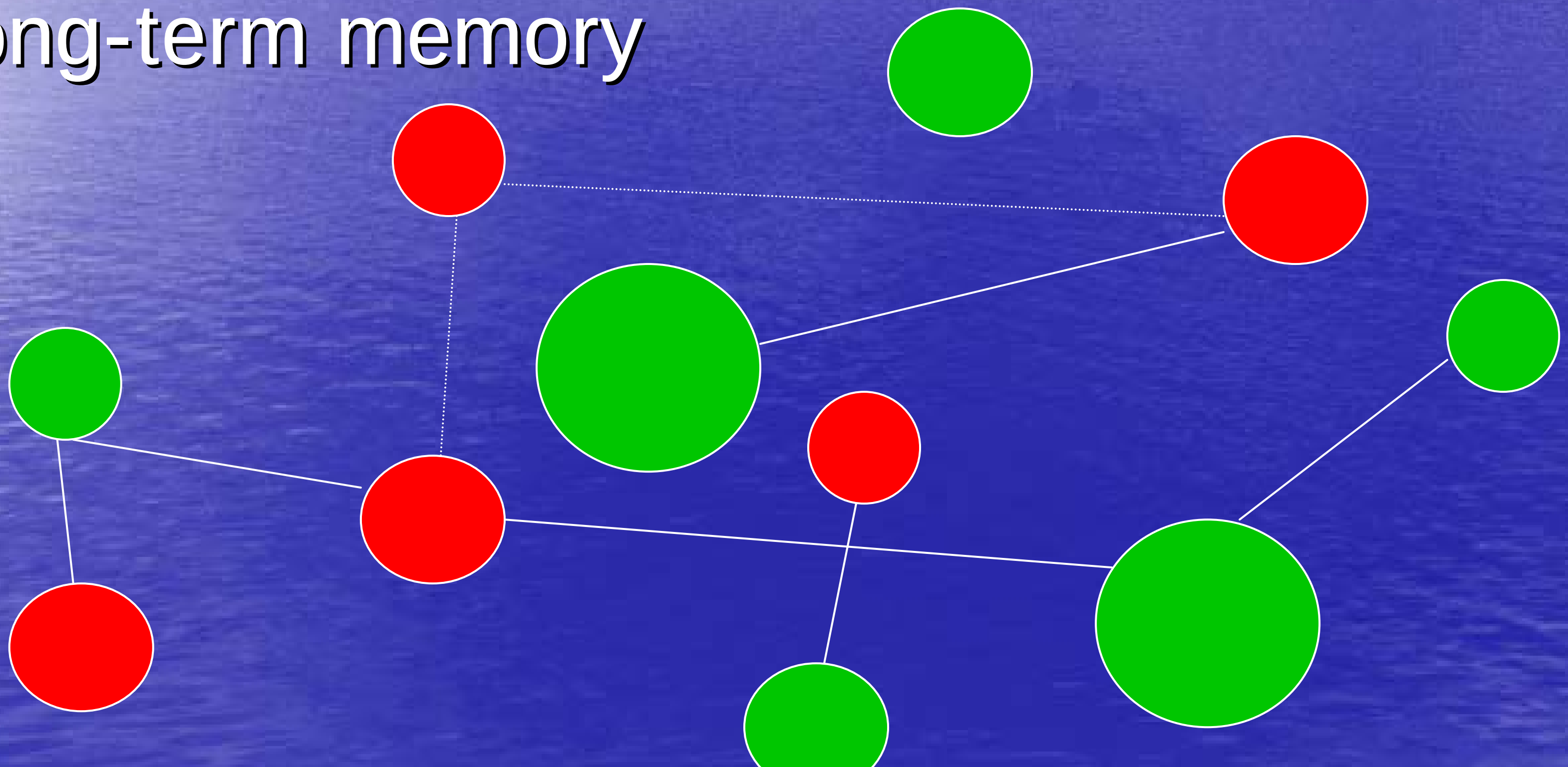
Teaching Effectiveness, Region by Region



- In central **black** region, difficult to make significant relative gains: instead, polish and refine a well-established body of knowledge
- Learning gains in **white** region minor, infrequent, and poorly retained: lack anchor to regions containing well-understood ideas
- 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.

Constructivist theory

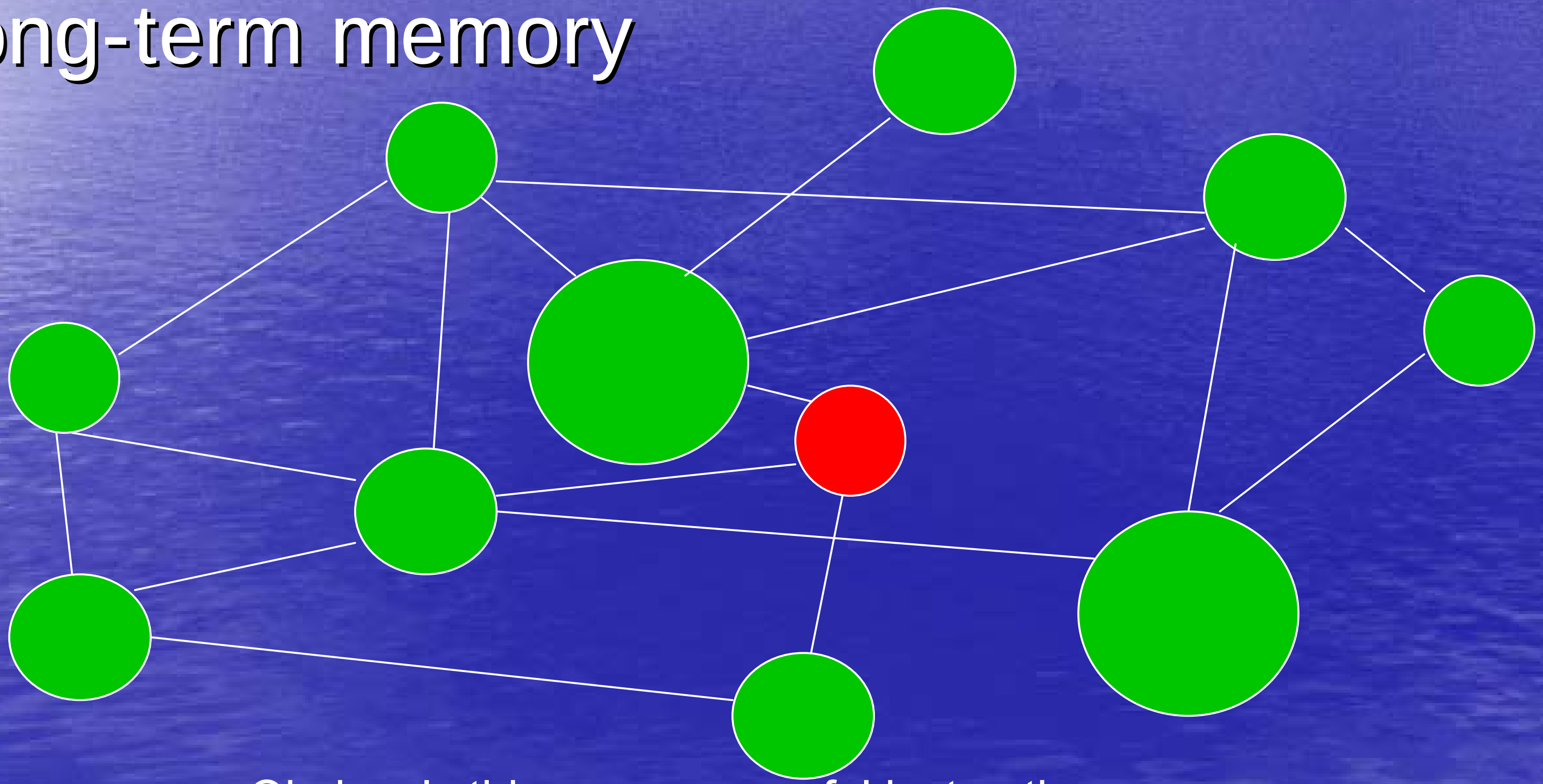
- Knowledge consists of building blocks that are assembled and organized in short- and long-term memory



BRING ON THE INSTRUCTION!!!!!!!!!!!

Constructivist theory

- Knowledge consists of building blocks that are assembled and organized in short- and long-term memory



Obviously this was successful instruction…

How do we measure knowledge?

- One-on-one Interviews
  - Deepest probe of student understanding
  - Time consuming, small sample size, and self-selection issues
- Free-response questions
  - Allows for explanation of answers, but no dialogue
  - Fairly quick and very informative
- Multiple-choice questions
  - Least desirable, difficult to understand why students are giving a particular answer
  - Fastest by far, and big sample sizes

What does our data tell us?

- For most physics topics, “traditional instruction”, “good teachers”, and even “reformed instruction” methods fail to help **many** students
  - learn basic conceptual ideas about physics
  - improve problem solving skills
  - activate their ability to think scientifically

- Let’s define these terms clearly...

Traditional Instruction

- The majority of physics courses
  - Instructors lecturing at the board for most of the class period, or passive class demonstrations
  - Cookbook-type physics labs
  - Working problems in-class and for homework that are end-of-the-chapter, plug-and-chug-type problems that don’t require any conceptual understanding but rather equation hunting
- BUT physicists still learned this stuff, right?
  - They aren’t representative of a standard student
  - They may have substantial conceptual gaps also

"Good" Teachers

- Many potentially desirable characteristics
  - Enthusiastic about the subject matter
  - Good Speaker
  - Speaks at an appropriate level for the students
  - Fosters interest in the nature of science
  - Fair grader
  - Tests fairly
  - Friendly person
- These qualities may be useful...

...but there is no definitive research evidence that they help students learn physics concepts or develop scientific reasoning and problem solving skills.

Reformed Instruction

- Lots of ideas and buzz words about working in groups, student-centered learning, active engagement, etc.
  - It may be better than traditional, but it may also be worse
- Too much done in the traditional educational research mode... “I tried something and the students seem to like it.”
- Lacking proper assessment of the materials

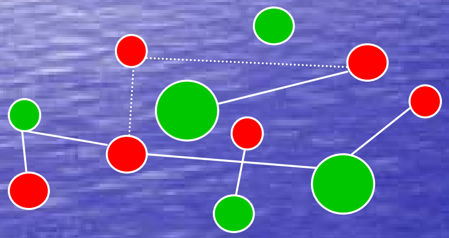
Research-based instruction

- Curricular materials that are developed using proven methods of physics education research and are rigorously tested for how they affect student learning

- To develop materials that will help students learn physics we must know:
  – How do people learn?
  – How do people learn physics?

Using a Constructivist Model

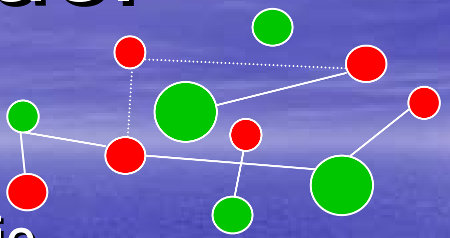
- Students are not blank slates on which you can simply "write" correct knowledge and reasoning.
  - Must modify incorrect or incomplete existing knowledge and build on correct understanding



This is not easy!

  - "Give me a list of misconceptions, so that I can think of a way to carefully explain it to the students so that they understand." – Traditionalist

Using a Constructivist Model



- Cognitive Conflict
  - Elicit student ideas about a particular topic
  - Present potentially conflicting situation and force students to confront their previous ideas
  - Require students to resolve any inconsistent ideas
- Multiple Representations
  - Use various contexts and representations to develop more robust understanding
- Inquiry
  - Include student “discovery” as part of instruction

Why do I believe in this theory?

- It works... over 25 years of success.
- Definitely not the only thing that might work, but it does work
- So do we have a theory?

YES!

BUT, there isn’t a theory of PER that provides predictive power.

Let's do some PER, shall we?

- Set the constraints for what we want to study
  - Student understanding of entropy in a second semester calculus-based physics course
- Identify the concepts we want to test
  - The overall entropy of a system and its surroundings must increase during any naturally occurring process.
- What do our students need to know before we try to teach them entropy?
  - 1st law of thermodynamics
  - Kinetic theory of gases
  - Heat and temperature
  - Ideal gas law
  - Ideal thermodynamic processes

"General-Context" Question

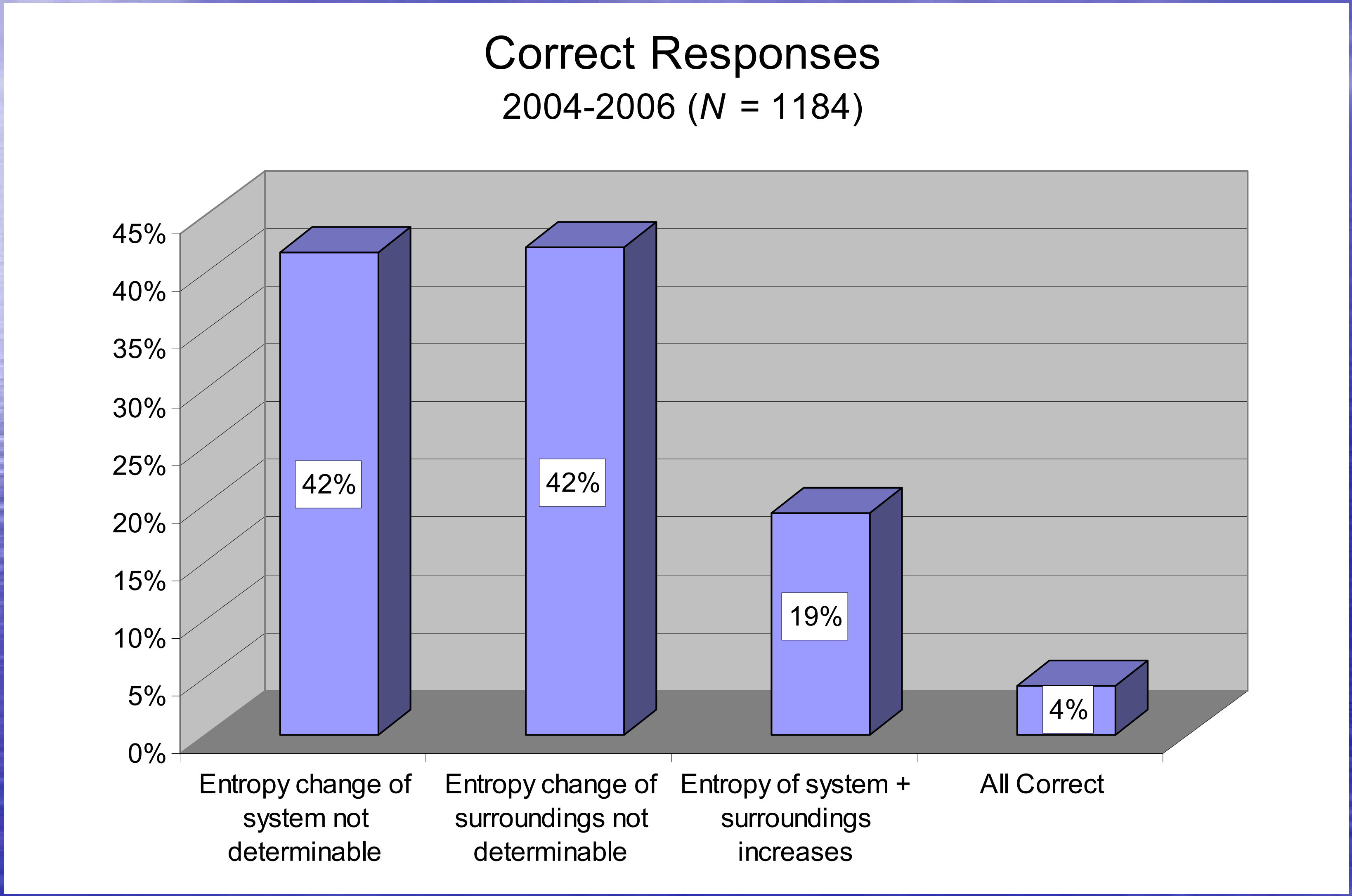
For each of the following questions consider a system undergoing a naturally occurring ("spontaneous") process. The system can exchange energy with its surroundings.

A. During this process, does the entropy of the **system** [S_{system}] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

B. During this process, does the entropy of the **surroundings** [$S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

C. During this process, does the entropy of the system *plus* the entropy of the surroundings [$S_{system} + S_{surroundings}$] *increase*, *decrease*, or *remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

Pre-instruction Data



"Concrete-Context" Question

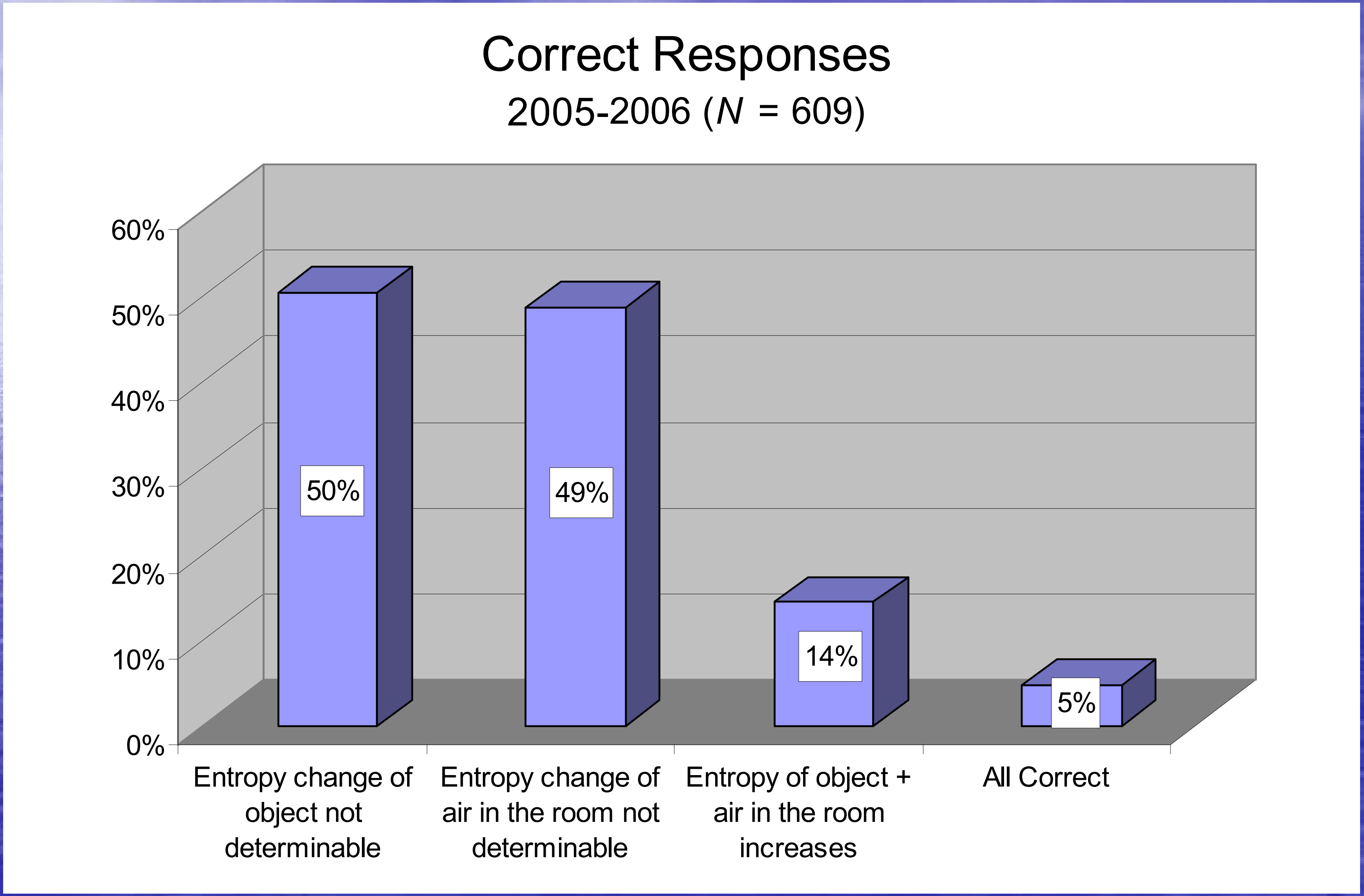
An object is placed in a thermally insulated room that contains air. The object and the air in the room are initially at different temperatures. The object and the air in the room are allowed to exchange energy with each other, but the air in the room does not exchange energy with the rest of the world or with the insulating walls.

A. During this process, does the entropy of the **object** [S_{object}] *increase, decrease, remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

B. During this process, does the entropy of the **air in the room** [S_{air}] *increase, decrease, remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

C. During this process, does the entropy of the object *plus* the entropy of the air in the room [$S_{object} + S_{air}$] *increase, decrease, remain the same*, or is this *not determinable* with the given information? ***Explain your answer.***

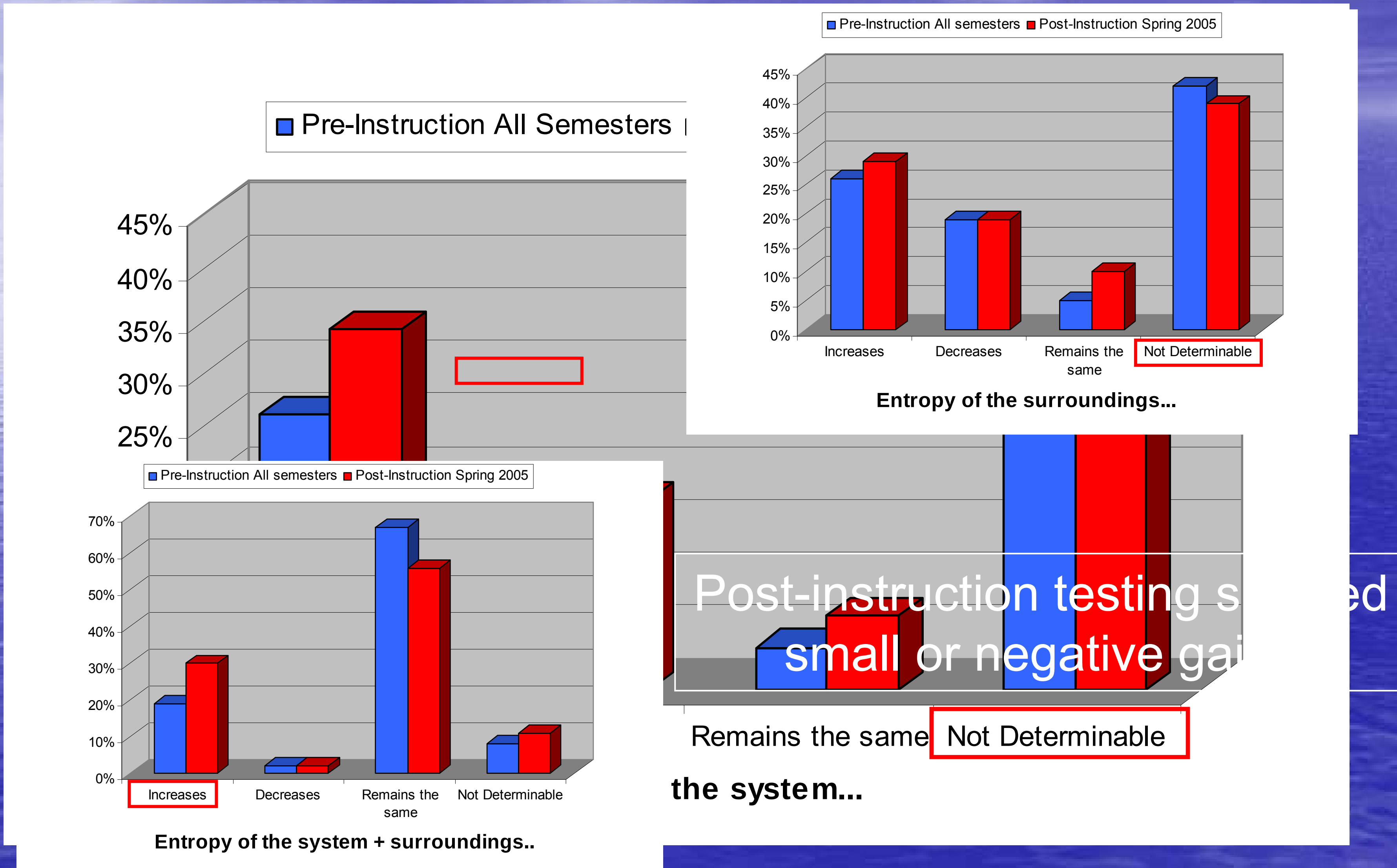
Consistent response across context



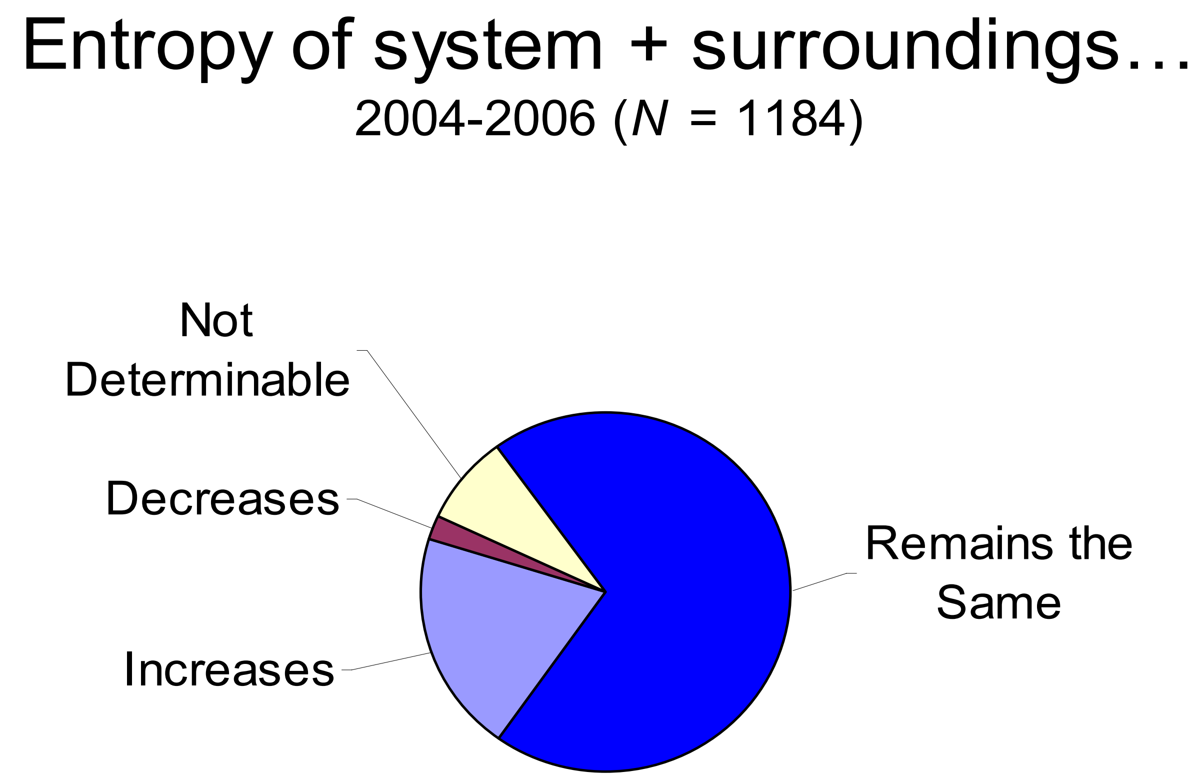
Post-Instruction Testing

- Students received two full lectures on entropy with one 50-minute recitation period
- Instructor was fully aware of student difficulties on these questions
- Post-instruction testing took place after all lecture and testing on entropy was complete

Pre- v. Post-Instruction Data



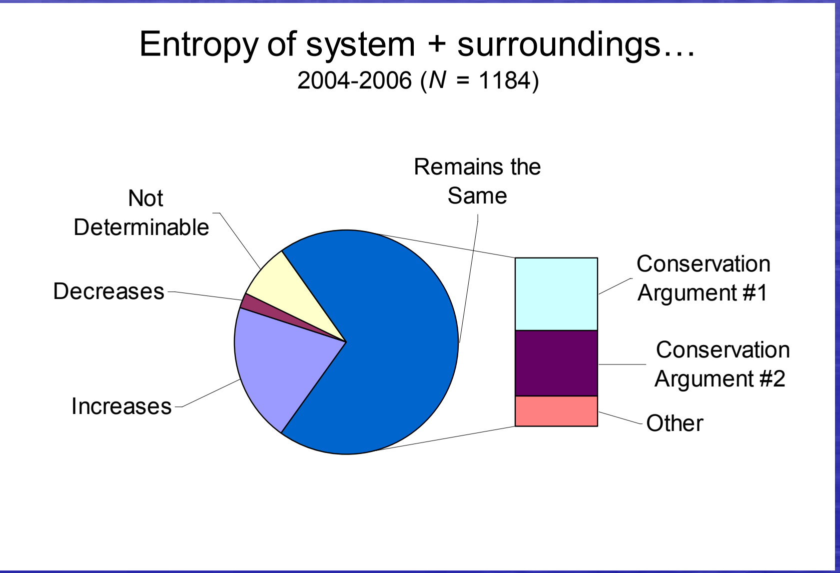
Total Entropy Responses



Nearly three-quarters of all students responded that the "total entropy" ("system plus surroundings" or "object plus air") remains the same.

"Total entropy" responses

- We can further categorize these responses according to the ways in which the other two parts were answered
- 90% of these responses fall into one of two specific conservation arguments:



Conservation Arguments

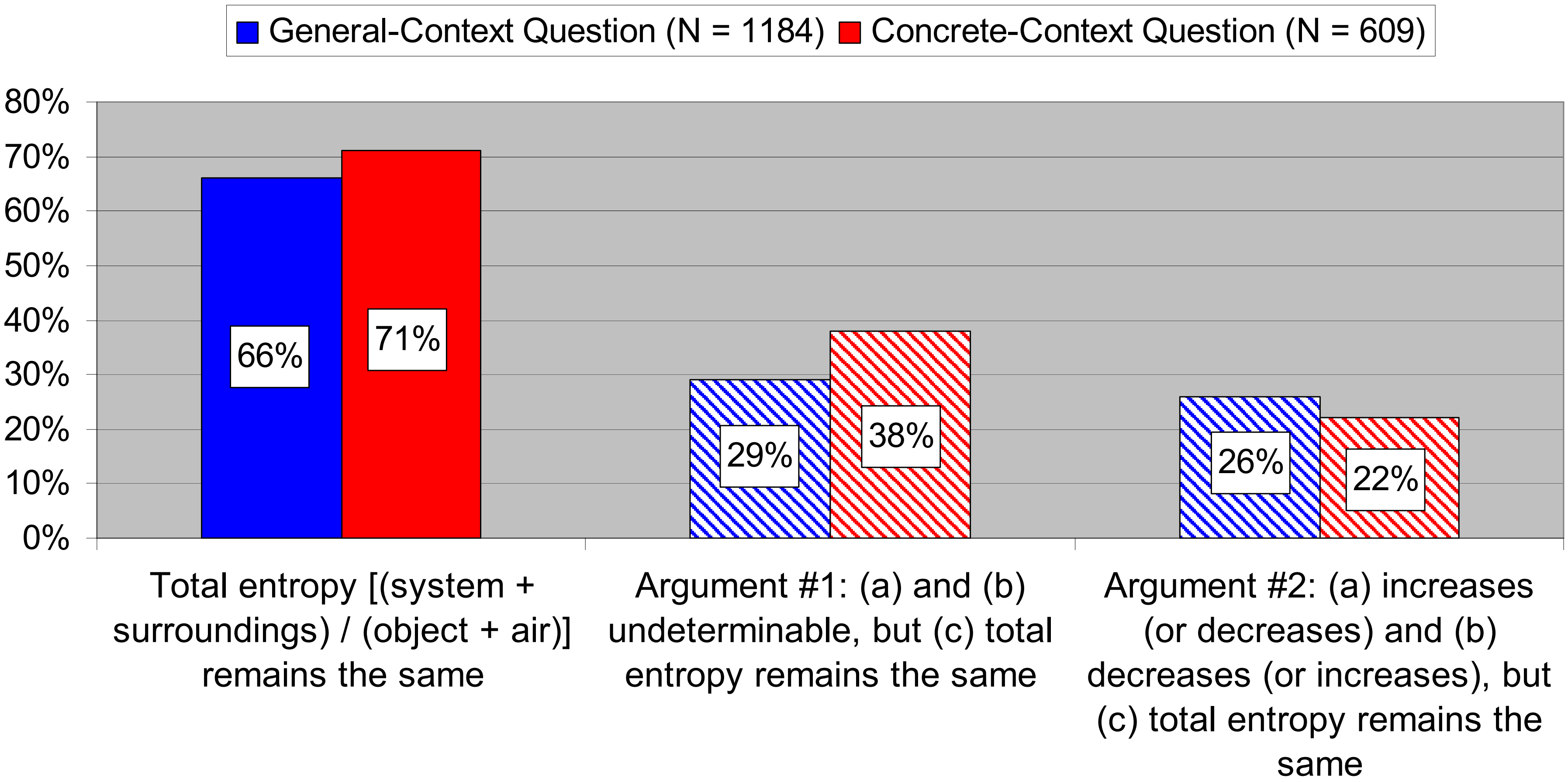
- **Conservation Argument #1 (29%)**

  S_{System} increases [*decreases*],
  $S_{Surroundings}$ decreases [*increases*], and
  $S_{System} + S_{Surroundings}$ stays the same

- **Conservation Argument #2 (26%)**

  S_{System} not determinable,
  $S_{Surroundings}$ not determinable, and
  $S_{System} + S_{Surroundings}$ stays the same

Pre-Instruction Responses Consistent with Entropy "Conservation"



Entropy Tutorial Design

- Consider slow heat transfer process between two thermal reservoirs (insulated metal cubes connected by thin metal pipe)
  - Does total energy change during process?
  - Does total entropy change during process?

Entropy Tutorial Design

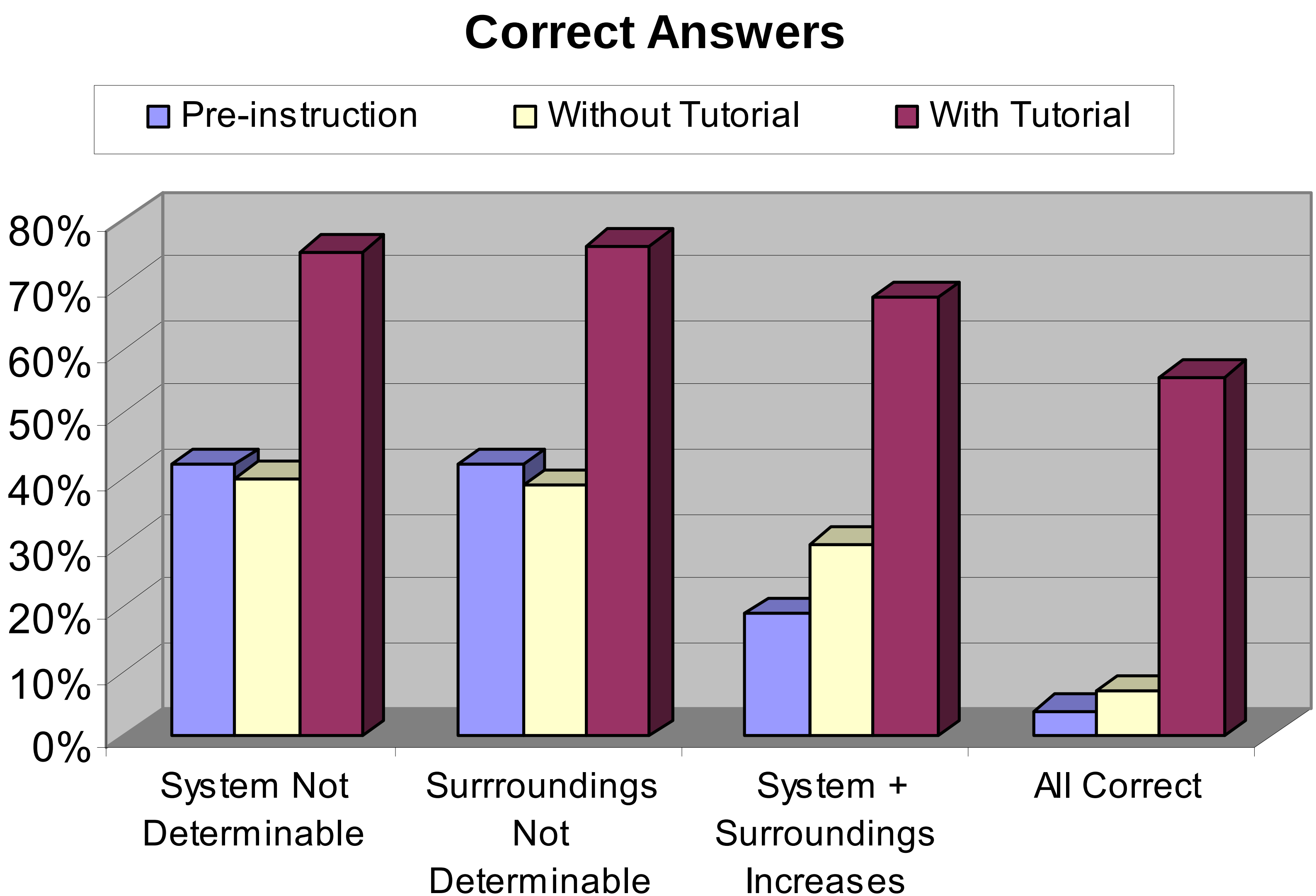
- Guide students to find that:

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

  and that definitions of “system” and “surroundings” are arbitrary

- Examine situation when $\Delta T \rightarrow 0$ to see that $\Delta S \rightarrow 0$ and process approaches “reversible” idealization.

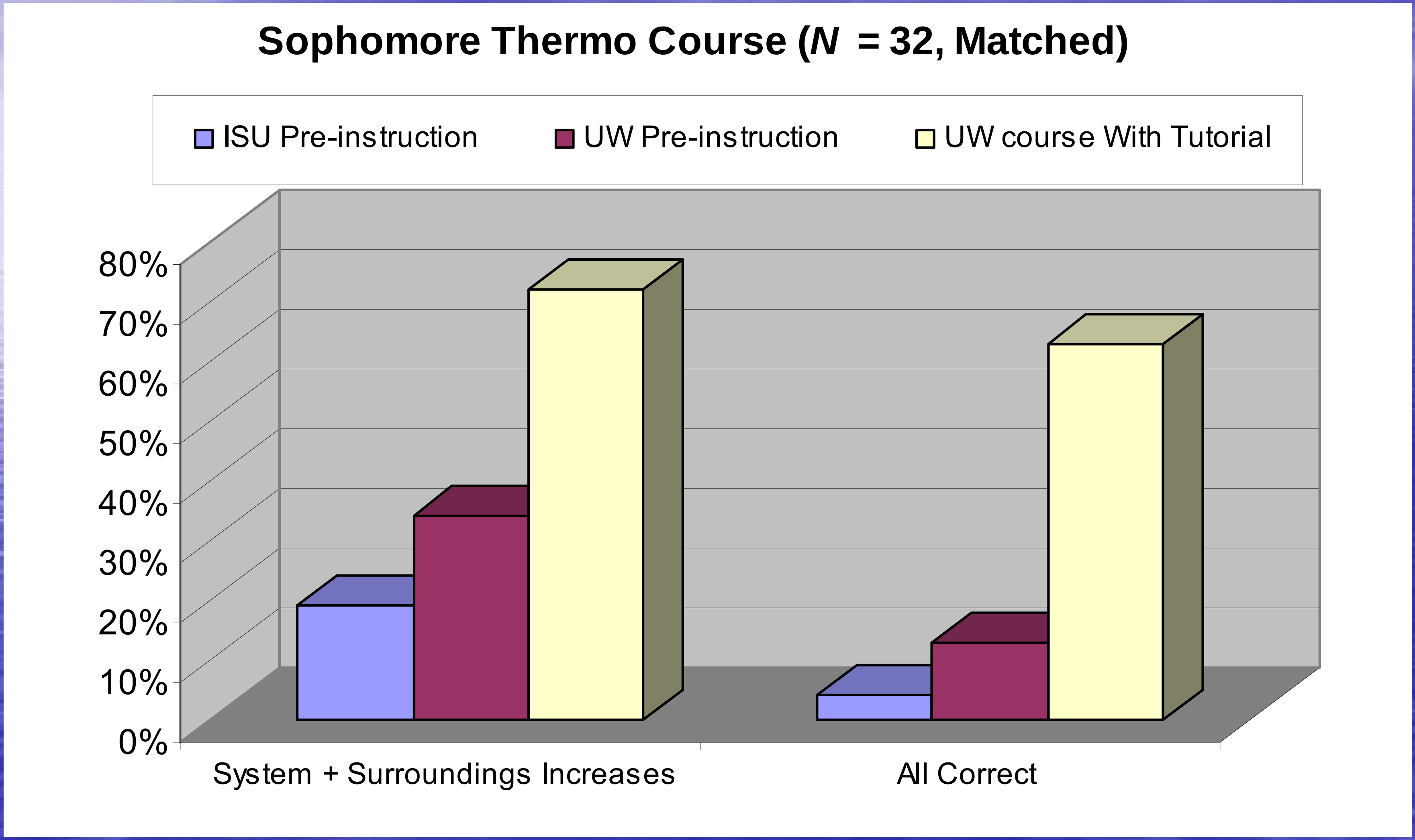
Pre/Post-instruction comparison



Off-site implementation

- Sophomore-level course covering fluid mechanics and thermal physics at University of Washington
- Students are primarily physics majors and would normally be associated with the top 10% of ISU’s introductory course

Pre/Post-instruction comparison



Two data points does not a conclusion make

- This work is far from complete
- Iterative testing runs needed both at ISU and other institutions before we can draw significant conclusions about the effectiveness of this instruction

Just a sampler of PER:

- Studies on group dynamics – U Maryland
- Interactive Simulations – U Colorado
- Science writing – OSU, (ISU Chemistry)
- Formative assessment techniques MIT, OSU, U Illinois
- Student attitudes and beliefs – U Maryland, U Colorado
- Searching for a theory – U Maryland, U Maine

Conclusions

- Physics Education Researchers attempt to approach education as a physicist approaches physical phenomena.
- We use what is known about learning theory and cognitive science to guide our instruction methods.
- Creating effective and efficient curricula is a very laborious process. There are no shortcuts.

Further reading:

“Guest Comment: How we teach and how students learn – A mismatch?” Lillian McDermott, *AJP* 1993