Introductory Thermal Concept Evaluation:

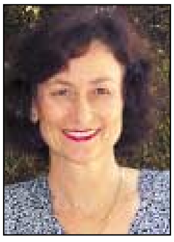
Assessing Students' Understanding

Shelley Yeo and Marjan Zadnik

Many studies have exposed and explored the existence and resilience of students' various naive understandings about the physical world.[1,2] Despite the diversity of students' views, different researchers have repeatedly reported similar results across age and cultural groups. It is generally agreed that traditional instruction, which does not take into account existing beliefs of students, is largely ineffective in changing their naive scientific ideas.[3] Many students leave school, and often university, with intuitive physics understandings intact or existing alongside more accepted scientific views.[4] An effective teacher's strategic action is therefore to find out the relevant beliefs of his/her students before planning a physics teaching/learning segment.

Conceptual-change research has led to the development of a variety of teaching methods and strategies that encourage students to actively reflect on and evaluate their existing knowledge.[5] Such strategies involve fostering a learning environment that is supportive of conceptual-change learning. In physics, there are various well-publicized interactive-engagement teaching methods that encourage students to make their understandings explicit through discussion and other forms of social interaction, often facilitated by computer environments.[6–10] Students are assisted in comparing their understandings with those of peers and against the accepted ideas of the scientific community.

Evidence for the effectiveness of teaching initiatives aimed at producing conceptual change may be provided by initial and final assessments of students' conceptual beliefs. The Force Concept Inventory[3] and more recently the Force and Motion Conceptual Evaluation[11] have enabled teachers of introductory mechanics to efficiently assess the alternative conceptions of their students as well as the learning gains made by students following instruction. Such information has facilitated the comparison of different courses and instructional methods.[12,13] Similar tests have been developed for assessing understanding in astronomy,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electricity and electromagnetism, optics, quantum mechanics, and heat and temperature.

The instrument we developed was specifically designed to assess a wide range of beliefs or understandings about thermodynamic concepts in 15- to 18-year-old students. It can be administered easily, usually takes less than 30 minutes to complete, and provides a convenient single numerical total.

Alternative Thermal Physics Conceptions

Thermodynamics presents students with many conceptual difficulties.[14–16] Adolescents who do not differentiate between the concepts of heat and temperature, for example, have an inadequate knowledge framework for deeper thinking about thermodynamic processes, such as conduction of thermal energy. This, in turn, limits the extent to which appropriate new knowledge can be constructed. Strongly held alternative conceptions also inhibit the development of more useful conceptions because students perceive no need to seek different explanations.

Belief is different from knowledge. In psychology, belief has a higher status than knowledge in that, for the believer, a belief is a taken-for-granted truth that requires no justification or proof. Beliefs lead the believer to talk or act or reason in particular ways, even though the believer may not be able to articulate that belief.[17,18] Physics or science education research reports many incidents of discrepancies between what students *learn*, often for the purpose of assessment, and what they actually *believe*. Newton's laws are a prime example. Instruments such as the Force and Motion Conceptual Evaluation[11] assess the extent of students' underlying non-Newtonian beliefs.

Some general findings about students' thermal understandings learned from research are:

1. Many conceptions are context-dependent and explanations are related to single or isolated situations. Appropriate generalizations are often not recognized.
2. Students are inconsistent in their explanations; they use different conceptions to explain similar phenomena and generally do not recognize contradictions.
3. Students do not apply ideas learned in school to "everyday" situations; they are more likely to express alternative conceptions when explaining real-life situations.
4. Students' knowledge frameworks often allow them to accept a statement of what *is* as a sufficient explanation of *why*. For example, students believe that heat rises, but many accept this as a definitive explanation for convection currents.
5. Even when students make correct statements, they often admit to being unclear about their ideas.

Children's alternative beliefs arise through interaction with their physical and social environment, including the cultural use of imprecise language.[19] Hence, when using skin to judge the temperature of objects, children become accustomed to materials that usually feel warm or cool to touch and combine such experiences into a generalization that provides some explanation for that experience. Common statements such as "to take one's temperature" lead to beliefs that may be in conflict with scientific views. Society's use of materials for heat-related purposes, for example using aluminum foil to keep things cold, leads to confusion about conductors, insulators, radiators, and reflectors and the mechanism by which they work in different situations. Naive beliefs are also developed though classroom instruction and reading textbooks

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Table I. Links between possible alternative conceptions and test questions. The alternative conceptions, taken from research literature, are expressed in the naive form.

Alternative conceptions	Question Numbers
A: Students' conceptions of heat	
• Heat is a substance.	10, 22
• Heat is not energy.	22
• Heat and cold are different, rather than opposite ends of a continuum.	10, 13, 18, 23, 24
• Heat and temperature are the same thing.	15, 18
• Heat is proportional to temperature.	7, 11, 15
• Heat is not a measurable, quantifiable concept.	7
B: Students' conceptions of temperature	
• Temperature is the "intensity" of heat.	15
• Skin or touch can determine temperature.	16
• Perceptions of hot and cold are unrelated to energy transfer.	10, 18, 21, 22
• When temperature at boiling remains constant, something is "wrong."	5
• Boiling point is the maximum temperature a substance can reach.	19
• A cold body contains no heat.	7, 10, 11, 22, 26
• The temperature of an object depends on its size.	1, 9, 14
• There is no limit on the lowest temperature.	25
C: Students' conceptions about heat transfer and temperature change	
• Heating always results in an increase in temperature.	3, 4, 5
• Heat only travels upward.	20
• Heat rises.	20
• Heat and cold flow like liquids.	10, 13
• Temperature can be transferred.	7, 13
• Objects of different temperature that are in contact with each other, or in contact with air at different temperature, do not necessarily move toward the same temperature. (Thermal equilibrium is not a concept.)	1, 2, 3, 6, 9, 10, 17, 24
• Hot objects naturally cool down, cold objects naturally warm up.	3, 13
• Heat flows more slowly through conductors making them feel hot.	25
• The kinetic theory does not really explain heat transfer. (Explanations are recited but not believed).	18, 20, 21
D: Students' conceptions about "thermal properties" of materials.	
• Temperature is a property of a particular material or object.	9, 14, 16, 24
• Metal has the ability to attract, hold, intensify or absorb heat and cold.	9, 14, 16, 20
• Objects that readily become warm do not readily become cold.	25
• Different materials hold the same amount of heat.	11
• The boiling point of water is 100°C (only).	4, 8, 19
• Ice is at 0°C and/or cannot change temperature.	1
• Water cannot be at 0°C.	2, 11
• Steam is more than 100°C.	6, 19
• Materials like wool have the ability to warm things up.	17, 23
• Some materials are difficult to heat: they are more resistant to heating.	26
• Bubbles mean boiling.	
• The bubbles in boiling water contain "air," "oxygen," or "nothing."	12

or other education materials. A recent editorial in the *American Journal of Physics*[20] outlines confusion about use of the word *heat.* Bauman[21] apportions the blame between poorly understood or inconsistent use of terminology in textbooks, teachers' inadequate knowledge, and the inherent conceptual difficulty of the topic.

Instrument Development

In Western Australia, most students undertake formal instruction in thermal physics or introductory thermodynamics in Year 11 and/or in their first year at university. We required a single instrument that would be useful for assessing understanding and application of thermodynamic concepts in either population. An inventory of alternative conceptions was extracted from research literature on students' beliefs about thermal phenomena (see Table I). The beliefs are expressed in the naive form. A trial instrument consisting of 32 multiple-choice items was developed, and later revised to just 26 questions. This second version has recently undergone a further period of trial and minor modification (see Appendix I).

The questions allow students to apply either "everyday" physics or "classroom" physics. By situating examples in common contexts, we believe that students select responses that match their *own* conceptions rather than choose those that reflect statements learned but not necessarily believed. Many questions model a conversation occurring between adolescents at home or in a school cafeteria. The general question style is a scenario followed by statements representative of the opinions of students holding one or more alternative conceptions. In recognition of the importance of personal experience in developing and maintaining alternative conceptions, each scenario features everyday objects that students are likely to have handled or experienced directly. Diagrams or graphical representations are not used to avoid unintended misinterpretation or misunderstanding. The reading level is low to reduce the cognitive load imposed by considering simultaneously the veracity of four or more different statements.

There are two ways in which students' alternative conceptions may affect their choice of answer. First, a firmly held alternative conception may prompt students to dismiss the "correct" response as implausible. For example, a student who believes that plastic is "naturally warmer than metal" will not accept that plastic and metal containers taken from the refrigerator can be at the same temperature (see question 9). Second, a different alternative conception may make an incorrect response seem the most plausible one. For example, a student who believes that the temperature of boiling water cannot remain constant might select 110°C as the temperature of water that has been boiling for some time (see question 5). Possible conceptions underlying students' selection of an answer in different questions are shown in Table I. Students may also select rote-learned statements, such as "heat rises" or "evaporation causes cooling," as explanations, whether appropriate or not. Students with fewer alternative conceptions, and for whom everyday physics and classroom physics are consistent, are more likely to select the correct responses.

Testing the Instrument

The instrument was administered to 478 Western Australian students in four consecutive year (grade) levels, 10 to 13, in nine different institutions. The Year 10 students were in science classes and their only formal prior instruction in thermodynamics concepts had been within their general-science curriculum. The Year 11 students were all in physics classes and had recently completed a six-week topic called Heating and Cooling, which covers concepts of heat, temperature, heat transfer, and specific and latent heats. The Year 12 students were in physics classes and many were also studying chemistry. The chemistry syllabus contains a small but significant thermodynamics component (reaction kinetics). Year 13 is the first year of university. The Year 13 students were all in calculus-based physics classes and had previously studied Year 11 and 12 high school physics or its equivalent. The test was later given to the Year 13 classes as a post-test following instruction in thermodynamics. The test reliability, determined using a split half-correlation with Spearman-Brown correction, was 0.81.

The results are shown in Fig. 1. The distribution of results from one year group to the next indicates that as students are exposed to more instruction in thermal physics, their alternative conceptions are gradually replaced by more appropriate ones. The two populations where discrimination is important are represented by the Year 10/Year 11 and Year 13pre/Year 13 post divisions. The test proved adequate in this regard.

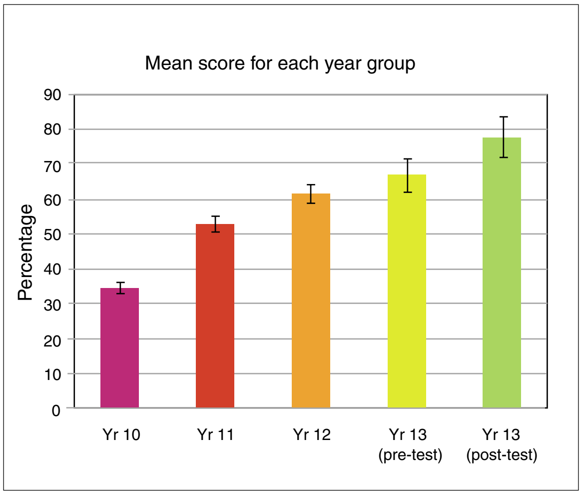

Fig. 1. Mean scores with confidence intervals for each year group. Final column is the post-test data for the university classes.

A comparison between the pre-test and post-test scores of the Year 13 population yielded an effect size of 0.70, using a pooled standard deviation of 14%. The average normalized gain, *g*, which is the ratio of the actual average gain to the maximum possible average gain[13] was 0.30. The difference between means was statistically significant ($p < 0.05$).

Test Validity

To be valid, this instrument must award a high score to students whose ideas about thermal physics approach those of "experts" and a low score to those who believe or apply naive or less well developed ideas. There are many types of validity but no simple procedure for determining the validity of either separate items or a whole test.[22] Three types of validity that are relevant here are content, face, and construct validity. Content validity is concerned with the adequate sampling of the content. Face validity refers not to what a test necessarily measures but to what it appears to measure. Construct validity is concerned with what psy-

Kim takes a metal ruler and a wooden ruler from a pencil case. He announces that the metal one feels colder than the wooden one. What is your preferred explanation?

	Percentage of students selecting each choice	
	Lower group (N = 131)	Upper group (N = 131)
A. Metal conducts energy away from his hand more rapidly than wood.*	15	95
B. Wood is a naturally warmer substance than metal.	23	0
C. The wooden ruler contains more heat than the metal ruler.	19	2
D. Metals are better heat radiators than wood.	20	2
E. Cold flows more readily from a metal.	23	1

Difficulty = 54%   Discrimination Index = 0.80

Fig. 2. Example of a question with an average level of difficulty but highly discriminating in terms of distinguishing between students with naive beliefs and those with appropriate physics beliefs.

chological qualities a test measures and is evaluated by demonstrating that certain explanatory constructs account to some degree for performance on the test. Ultimately validity depends to a large extent on human judgment.

Adequate sampling of the content area is interpreted as adequate representation of alternative conceptions within question choices rather than adequate coverage of the thermal physics content. Table I outlines the opportunities for alternative conceptions of students to be drawn on. Experienced lecturers in the Department of Applied Physics have provided feedback on the "correctness" of the physics represented and the appropriateness of the "right" answer. This also addresses the face validity of the instrument. In addition, interviews with students showed that their interpretation of the question context, as well as their understanding of what is being asked, was consistent with the intent of the instrument. When students expressed difficulty with questions, in most instances it was because the question contained a statement that was inconsistent with the student's own naive belief. *"I felt a bit confused over the water at zero degrees so I thought that there is no answer, because you can't get water at zero degrees."*

The construct validity of the test depends on its ability to represent the existence of alternative conceptions in students or the degree of triumph of their naive beliefs over correct but rote-learned conceptions. Valid items expose the beliefs of naive thinkers and yet allow conceptually advanced students to reject these ideas in favor of more correct ones. Construct validity was established though a detailed examination of the distribution of student selection of alternatives and through interviews with students. Item Difficulty and Index of Item Discrimination have been determined for each question. The first reflects the proportion of correct responses and the second, the extent to which better students were correct on any one item, and those harboring more alternative conceptions were incorrect. These measures provide evidence for the efficacy of each question and that each performs its task in contributing to the effectiveness of the instrument as a whole. Support for construct validity is also provided by the correlation between students' results and amount of exposure to thermodynamics instruction (see Fig. 1).

An effective question is illustrated in Fig. 2. The first column of data to the right of the choices indicates the percentage of students in the lower 27% (lower group, N = 131) selecting each alternative choice. The second column indicates the percentage of students in the upper 27% (upper group, N = 131) selecting each alternative choice. The asterisk marks the correct response.

This highly discriminating item shows that only 15% of students in the lower group believed that in this context, heat is a form of energy and that our perception of hotness (or coldness) is related to the rate of conduction of energy. Each of the other choices, representative of different alternative beliefs, was equally attractive to students. On the other hand, 95% of the upper group chose the correct response.

Test Availability

The test is being made available to the physics teaching community for:

1. use as either a pre-test/post-test instrument;
2. assessing alternative conceptions in a class at any point during instruction; or
3. planning instruction or remediation as required.

The test is suitable for students of introductory thermodynamics at the high school level and at the first-year university or college level. The version supplied here has been revised to reflect U.S. idiom and common words. An "Australian" version is also available on the Curtin University of Technology, Department of Applied Physics website for interactive use by students working under the guidance of a teacher. The site, which contains information for teachers about use of the test, will remain active in its present form until December 2002. Students' selections are automatically e-mailed to the teacher's nominated e-mail address as well as being recorded by the Curtin Physics Education Research and Development Group for future test analysis. For access details, teachers should e-mail the first author (S.Y.) at the following address: ryeosr@alpha2.curtin.edu.au.

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Appendix I
Thermal Concept Evaluation

- This questionnaire is about your understandings about *heat* and *temperature*.
- To help visualize each situation, think of a group of friends in a kitchen or cafeteria. Imagine that they are observant and interested in understanding common phenomena. They explain their ideas to one another.
- For each question, choose the answer that is *closest to your understanding*.
- Be careful to mark the alternative you want to. Some questions have five choices.

1. What is the most likely temperature of ice cubes stored in a refrigerator's freezer compartment?

- **a.** –10° C
- **b.** 0° C
- **c.** 5° C
- **d.** It depends on the size of the ice cubes.

2. Ken takes six ice cubes from the freezer and puts four of them into a glass of water. He leaves two on the countertop. He stirs and stirs until the ice cubes are much smaller and have stopped melting. What is the most likely temperature of the water at this stage?

- **a.** –10° C
- **b.** 0° C
- **c.** 5° C
- **d.** 10° C

3. The ice cubes Ken left on the counter have almost melted and are lying in a puddle of water. What is the most likely temperature of these smaller ice cubes?

- **a.** –10° C
- **b.** 0° C
- **c.** 5° C
- **d.** 10° C

4. On the stove is a kettle full of water. The water has started to boil rapidly. The most likely temperature of the water is about:

- **a.** 88° C
- **b.** 98° C
- **c.** 110° C
- **d.** None of the above answers could be right.

5. Five minutes later, the water in the kettle is still boiling. The most likely temperature of the water now is about:

- **a.** 88° C
- **b.** 98° C
- **c.** 110° C
- **d.** 120°C

6. What do you think is the temperature of the steam above the boiling water in the kettle?

- **a.** 88°C
- **b.** 98 °C
- **c.** 110 °C
- **d.** 120 °C

7. Lee takes two cups of water at 40°C and mixes them with one cup of water at 10°C. What is the most likely temperature of the mixture?

- **a.** 20° C
- **b.** 25° C
- **c.** 30° C
- **d.** 50° C

8. Jim believes he must use boiling water to make a cup of tea. He tells his friends: "I couldn't make tea if I was camping on a high mountain because water doesn't boil at high altitudes."

- **a.** Joy says: "Yes it does, but the boiling water is just not as hot as it is here."
- **b.** Tay says: "That's not true. Water always boils at the same temperature."
- **c.** Lou says: "The boiling point of the water decreases, but the water itself is still at 100 degrees."
- **d.** Mai says: "I agree with Jim. The water never gets to its boiling point."

Who do you agree with?

9. Sam takes a can of cola and a plastic bottle of cola from the refrigerator, where they have been overnight. He quickly puts a thermometer in the cola in the can. The temperature is 7° C. What are the most likely temperatures of the plastic bottle and cola it holds?

- **a.** They are both less than 7° C.
- **b.** They are both equal to 7° C.
- **c.** They are both greater than 7° C.
- **d.** The cola is at 7° C but the bottle is greater than 7° C.
- **e.** It depends on the amount of cola and/or the size of the bottle.

10. A few minutes later, Ned picks up the cola can and then tells everyone that the countertop underneath it feels colder than the rest of the counter.

- **a.** Jon says: "The cold has been transferred from the cola to the counter."
- **b.** Rob says: "There is no energy left in the counter beneath the can."
- **c.** Sue says: "Some heat has been transferred from the counter to the cola."
- **d.** Eli says: "The can causes heat beneath the can to move away through the countertop."

Whose explanation do you think is best?

11. Pam asks one group of friends: "If I put 100 grams of ice at 0° C and 100 grams of water at 0° C into a freezer, which one will eventually lose the greatest amount of heat?

- **a.** Cat says: "The 100 grams of ice."
- **b.** Ben says: "The 100 grams of water."
- **c.** Nic says: "Neither because they both contain the same amount of heat."
- **d.** Matt says: "There's no answer, because ice doesn't contain any heat."
- **e.** Jed says: "There's no answer, because you can't get water at 0° C."

Which of her friends do you most agree with?

12. Mel is boiling water in a saucepan on the stovetop. What do you think is in the bubbles that form in the boiling water? Mostly:

- **a.** Air
- **b.** Oxygen and hydrogen gas

c. Water vapor
d. There's nothing in the bubbles.

13. After cooking some eggs in the boiling water, Mel cools the eggs by putting them into a bowl of cold water. Which of the following explains the cooling process?
- **a.** Temperature is transferred from the eggs to the water.
- **b.** Cold moves from the water into the eggs.
- **c.** Hot objects naturally cool down.
- **d.** Energy is transferred from the eggs to the water.

14. Jan announces that she does not like sitting on the metal chairs in the room because "they are colder than the plastic ones."
- **a.** Jim agrees and says: "They are colder because metal is naturally colder than plastic."
- **b.** Kip says: "They are not colder, they are at the same temperature."
- **c.** Lou says: "They are not colder, the metal ones just feel colder because they are heavier."
- **d.** Mai says: "They are colder because metal has less heat to lose than plastic."

Who do you think is right?

15. A group is listening to the weather forecast on a radio. They hear: "*... tonight it will be a chilly 5°C, colder than the 10°C it was last night.*"
- **a.** Jen says: "That means it will be twice as cold tonight as it was last night."
- **b.** Ali says: "That's not right. 5°C is not twice as cold as 10°C."
- **c.** Raj says: "It's partly right, but she should have said that 10°C is twice as warm as 5°C."
- **d.** Guy says: "It's partly right, but she should have said that 5°C is half as cold as 10°C."

Whose statement do you most agree with?

16. Kim takes a metal ruler and a wooden ruler from his pencil case. He announces that the metal one feels colder than the wooden one. What is your preferred explanation?
- **a.** Metal conducts energy away from his hand more rapidly than wood.
- **b.** Wood is a naturally warmer substance than metal.
- **c.** The wooden ruler contains more heat than the metal ruler.
- **d.** Metals are better heat radiators than wood.
- **e.** Cold flows more readily from a metal.

17. Amy took two glass bottles containing water at 20°C and wrapped them in washcloths. One of the washcloths was <u>wet</u> and the other was <u>dry</u>. 20 minutes later, she measured the water temperature in each. The water in the bottle with the wet washcloth was 18°C, the water in the bottle with the dry washcloth was 22°C. The most likely room temperature during this experiment was:
- **a.** 26°C **c.** 20°C
- **b.** 21°C **d.** 18°C

18. Dan simultaneously picks up two cartons of chocolate milk, a cold one from the *refrigerator* and a warm one that has been sitting on the *countertop* for some time. Why do you think the carton from the refrigerator ***feels*** colder than the one from the countertop? Compared with the warm carton, the cold carton —
- **a.** contains more cold.
- **b.** contains less heat.
- **c.** is a poorer heat conductor.
- **d.** conducts heat more rapidly from Dan's hand.
- **e.** conducts cold more rapidly to Dan's hand.

19. Ron reckons his mother cooks soup in a pressure cooker because it cooks faster than in a normal saucepan but he doesn't know why. [Pressure cookers have a sealed lid so that the pressure inside rises well above atmospheric pressure.]
- **a.** Emi says: "It's because the pressure causes water to boil above 100°C."
- **b.** Col says: "It's because the high pressure generates extra heat."
- **c.** Fay says: "It's because the steam is at a higher temperature than the boiling soup."
- **d.** Tom says: "It's because pressure cookers spread the heat more evenly through the food."

Which person do you most agree with?

20. Pat believes her Dad cooks cakes on the top shelf inside the electric oven because it is hotter at the top than at the bottom.
- **a.** Pam says that it's hotter at the top because heat rises.
- **b.** Sam says that it is hotter because metal trays concentrate the heat.
- **c.** Ray says it's hotter at the top because the hotter the air the less dense it is.
- **d.** Tim disagrees with them all and says that it's not possible to be hotter at the top.

Which person do you think is right?

21. Bev is reading a multiple-choice question from a textbook: "Sweating cools you down because the sweat lying on your skin:
- **a.** wets the surface, and wet surfaces draw more heat out than dry surfaces."
- **b.** drains heat from the pores and spreads it out over the surface of the skin."
- **c.** is the same temperature as your skin but is evaporating and so is carrying heat away."
- **d.** is slightly cooler than your skin because of evaporation and so heat is transferred from your skin to the sweat."

Which answer would you tell her to select?

22. When Zack uses a bicycle pump to pump up his bike tires, he notices that the pump becomes quite hot. Which explanation below seems to be the best one?
- **a.** Energy has been transferred to the pump.
- **b.** Temperature has been transferred to the pump.
- **c.** Heat flows from his hands to the pump.
- **d.** The metal in the pump causes the temperature to rise.

23. Why do we wear sweaters in cold weather?

- **a.** To keep cold out.
- **b.** To generate heat.
- **c.** To reduce heat loss.
- **d.** All three of the above reasons are correct.

24. Vic takes some Popsicles from the freezer, where he had placed them the day before, and tells everyone that the wooden sticks are at a higher temperature than the ice part.

- **a.** Deb says: "You're right because the wooden sticks don't get as cold as ice does."
- **b.** Ian says: "You're right because ice contains more cold than wood does."
- **c.** Ross says: "You're wrong, they only feel different because the sticks contain more heat."
- **d.** Ann says: "I think they are at the same temperature because they are together."

Which person do you most agree with?

25. Gay is describing a TV segment she saw the night before: "I saw physicists make super-conductor magnets, which were at a temperature of –260°C."

- **a.** Joe doubts this: "You must have made a mistake. You can't have a temperature as low as that."
- **b.** Kay disagrees: "Yes you can. There's no limit on the lowest temperature."
- **c.** Leo believes he is right: "I think the magnet was near the lowest temperature possible."
- **d.** Gay is not sure: "I think super-conductors are good heat conductors so you can't cool them to such a low temperature."

Who do you think is right?

26. Four students were discussing things they did as kids. The following conversation was heard: Ami: "I used to wrap my dolls in blankets but could never understand why they didn't warm up."

- **a.** Nick replied: "It's because the blankets you used were probably poor insulators."
- **b.** Lyn replied: "It's because the blankets you used were probably poor conductors."
- **c.** Jay replied: "It's because the dolls were made of material which did not hold heat well."
- **d.** Kev replied: "It's because the dolls were made of material which took a long time to warm up."
- **e.** Joy replied: "You're all wrong."

Who do you agree with?

Appendix II
Notes on Statistical Procedures

Effect size = $|X_2 - X_1|/\sigma_1$ where X = mean, σ = standard deviation.
Use of this form assumes equal variances (σ^2). If the variances are unequal, a "pooled" variance can be determined using the equation:

$$\sigma^2 = [\,\sigma_1{}^2(N_1 - 1) + \sigma_2{}^2(N_2 - 1)] \,/\, [N_1 + N_2 - 2].$$

The average normalized gain was calculated using the equation:

$$g = [X_{post} - X_{pre}] \,/\, [100 - X_{pre}].$$

Index of item difficulty (E) is defined as:

$$E = \frac{\textit{(number correct in upper 27\%) + (number correct in lower 27\%)}}{\textit{total number in upper and lower groups}}.$$

E is normally expressed as a percentage; the higher the percentage, the easier the item.

Index of item discrimination (D) is defined as:

$$D = \frac{\textit{(number correct in upper 27\%) – (number correct in lower 27\%)}}{\textit{number in upper (or lower) group}}.$$

An index of discrimination facilitates differentiation between high- and low-achieving students. D is normally expressed as a quotient. The higher the quotient, the greater the difference between upper and lower group responses to the item, with more of the upper group answering correctly.
The upper and lower 27% of students were on the basis of their ranked test scores. The value 27% is an optimum value maximizing separation between the high and low groups (resulting in small group numbers) while having sufficient numbers in either group to produce reliable statistics.