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ABSTRACT

The target of difficulty of the Educational Technology Center (ETC) Heat and Temperature Group is basic thermal physics, particularly the differentiation between heat and temperature. High school teachers often find that thermal concepts are very difficult for their students to master and attribute students' difficulties at least in part to the failure to differentiate between heat and temperature. This failure would indeed account for the students' poor learning, since most thermal variables, laws, and principles are based on the differentiation and relation between heat and temperature. This group's curriculum has used microcomputers as laboratory tools: Microcomputer-Based Laboratories (MBL) allow students to collect, display, and summarize data collected from the "real world," while with Computer Laboratory Simulations students watch "ideal" experiments on the screen, setting parameters, not collecting data. Classroom interventions have helped students at the problem-solving level: students taught with microcomputers were better than control students at solving quantitative problems of the type given in science tests, but no evidence was found that the computer-based curriculum facilitated conceptual change. This report summarizes past work and the development of computer conceptual models, and reports the results of a pilot study conducted to test the models. (CW)

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CAN MODELS FOSTER CONCEPTUAL CHANGE?
THE CASE OF HEAT AND TEMPERATURE

Technical Report

May 1988

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INTRODUCTION

Our target of difficulty is basic thermal physics, particularly the differentiation between heat and temperature. High school teachers find that thermal concepts are very difficult for their students to master and attribute students' difficulties at least in part to the failure to differentiate between heat and temperature. This failure would indeed account for the students' poor learning since most thermal variables, laws, and principles are based on the differentiation and relation between heat and temperature.

We view learning as the interaction between the information presented in class and in textbooks about a domain of knowledge and the internal mental state of the student (i.e., the pre-existing knowledge a student has about that domain; Driver and Erikson, 1983). Consequently, our group has had three interrelated goals: to characterize the initial state (i.e., the ideas and concepts students have developed on their own and bring to the classroom), to develop a microcomputer-based curriculum optimally adapted to those preconceptions, and to monitor the resulting interaction between the students and the curriculum. This is obviously a feedback process: by watching students in the classroom and evaluating the effects of our teaching interventions, we update our characterization of the students' conceptions and modify the curriculum accordingly. A fourth goal is to develop suitable methods to assess the effects of our teaching interventions.

Our research so far has enabled us to define students' alternative framework to basic thermal physics. The misconceptions they bring to the classroom are deeply entrenched, forming a well-integrated network of ideas that allow the students to make sense of all everyday phenomena they are likely to encounter. The textbook theory, because it is based on concepts and explanatory schemata that differ from those students have, cannot be assimilated without a complete conceptual reorganization, which typically fails to take place. Instead, students attempt to integrate the information presented in class into their own framework, distorting it in the process, sometimes severely enough to form additional misconceptions. When the information is incompatible with the students' framework, it is generally ignored.

Clearly, misconceptions have to be taken into account in the curriculum. Our approach has been to challenge the students' beliefs at the empirical level, by having them perform experiments whose results do not easily fit into their framework. We also tried to make the textbook theory easier to understand, by emphasizing key concepts that either are not part of their framework (specific heat, fixed points) or have a different meaning in it (amount of heat) and by making students discover the quantitative relations between them.

In the past two years our curriculum has used microcomputers as laboratory tools: Microcomputer-Based Laboratories (MBL) allow students to collect, display, and summarize data collected from the "real world," while with Computer Laboratory Simulations students watch "ideal" experiments on the screen, setting parameters, not collecting data. Our classroom interventions have helped students at the problem-solving level: students taught with microcomputers were better than control students at solving quantitative problems of the type given in science tests, but we found no evidence that the computer-based curriculum facilitated conceptual change.

We now believe that to differentiate between heat and temperature students need to be exposed to visual models in which the two concepts and their relations are represented explicitly. These models should include a macrolevel corresponding to the empirical and phenomenological level where variables are apprehended and measured, and a molecular level where those variables, and the laws relating them, find their meaning. Because such models depict concepts rather than phenomena we call them "conceptual" models. They should help students for the following reasons: (1) The key concept students lack, and have great difficulty acquiring, is *amount of heat*, an extensive variable; visual conceptual models can make it easier to grasp because they are well suited to represent its extensivity. (2) In real experiments, heat transfer is not so easy to control as temperature and cannot be dissociated from it. In a model heat content and temperature can be set independently, thus providing a more flexible setting for understanding the distinction between heat and temperature. (3) Kinetic conceptual models are mechanical models, dealing with motions and collisions; with them, students can exploit a much richer store of pre-existing knowledge, which helps give meaning to the textbook theory and consequently should help them give up their own[1]. (4) While the macrolevel models represent the laws and principles students have to learn, the molecular level models provide an explanatory mechanism for those laws and principles which gives them a necessity they do not have at the macroscopic level. (5) In our previous research, we found that the only students who learned to differentiate between heat and temperature already had a conceptual (molecular) model for thermal phenomena.

Presenting conceptual models on the computer offers several advantages: (6) They can be dynamic (e.g., showing molecules in motion) and interactive. (7) Parameters can be set quickly, allowing students to compare different cases effectively. (8) Finally, we were encouraged by the success of the Weight and Density group with computer models (Smith, Snir, & Grosslight, 1987), who are also dealing with the differentiation of an intensive and an extensive variable, although in their case the variable that gives the students more trouble is intensive (density) while in ours it is extensive (heat).

Our goal during 1986-87 was to develop computer conceptual models for thermal phenomena suited to the students' own framework. By taking into account both the theory to be taught and students' pre-existing concepts as well as the misinterpretations that result from traditional teaching, we ended up focusing on the concepts of energy unit and amount of heat energy, linking them to the mechanics of molecular collisions. The curriculum developed, which integrates those computer models, MBL, and Laboratory Simulations, will be tested in the classroom in January 1988.

This report first summarizes our past work and how it led us to develop computer conceptual models, then presents the models, and, finally, reports the results of a pilot study conducted to test the models.

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[1] Granted, students have many misconceptions about mechanics as well (DiSessa, 1983; Clement, 1983), but their mechanical knowledge provides them with useful intuitions.

PREVIOUS RESEARCH: STUDENTS' FRAMEWORK AND MBL INTERVENTIONS

Our previous research is reviewed here in some detail because its outcomes were crucial in determining the course of this year's research. We first established the students' major preconceptions about thermal phenomena and then devised an MBL curriculum aimed at dispelling them and replacing them with the textbook theory.

STUDENTS' CONCEPTUALIZATION OF THERMAL PHENOMENA

The following model for students' conceptualization was established on the basis of numerous clinical interviews (Wiser, 1985; 1987). Students think of heat basically as an intensive quality measured with a thermometer: the stronger the heat, the higher the level in the thermometer. Many think of heat as having force and actually pushing up the level in the thermometer. Cold is a separate and opposite entity and, like heat, has force and is measured with a thermometer. Thus, temperature (the thermometer reading) is seen either as the synonym of heat or as a superordinate term for both heat and cold, or as the measure of heat and cold. Students conceive of thermal phenomena as produced by sources of heat (or cold) acting on passive recipients ("passive" in the sense that the state of the recipient does not influence heat transfer). Hot sources emit heat spontaneously: they apply more or less intense heat, depending on their temperature (e.g., heat emitted by a stove burner on a high setting is hotter than heat emitted by a burner on a low setting). Students have *no concept of* amount of heat *in the extensive sense*. They rarely use the words, and only do so in the sense of heat intensity. They account for extensivity by a causal scheme: larger sources have more effect not because they give off more heat but because they have more contact area with the recipient, applying their heat to a larger portion of the recipient. A source will also have more effect the longer it stays in contact with the recipient. For example, a large amount of boiling water has the same heat as a small amount but will melt more snow because it covers more of the snow or because it stays hot longer, or both.

Because students think of sources of heat as communicating *their heat* (i.e., heat of a certain degree or intensity) to recipients, the physicist's notion of fixed points is impossible for them to understand. How could the recipient stay at the same temperature while changing state, since it is receiving heat and therefore increasing in hotness? Their interpretation of fixed points is consistent with their own framework: that temperature stays constant during phase change is either ignored or interpreted as an absolute limit for the substance. For example, the freezing point of a substance is "as cold as it can get" (even in its solid state), or "no matter how much cold is applied to the substance, its temperature will not get lower." Thermal equilibrium, in the physicist's sense, is also not intelligible because it requires a concept of heat distinct from temperature. Sometimes students can understand that two bodies in contact reach the same temperature, but they do so on the basis of a single thermal concept: the source cannot make the recipient hotter than itself because it is communicating to the recipient heat of a certain degree. Specific heat phenomena are also hard to understand: if the same heat is applied to the same amount of two different substances, the temperature changes should be the same.

The students' concept of heat, clearly undifferentiated with respect to the physicist's heat and temperature, is both intensive – its measure is the same at every point in the source

– and extensive – the heat in a larger quantity of hot water has more effect. Like the physicist's heat, the student's heat is transmitted from hot to cold objects and can be generated by chemical reactions. Like temperature, the student's heat is measured with a thermometer, its intensity corresponds to felt hotness, and (at least for some students) it reaches the same level in two objects in contact. The student's concept lacks critical components of both heat and temperature: the notion of amount of heat or a clear understanding of thermal equilibrium.

Not surprisingly, this undifferentiated concept is resistant to change: the students' concept of heat is well articulated, rich, and coherent. It is adapted to everyday experience of thermal phenomena; for example, it captures the fact that hot and cold are different sensations and that it takes longer to boil more water (because heat has to spread through more water). The language we use to talk about thermal phenomena reflects and reinforces the lack of differentiation between heat and temperature. "Hot" generally refers to temperature but is morphologically related to "heat." Everyday experiences may also reinforce misconceptions: the dials on stoves and ovens are marked in degrees; since stoves and ovens sources of heat, 350° F appears to be the measure of the heat given off by the flame. More important, heat plays a very different explanatory role in the students' account of thermal phenomena than heat and temperature in the physicist's account of them. For example, in physics, thermal equilibrium states the conditions under which heat is exchanged. The students' conceptualization has no need to account for heat exchanges: sources emit heat spontaneously. If thermal equilibrium is part of the students' beliefs at all, it is seen as a consequence of the fact that sources transmit heat of a certain temperature to the recipients. Causal schemata are at the center of students' explanations, but not of modern physics (see also de Kleer and Brown, 1985). In other words, the students' undifferentiated concept is embedded in a very different theory from the scientifically accepted one. If they are to learn thermal physics, students must undergo a deep conceptual reorganization – a theory change (Posner, Strike, Hewson, and Gertzog, 1982) – part of which requires them to give up the notion that heat has intensity or hotness and to acquire the notion of amount of heat.

WHY MBL SHOULD DISPEL STUDENTS' MISCONCEPTIONS

During 1984-1986, we developed and tested a curriculum that makes use of MBL to teach basic thermal physics to ninth graders. The topics we chose (quantitative relation of heat, mass, and temperature; specific heat; latent heat; cooling curves) emphasized the difference between heat and temperature at the empirical level: Heat and temperature are different physical entities whose relation is not a simple linear function. MBL were meant to help students understand these topics better by giving them direct phenomenological access to a measure of heat independent of the measure of temperature, by displaying the relation between heat input and temperature change as they are recorded, and by emphasizing visually the distinction between heat and temperature (for details, see Wiser, 1986).

In the traditional curriculum, students are taught that amount of heat is measured with a calorimeter. Unfortunately, to measure heat with a calorimeter one measures temperature and has to perform computations involving the mathematical relation of temperature, heat, mass, and specific heat, a relation based on the very distinction students lack. In other words, calorimeters do not give *direct phenomenological access* to the concept of amount of heat, and they do reinforce the misconception that heat is measured with a thermometer. The concept of *amount of heat* remains very abstract, remote from immediate experience, and unlikely to displace the well-entrenched notions that the measure of heat is its temperature and that heat is an intensive variable.

In contrast to traditional laboratory methods, MBL use heat pulse generators – called "heat dollopers" during the teaching interventions – to heat up and melt substances and thermal probes to record temperature. Both are connected to the game controller port of an Apple II computer. Each "dollop" of heat delivered by pressing a key is displayed on the screen as an arrow. The software allows students to display graphs of temperature (as recorded by the thermal probe) varying in real time. The graph includes all the heat "dollops" as they are delivered (Fig. 1), so the student can watch the temperature changes as a function of the heat pulses delivered.

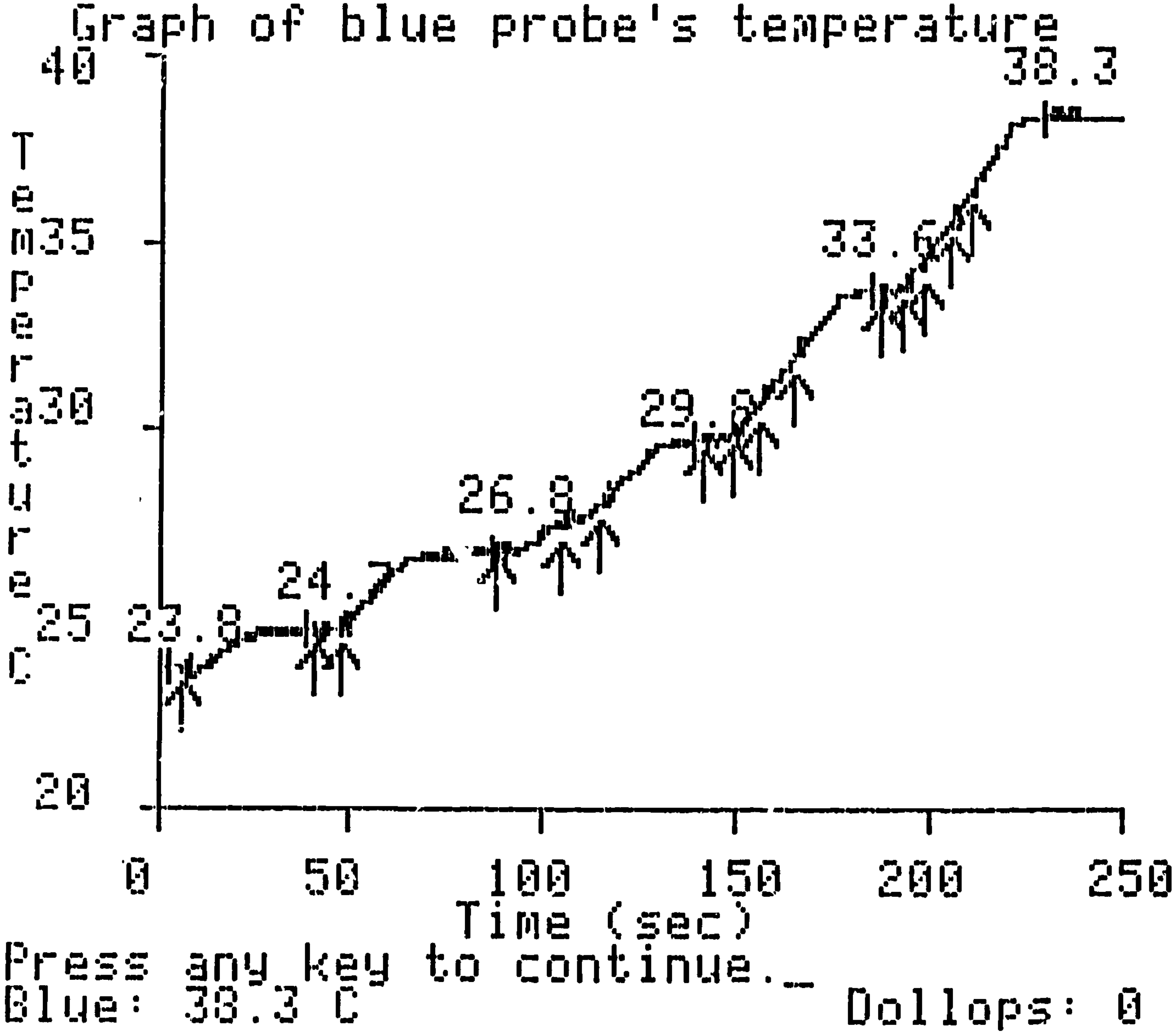
Thus, the MBL hardware and software give students a sense of the extensivity of heat (amount of heat = number of dollops) and emphasize the distinction between heat and temperature as data are recorded (dolloper versus thermal probe) and displayed (graph versus arrows). As long as students accept that the curve on the screen is a temperature curve while the number of dollops is a measure of heat, they can "see," with minimal inferential processing, that heat and temperature are different entities. Students who make these rudimentary distinctions may then be able to interpret the specific and latent heat demonstrations correctly. The information given in the demonstrations would, in turn, enrich their concepts of heat and temperature and consolidate the differentiation. It was hoped that the MBL lessons would trigger the reorganization of their beliefs about thermal phenomena.

CLASSROOM STUDIES

Procedure

Two classroom studies were conducted in which students were divided into a computer group who received the MBL curriculum and a control group who were exposed to traditional laboratory teaching. In the second study, we added Laboratory Simulations (see below) to MBL. In both studies, the students were ninth graders from a middle-class suburban high school. The teaching intervention, consisting of four lessons, was administered by the students' regular science teachers, who had participated in the design of the study; each teacher taught both types of curriculum for about two weeks. The content of the four lessons was the same for both groups. In the computer group, students collected data using electric heaters and thermal probes connected to the microcomputers. The control students used the same heaters, which they plugged into and unplugged from wall outlets, and traditional thermometers.

The teaching intervention was immediately preceded and followed by an evaluative test (Quantitative Problems Test) consisting of a series of quantitative problems similar to those generally given in science classes and closely related to the content of the teaching intervention. Some problems probed the situations of the laboratory activities



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Press any key to continue._
Blue: 38.3 C                              Dollops: 0
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Figure 1. Screen from the MBL program. Arrows on the temperature graph indicate "dollops" of heat.

(same material, same values for some physical parameters), others tested that knowledge applied to novel instances. The students' conceptual state was evaluated before and after the intervention (Conceptual Test). For the first study, a clinical interview was used in which students' conceptions about heating, cooling, and phase changes were probed by posing them a series of open-ended, qualitative problems. For the second study, the interview was turned into a written, multiple-choice test probing the same issues.

The topic of **Lesson 1** was the quantitative relations between heat input, mass of substance heated, and temperature change, as well as the quantitative dependence of temperature change upon the kind of substance heated (water versus alcohol). The control group collected their data and then drew graphs representing temperature change as a function of heat input. For the computer group, the software directly showed the quantitative relations between heat and temperature: as the liquids were heated, each dollop caused a fixed step in the temperature curve inversely related to the quantity being heated and dependent on the nature of the liquid. Thus, temperature changes should be viewed as *caused* by heat input but *not as the measure* of heat, because other variables are involved in the relation between the two: heat is measured in dollops, it does not "carry its own degree or temperature."

The topic of **Lesson 2** was heat storage capacity (specific heat): equal masses of different substances absorb and release different amounts of heat when their temperatures increase or decrease by the same number of degrees. In the first study, both groups performed the same experiment: dropping equal masses of iron and aluminum into cold water baths and recording the resulting temperature rises. In the second study, MBL were combined with Computer Laboratory Simulation (using software developed by George Martins, of the Newton North High School, Newton, Mass.) to teach about specific heat. Computer Laboratory Simulation allows entire experiments to be performed on the screen. The user chooses an experiment, then chooses the parameters in the experiment (e.g., quantities of liquids, initial temperatures), and monitors its unfolding. On the screen a cartoon presents experimental manipulations (e.g., a beaker is filled and its contents poured into another beaker), data collection (a thermometer is put into a beaker), data recording (the temperature in a beaker continuously appears on the screen), and data summarizing (graphs and tables).

In the second study, the students in the computer group first performed an MBL experiment and then several similar experiments using Computer Laboratory Simulation. This combination of both laboratory activities offers certain advantages. It may alleviate a major problem inherent in simulations: why should students believe that the simulation models the real phenomena they are studying? MBL gave students hands-on experience and a sense of what the Computer Laboratory Simulation would be if performed with real substances and instrumentation. The Computer Simulations allowed the students to perform more, and more varied, experiments, because substances that have attractive physical properties (in this case, very high or very low specific heat) but are either dangerous (mercury) or messy (oil) could be used. Many more experimental situations could be explored, because Computer Laboratory Simulation experiments are much faster to run than the real thing. For example, students could establish empirically that substances that require a lot of heat to increase in temperature also release a lot of heat when they decrease in temperature. More important, such experiments when performed hands-on are plagued by huge experimental errors (owing to heat losses), which weaken the empirical evidence considerably. Consequently, the experiments performed by the computer group with MBL and Computer Simulations could not be duplicated with the control group. Instead, that group performed the same experiment (iron and aluminum blocks in cold water) as in the first study.

In **Lesson 3**, students recorded the temperature of PDB (Paradichlorobenzene) placed in a cold water bath and established that, on one hand, while freezing PDB stays at a constant temperature and that, on the other, PDB and the water end by reaching thermal equilibrium. In the first study the computer group performed this experiment with MBL and in the second study with Computer Laboratory Simulations, thus remedying several difficulties inherent in the "real" lab experiment. First, the temperature plateau during freezing may be missed if the cooling bath is too cold, or it may not be constant if the freezing substance is not pure. Second, it is almost impossible to convince students on experimental grounds that heat is released during freezing. If a water bath is used, the temperature change in the water is very small, owing to the high specific heat of the water. Even if an alcohol bath is used, however, the bath receives ambient heat as well, so its temperature does not reflect the latent heat realeased by the PDB. Thus, the temperatures recorded are often far from what they would be in a carefully controlled lab environment, and, again, the experimental evidence loses its force: the temperature plateau in a freezing liquid must be horizontal for students to believe that temperature stays constant during phase changes, and there must be no doubt that the increasing temperature in the bath is due to heat released by the freezing liquid. By by-passing all these experimental problems, Computer Laboratory Simulation makes the experimental evidence more convincing.

In **Lesson 4**, also about latent heat and fixed points, students added ice and then heat to a mixture of ice and water and verified that the temperature stays constant as long as both ice and water are present. Like the content of Lesson 3, this demonstration was meant to dispel the misconception that adding/removing heat necessarily raises/lowers temperature. It showed that adding ice to a mixture of ice and water does not necessarily make the mixture cooler, thereby dispelling another prevalent misconception (based on the fact that two ice cubes make a drink colder than one). For the computer group, the focus of this lesson was on the contrast between the temperature plateau and the large number of arrows on the graph, representing the amount of heat delivered to the mixture of ice and water.

Results

Problem solving

The results of both studies were very similar. On the Quantitative Problems Test, the computer group showed a significant advantage. There was an interaction between novelty of the context mentioned in the problems, the level of difficulty of the problems, and the group. The computer group did better than the control group on the familiar problems and only they progressed on the novel easy problems, but neither group did well on the difficult novel problems. We also found an interaction between group and problem content. The difference between the two groups was greatest on the problems dealing with the quantitative relation between heat, mass and temperature (for details, see Wiser, 1986).

We attribute the superiority of the computer group over the control group to the concept of unit of heat given by MBL, which helped them deal with the quantitative laws. It may also have helped them to conceptualize novel situations correctly. When a problem mentioned objects kept on a hot plate for certain amounts of time, the computer students may have been able to think of the hot plate as delivering a certain number of units of heat in a certain amount of time. The computer students were also better on phase change questions, presumably because MBL visually impressed on them that during a phase change temperature stays constant despite the heat input. Finally, the computer students' greater progress on the specific heat questions in the second study can be attributed in part to the Laboratory Simulation's illustration of the concept of specific heat in a variety of situations, which prevented some of the misconceptions that result from a narrower exposure to the topic.

Reconceptualization

Despite the relative success of the computer intervention at the problem-solving level, we found no superiority in the computer group at the conceptual level. In fact, the computer students tended to perform less well than the control students on the conceptual posttest. Very few students moved from no differentiation in the pretest to full differentiation in the posttest; of the few who did, most were in the control group. Answers to the conceptual test questions, especially in the clinical interview of the first study, shed some light on this finding. The patterns of wrong answers in the Quantitative Problems Test were also informative.

At the conceptual level, the students in both groups learned from Lesson 1 that, somehow, mass had something to do with heat. For many, that knowledge remained purely procedural: "When units of heat and units of mass are mentioned in a problem, divide the former by the latter." The rule is useless, of course, when units of heat are not mentioned (e.g., when the heating is done on a hot plate); not surprisingly, mistakes on such problems were plentiful. When learning went beyond procedures, the physical laws internalized by the students were often vague and incomplete, and therefore wrong. For example, they retained from Lesson 1 that "larger masses absorb/have more heat," a notion that fits everyday experiences (it takes longer to boil a big pot of water or to raise the temperature in a big room), but they applied it indiscriminately because they ignored the second part of the law, "[larger masses take more heat] *to increase in temperature by the same number of degrees.*" Consider, for example, the following problem. Two pieces of steel of the same cross section, one twice as tall as the other, are held briefly on a hot plate. Will one get hotter than the other? Will one absorb more heat? They are then dropped in identical cold water baths; will the two baths reach the same temperature? In the posttest many students thought that the big piece would absorb more heat because "there is more room," thus not distinguishing the case presented to them (in which – roughly – the same amount of heat is absorbed and released by both pieces) from one in which the two pieces would be left on the hot plate long enough to reach equilibrium.

We believe students distort physical laws such as this one, not out of carelessness nor information processing limitations (although those probably play a role as well), but because they retain only the parts or aspects of those laws that make sense within their own framework. For example, the students' framework does not contain conditions for heat transfer. Sources emit heat spontaneously; equilibrium is either not part of the framework or, if it is, it is peripheral, seen as a consequence of the fact that "sources cannot make recipients hotter than themselves." Consequently, whether equilibrium is achieved is not a basis for classifying and solving problems, just as novices do not use conservation of energy to classify and solve problems in mechanics (Larkin, 1983). Heating is pictured as a "hot front" moving through the recipient (rather like images used by meteorological reporters on television news programs to depict changing weather across the nation). In the steel problem (described above), as envisioned by the students, the level of hotness rises through the two pieces of steel until both are "filled." The heat going through the two pieces is the same degree of heat (because it comes from the same hot plate), but a bigger volume of it is needed to fill the bigger piece – and that makes sense of the law the student is trying to learn.

In Lesson 1, students also learned that "if the same amount of heat is given to different masses of the same substance, the temperature rise is greater in the smaller mass." Some students could not assimilate that law at all: they interpreted "amount of heat" as heat intensity (for them it is the only measure of heat). If the same heat is given, clearly the temperature has to be the same! Others used a "diffusion" schema to make sense of it. They imagined the heat spreading out into the recipient. In a bigger mass there is more room to spread out, so the heat thins out more and its intensity (temperature) becomes less. This schema accounts for the difference in temperature between the different masses, but only qualitatively; it is not based on an extensive concept *amount of heat*, which would allow students to conceptualize temperature as (roughly) heat/mass [2], and solve problems quantitatively.

A similar case can be made about specific heat. Students who learned anything from Lessons 1 and 2 learned a new misconception–that specific heat characterizes how much heat a substance absorbs when exposed to a given source and, therefore, how hot it becomes– again ignoring the crucial component of the law (in this case, "It takes different amounts of heat to raise the temperature of equal amounts of different substances *by the same number of degrees*," or "*If the same amount of heat* is put into the same mass of two different substances, their temperatures will rise by a different number of degrees"). We believe that the students ignored the clause "If the same amount of heat" because they cannot fit it into their framework. For example, in Lesson 1 students delivered the same amount of heat into equal masses of water and alcohol and discovered that the temperature rise was greater in

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[2] Some experts may cringe at such a definition. We believe that such a conceptualization is a good intermediate one, a stepping stone to the expert's one. It ignores the distinction between kinetic energy in the center of mass and energy of the internal modes of molecular motion, but it captures the extensive/intensive distinction between heat and temperature. In fact, it is the idea developed in our second computer model (CONTAINERS, see below).

the alcohol (a fact captured by the notion of specific heat: water has a higher specific heat than alcohol, i.e., it takes more heat to raise the temperature of 1g of water by 1° C). What sense could they make of this finding without giving up the belief that temperature measures heat? If the alcohol gets hotter, it must be that it absorbs more heat. Such an interpretation is reinforced by the students' mechanical model for heating which allows them to accept easily that different substances react differently to heat: Denser substances "resist" heat more than ligther ones. So, for most students, the point of the alcohol and water lesson was lost; instead of learning that the same amount of heat causes different temperature rises in different substances, they "learned" that different substances absorb heat at different rates (which, while true, is not the point), and that higher specific heat means "able to absorb more heat from a given source." The students did not see the conflict between their interpretation (alcohol absorbs more heat) and the concept of *"same amount of heat"* emphasized in class, because they interpreted "same amount of heat is given" to mean "same heat" or "same degree of heat is applied," which does not imply that the same heat is absorbed (see STUDENTS' CONCEPTUALIZATION OF THERMAL PHENOMENA, above). The lab activities of the control group did little to dispel this interpretation. The heaters the students used applied the "same" heat to the two liquids, but left it easy for them to imagine that one liquid absorbed more heat than the other. In the computer group, the heat was delivered in "dollops" that should have made it obvious that the same amount of heat actually went into the liquids. The significantly larger number of students in the computer group who chose the correct answers on the specific heat questions in the posttest may be attributed to their using the dolloper.

Another conflict may be apparent: according to their interpretation, the students should have believed that alcohol had a higher specific heat than water, which is the reverse of what the intervention taught, and class discussions revealed this was exactly what most students had learned. In the clinical interviews most students who had something to say about water and alcohol either said that alcohol got hotter because it had a higher specific heat or, distorting the empirical evidence to fit rote-learned knowledge, that water would get hotter because it had a higher specific heat.

On the other hand, the iron and aluminum activity in Lesson 2, which showed that a substance with a higher specific heat made the water hotter, was easily assimilated because it fits well into their pre-existing schema; it even reinforced their core belief that higher (specific) heat means higher temperature, and vice versa. Not surprisingly, students did well on questions related to this activity.

Thus, the students' failure to learn the correct laws from Lessons 1 and 2 follows from their deeply held misconception – that temperature measures heat – and demonstrates a point made repeatedly in the education literature, that new information is assimilated into the students' framework, rather than displacing it, and often is distorted in the process.

The same conclusions apply to the concepts of heat and temperature. Either they were not changed, or they were modified only within the constraints of the pre-existing framework. Of the students who did not differentiate between heat and temperature before the teaching intervention, few did afterward, at least in the expert sense of differentiation. Many learned that there is a difference between heat and temperature, but hardly any were willing to give up the notion that temperature measures heat. The result was either total confusion (a bigger volume of hot water is hotter than a smaller volume of the same hot water) or a concept of heat with two measures: degree and amount. This "amount of heat" is very different from the physicist's concept; it is "amount of a certain degree heat." Such a concept does not allow, for example, a correct answer to the question "Is more heat available in a big container of warm water or in a small container of hot water?" because, being of different degrees, the "heats" in the two containers are not directly comparable. One consequence of this mis-assimilated extensivity is that its usefulness is very limited in applied situations. For example, in the steel problem (see above) students who (correctly) thought that the small piece would get hotter than the big piece went on predicting that the small piece would make the water bath hotter (because it released hotter heat). A few thought that the two pieces might possibly have the same effect on the water, because the larger area of contact might compensate for the lower temperature of the big piece. Such a solution is not really wrong, but it is qualitative (thus the uncertainty), not based on an expert concept of amount of heat (which allows the two pieces to be represented as absorbing and releasing the same amount of heat)[3]. To acquire the expert concept *amount of heat*, novices must do more than learn that heat is proportional to mass. They need to revise their concept of heat entirely and, especially, to give up the core notion of heat as hotness. Our teaching interventions did not accomplish this goal.

Even after the intervention, students continued to think of heat as an agent whose fundamental *nature* remained unknown. (When asked "What is heat?" most said they had no idea or that it was like a ray or a wave.) They understood only some of its properties and some of its effects. For example, in their view, one intrinsic property of heat was that it was hot and makes objects to which it is applied hotter. Heat also has the property of making molecules move faster, but while a physicist knows heat *is* a form of mechanical energy, the students thought of heat as an entity with the power of pushing molecules around but

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[3] The correct answer to the first question is that the small piece will be hotter than the big piece (neither had time to reach equilibrium with the hot plate). If the heating time is brief enough, or conductivity is low enough, or both, so that when the two pieces are removed from the hot plate the top of the small one is still in its initial shape, then the two pieces will have absorbed the same amount of heat. This is what we categorized as *the* correct answer. If these heating conditions do not obtain, the small piece will have absorbed less heat than the big piece. Some students said that the small piece would absorb less heat, but their answer to the first part of the question (the small one will be less hot), or their comments (the small one absorbs less heat because there is less room for it), or both, made it clear that such an answer should not be counted on as correct.

An expert answer to the second question is complex. The relative amount of heat absorbed by the two water baths depends on the amount and initial temperature of the water, the mass of the steel pieces and their temperature before being dropped into the water. On the assumption that initially both pieces and both water baths were at the same temperature and that both pieces absorbed the same amount of heat from the hot plate, a conceptually satisfactory solution is that the temperature rise will be the same in both water baths because both pieces of steel absorbed and thus released, the same amount of heat. A more advanced solution (correct under the assumptions above) is that the water temperature will be higher in the case of the small piece because, at equilibrium, the amount of heat initially received by each piece is then distributed between the water and the piece it contains in proportion to their masses and specific heats. By retaining less heat than the big piece, the small piece makes more heat available to the water.

without understanding the origin of this power. In other words, for almost all students, heat remained an opaque concept, with several fundamental and unrelated properties. Students who tried to relate the two properties of heat (hotness and pushing molecules) ended up with the following schema: A source of heat makes molecules in the recipient move faster, causing them to rub against each other, and the friction generates the heat that makes the recipient hotter. This schema also supports extensivity: a bigger mass contains more molecules, more molecules create more friction, generating more heat. This last example, besides demonstrating the influence on the assimilation of knowledge of pre-existing conceptions, shows the potential role of molecular models as unifying frameworks.

Conclusions

The students learned the material presented in the lessons well enough to answer problems and questions closely related to the content of the teaching; at that level, MBL and the Laboratory Simulations helped them. For many students, their concepts of heat and temperature were affected by the intervention, but only to a limited extent. The new information was sometimes learned by rote but more often integrated into the pre-existing conceptualization, resulting in further misconceptions. Very few students changed their basic conceptualization in favor of the textbook theory; the computer-based curriculum did not help in that respect.

Simply challenging students' beliefs with experimental evidence and encouraging them to discover the "correct" laws does not lead to conceptual change. Whatever clarifications MBL bring at the phenomenological level are insufficient at the conceptual level; MBL presented phenomena that challenged students' prior conceptions but did not demonstrate a new conception. We now believe that for an overall reconceptualization to occur a more radical intervention is needed. Students must be given not only empirical evidence that contradicts their own beliefs, but also a theoretical alternative they can understand in spite of those beliefs, so to speak. The nature of the key quantities (heat and temperature) has to be explicated, so students can see *how* they differ, not simply *that* they do. We think that our computer models may be the solution.

CONCEPTUAL MODELS

INTRODUCTION

We now believe that, to be assimilated, the textbook concepts have to be made explicit. It is not enough to give students definitions (e.g., "Temperature is the average kinetic energy per molecule") or to make them discover physical laws at the empirical level, because neither definitions nor laws are enough to give concepts new meaning. If the new meaning of old words (heat, temperature) is not made explicit, it is not surprising that students try to learn the new information using the old meanings. Two pedagogical solutions suggest themselves: (1) Train students to do what scientists do: revise their theories and concepts on the basis of new data (build meaning to fit facts, so to speak), or (2) Make the textbook theory directly learnable by explicating the concepts.

The first solution is more ambitious and offers potentially a bigger pay-off. Reconceptualization, if it could be taught as a general learning mechanism, would be applicable to all domains of learning. In such an enterprise in the case of thermal physics, students would clearly have to be strongly guided (toward textbook theory); they cannot be expected to accomplish by themselves in a few weeks what took so long in the history of science.

The second solution by-passes the discovery process and simply attempts to give students a sense of the nature of the variables (e.g, heat, specific heat, kinetic energy) and of the origin of the laws linking those variables (e.g., thermal equilibrium, law of mixtures). In the next section we argue that this is precisely what conceptual models can do for thermal physics. There is, of course, no guarantee that, even if the textbook theory is made meaningful, students will give up their own conceptualization. It may be necessary to incorporate into the curriculum discussions about theory building or the nature of models, i.e., to borrow from the first solution. (This issue will be addressed in the next technical report.)

The idea of teaching models of thermal phenomena is not new. For example, the molecular basis of thermal physics is already included in most existing ninth-grade physics curricula about heat, but it is not exploited at the explanatory level. Although mentioned in the definition of temperature and thermal equilibrium and in the account of dilation, molecules are not used, for example, to illustrate the difference between heat and temperature or to explain either changes of state or specific heat. The information generally is not structured to give students a sense of the underlying mechanisms at work or the reasons for the laws presented.

Traditionally taught, the molecular model accounts very well for thermal dilation (indeed, students find it compelling and easy to assimilate) but does little to dispel misconceptions or help students understand the nature of heat, its extensivity, or the meaning of the thermal laws. The same is true of existing visual models (films or software): they show molecules moving faster at higher temperature and the average distance between them increasing (again, illustrating dilation), but they do not address fundamental conceptual difficulties.

A typical chapter on heat is included in Appendix A (Heimler and Price, 1984). It would be hard for a student to understand the subject from the following excerpts: *"Temperature is the measure of the average kinetic energy of the particles in an object."* Average over what? *"Heat is the energy transferred between matter as a result of differences in temperature."* What kind of energy is heat? Why does it flow from *"regions of higher temperature to regions of lower temperature?"* Why does the heat transferred depend on mass? Why does heat stop flowing when temperatures are the same? What does heat transfer have to do with temperature being a measure of the average kinetic energy of particles? *"Heat and temperature are related. When the total energy of a substance is increased, its particles move faster."* Does that mean temperature measures heat? *"Specific heat is the ability of a material to absorb heat."* Does that mean specific heat is proportional to mass? What does specific heat have to do with molecules and their kinetic energy? Is it a kind of heat, as kinetic energy is a kind of energy? These are just a few questions that very intelligent, motivated, inquisitive students might ask, if they knew that studying consists of asking oneself a lot of questions. Most ninth graders do not know this, and, even if they did, where would they find the answers? Average students are left with a vocabulary lesson and no way to grasp the subject matter.

In contrast to traditional models, our conceptual models emphasize energy content, rather than molecular motion. They provide different visual representations for heat and temperature. Rather than simply illustrate definitions of heat and temperature at the molecular level, they explicate the relations of heat, mass and temperature ($Q = M*C*DT$, where Q is the amount of heat added or removed, C specific heat, and DT the temperature change; thermal equilibrium; law of mixtures) in molecular terms, making the extensivity of heat quite evident. They apply to specific heat phenomena. Thus, all the phenomena and laws students have to learn can be explained on the basis of these models (except for changes of state, which will be tackled in the future). Finally, students are taught how to use the models to solve problems.

INITIAL COMPUTER MODELS

We present first an overview of the models and a discussion of the choices made about what theoretical information to include in the models and what to leave out, and, then, a description of each model in detail.

The first model, called COLLISION, illustrates the exchange of energy that occurs when two molecules collide. Students are told that the amount of energy exchanged is represented by an exchange of dots between the two colliding molecules. This program explains that heat is motion energy[4] and accounts for thermal equilibrium in terms of molecular collisions.

In CONTAINERS, the main model, containers in the shape of rectangles are represented on the screen. The name suggests containers of liquids, reflecting the beakers filled with water and alcohol students use in laboratory experiments, but the students are told the rectangles could as easily represent chunks of solids (aluminum, steel) or containers filled with gases, and the information presented is general enough to apply to all cases. CONTAINERS focuses less on molecules than on their (disorganized) energy, i.e, thermal or heat energy [5]. The amount of heat energy is represented by a certain number of dots and the temperature (when a single substance is considered[6]) by their density. In the normal mode, the molecules are not represented in the container. The program is interactive and serves several purposes: it illustrates visually the difference between heat and temperature, shows the relation of heat, mass and temperature, and simulates conduction. The VIEW option allows users to view the molecules in motion (and thus to verify that higher temperature means faster moving molecules); it also reminds them that the energy dots do not represent molecules. The model includes a series of problems for students to solve.

[4,5,6] See below, "Simplified physics."

The third program, KINETIC & INNER ENERGIES, also shows collisions between two molecules, but it introduces the notions of energy of the center of mass motion (which is directly related to temperature) versus energy in the internal motions of the molecules. By demonstrating that the ratio between the two kinds of energy is constant for a given substance, the program accounts for specific heat.

"Simplified physics"

Like any model builders, we have struggled with the issues of truth and simplicity. Rather than include in an unclear way certain complex ideas (e.g., average kinetic energy, heat as energy in transfer, internal modes of motion, and so on) which at this point are beyond students' understanding, the group chose for clarity to "simplify" some principles of physics, deliberately violating them (e.g., all molecules have the same energy in the models), while addressing others only in enough depth to make them graspable (e.g., specific heat). The following simplifications have been made:

1) We talk about the amount of heat *in* a container. Most textbooks define heat as the energy exchanged between two bodies at different temperatures and strongly state, "There is no heat *inside* a body, heat is only a *transfer* of energy." While we understand the reason for this view, we believe that, at least in ninth grade, it is acceptable to speak of the quantity of heat inside a body (M*C*T), that is, we equate heat and internal energy.

We believe that not only is it acceptable to speak this way, it is necessary. The statement "There is no heat inside a body," which is actually a theory-relative statement about a definition, can be translated as "We reserve the term 'heat' to refer to the energy exchanged by two bodies at different temperatures (and will call that same energy when it is inside one or the other object 'internal' energy)." Ninth graders cannot appreciate the distinction, rooted as it is in thermodynamics and the kinetic theory of gases; they interpret "There is no heat inside a body" as a statement about the referent of "heat" (the energy inside a body that makes it hot) and are totally confused by trying to understand how objects get hot if there is no heat inside them. To speak of heat *in* a body spares them confusion and helps them focus on the important difference between heat and temperature (extensivity versus intensivity). This simplification is not detrimental, because nothing in the material ninth graders have to learn hinges on the distinction between heat and internal energy; should some of them encounter this distinction later, only a minor conceptual adjustment will be needed to understand it.

2) In the CONTAINERS model, we present temperature as the density of heat (heat per molecule), a presentation that can be considered wrong on several grounds: First, as argued above, energy in a body should be called internal energy, not heat. Second, temperature is the average *kinetic* energy of the molecules; the kinetic energy of the center of mass of molecules is only one portion of the energy of an object, the other being the energy of vibration and rotation inside the molecules. Third, the ratio of kinetic energy and rotational and vibrational energy varies from substance to substance, but when only a single substance is studied, the "density of kinetic energy" (i.e., temperature) and the "density of rotational and vibrational energy" covary, so that the density of internal energy (in our curriculum, heat) is proportional to temperature. To present temperature as equal to the density of heat captures an important difference between heat and temperature (extensivity

versus intensivity), which can be elaborated on later, once students are comfortable with the extensivity of heat (see footnote 2).

3) Along the same lines, in the first stages of teaching we refer to heat as energy of motion of the molecules, collapsing the energy associated with translational and internal degrees of freedom under one label. Students will interpret the phrase as referring to the kinetic energy of the molecules in the center of mass system because this is the only type of motion they know about. This interpretation, like those discussed above, is not a serious misconception; it gives students an important element of thermal physics – that is, that heat is mechanical energy – and can be revised later, without major reconceptualization.

4) We ignore the distribution of molecular velocities and pretend that all the molecules in a body at thermal equilibrium have the same speed. Everything in the heat and temperature curriculum for ninth grade can be understood without the concept of velocity distribution. Omitting this concept reduces the amount of material to be mastered and allows students to concentrate on the major issues.

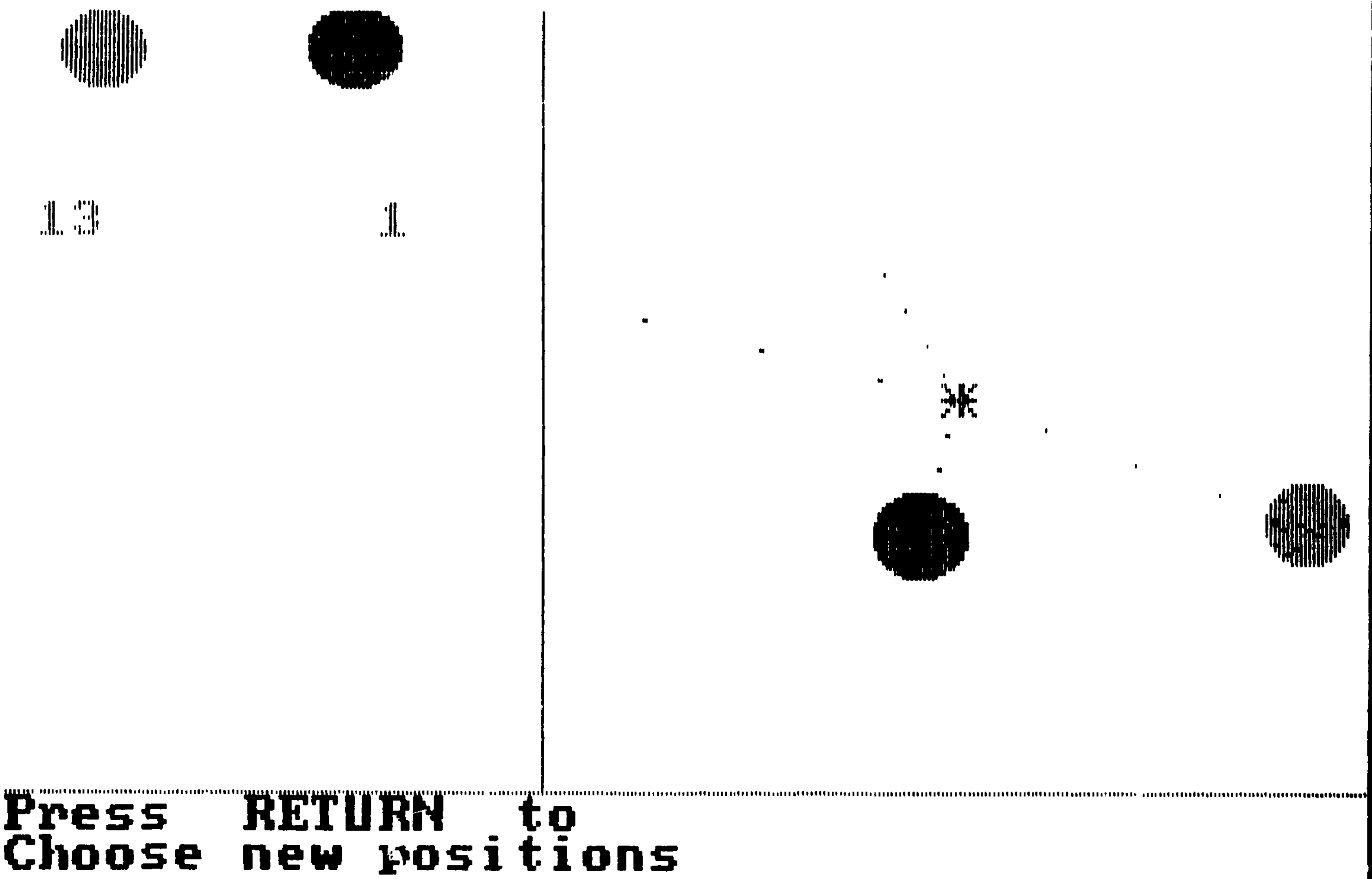
COLLISION program

The goal of this program is to give students the sense that the heat exchanged by two bodies at different temperatures is really an exchange of energy between moving molecules, thereby giving meaning to the "energy dots" in the next program. The screen shows two molecules, represented by two circles, one green, the other red, moving in straight lines, colliding, and then moving in different directions (Fig. 2). The masses of the molecules differ slightly, although the user is not told this (visually, the difference is negligible), because if the masses were exactly the same, the molecules would simply exchange energy; i.e., the first molecule would end up with the energy of the second, and vice versa, and thus the energy would never be redistributed. The user can choose the initial speed of the molecules (very slow, slow, medium, fast, very fast), but their initial positions are randomly determined. The trajectories are represented by dotted lines. Every time the user presses the SPACE BAR, both molecules move one step (one dot is added to each trajectory). The speed of a molecule is represented on the screen by the size of its steps (the distance between two successive dots = the distance travelled by a molecule in a fixed amount of time). After collision, the sizes of the steps (generally) changes, because the molecules have exchanged some energy. When the RETURN key is pressed, the molecules start from new random positions with the energies from the end of the previous collision.

The kinetic energy of each molecule is represented by energy dots inside the molecule. The user can verify that during collision the dots are redistributed between the two molecules, but the total number of dots is conserved. The same information is represented numerically on the left side of the screen. The amount of energy (number of dots or energy units) of the molecule after each collision is written in a column, and there is one column for each molecule (Fig. 3).

CONTAINERS program

The initial choice is "Try your own" or "Tasks." "Try your own," in which users set the parameters (mass, temperature, or energy), introduces the concepts of heat and

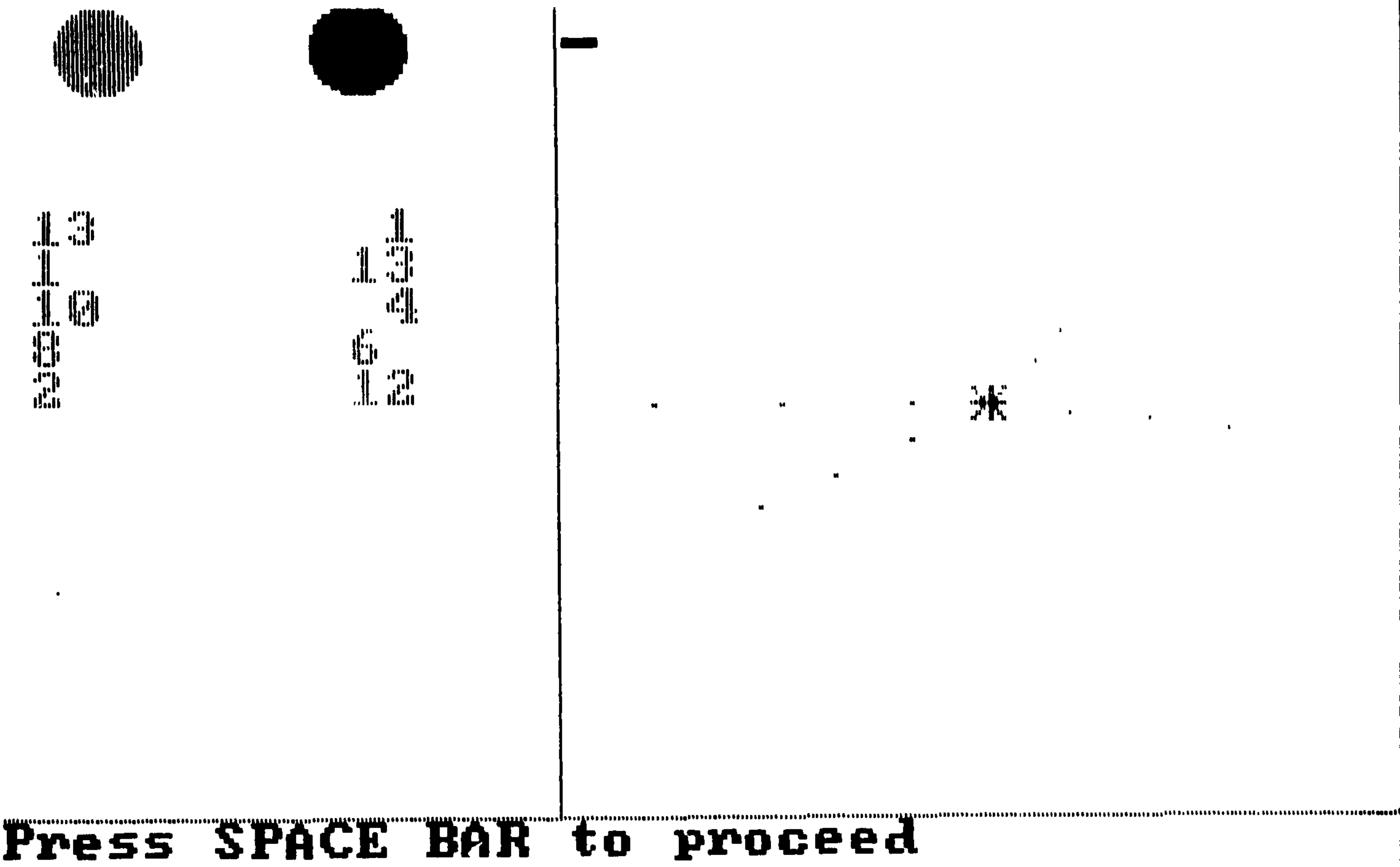


13

1

Press RETURN to
Choose new positions

Figure 2. Screen from the COLLISIONS program. On the left are the numbers that represent the energy of the molecules after collision. On the right are molecules and their trajectories before and after collision; the dots inside the molecules represent their energy. On the screen the molecule that appears dark gray in this figure is red and the light gray molecule is green.



```
13          1
1          13
10          4
8          6
2          12

Press SPACE BAR to proceed
```

Figure 3. Screen from the COLLISIONS program. The molecules (not shown) have undergone five collisions. The numbers on the left represent their energy after each collosion. The trajectories on the right are for the fifth collision.

temperature, the quantitative relation of heat, mass, and temperature, molecular motion, and conduction. "Tasks" is a series of problems to be solved by the user, which are applications of the concepts and laws just learned. The first choice in "Try your own" is between "One container" or "Two containers," the latter option allowing a comparison between two containers, e.g., between the temperatures in two different mass containers with the same energy. ("One container" works similarly without a comparison.) The second choice is "Same substance" or "Different substances" in the two containers. Here we deal first with the option "Same substance."

The user is asked to set a series of parameters: the masses of the two containers and either their temperatures or the thermal energies they contain. The choices for mass are 1, 2, 3, or 4 arbitrary units, which users are told can be thought of as grams, pounds, kilos. Temperatures can be set anywhere between 0° and 100°; these degrees are proportionally related to degrees Kelvin (at 0° there is no thermal energy in the container, a point explicated only with more sophisticated users) but otherwise arbitrary. Like the units of mass, the energy units are arbitrary and can be thought of as calories, Kcalories, joules, and so on.

After the parameters are set, two containers appear on the screen (Fig. 4), each represented by a rectangle with an area proportional to the mass chosen. The amount of heat energy in each container is represented by a number of small dots randomly placed, the number being proportional to the amount of heat energy in a container (one energy unit = one dot). The dots move randomly, simulating the constant exchange of energy. Above each container on the screen appear its mass (number of mass units), temperature, and energy (number of energy units). The screen shows two representations for each variable: pictorial (container size for mass, number of dots for heat, and density of dots for temperature) and numerical. Even though the units are arbitrary, the values of the variables obey the relation: *Number of heat units = (6)*(number of Mass units)*(Temperature in degrees).*

The user can interact with the display in several ways. The first option, VIEW (Fig. 5), allows the user to watch molecules in motion[7]. With left and right arrow keys, the user can choose a container to VIEW. A white rectangle (representing a small "region" of the container) appears on the screen, and it can be moved, by using the arrow keys, to view any region. The user "zooms in" on the chosen region (by pressing the RETURN key), and a window appears in which molecules are moving at a speed proportional to the square root of the temperature in the container; a bar graph in the lower right corner of the window represents the speed. This procedure can be repeated for the second container.

The user's other options are: ZAP and CONTACT. (ESCAPE, always an option, returns the user one level up in the hierarchy of commands.) ZAP allows the user to heat a container, i.e., to put more energy dots into it. Suboptions are: ZAPping both containers simultaneously or one at a time and the number of ZAPs (each ZAP is worth 100 energy dots). The added energy dots appear at the bottom of the container (to simulate heating on a hot plate; see Fig. 6). "Adding energy" appears over the containers, and the new number of energy units replaces the old one in the caption. When the user presses RETURN, the dots

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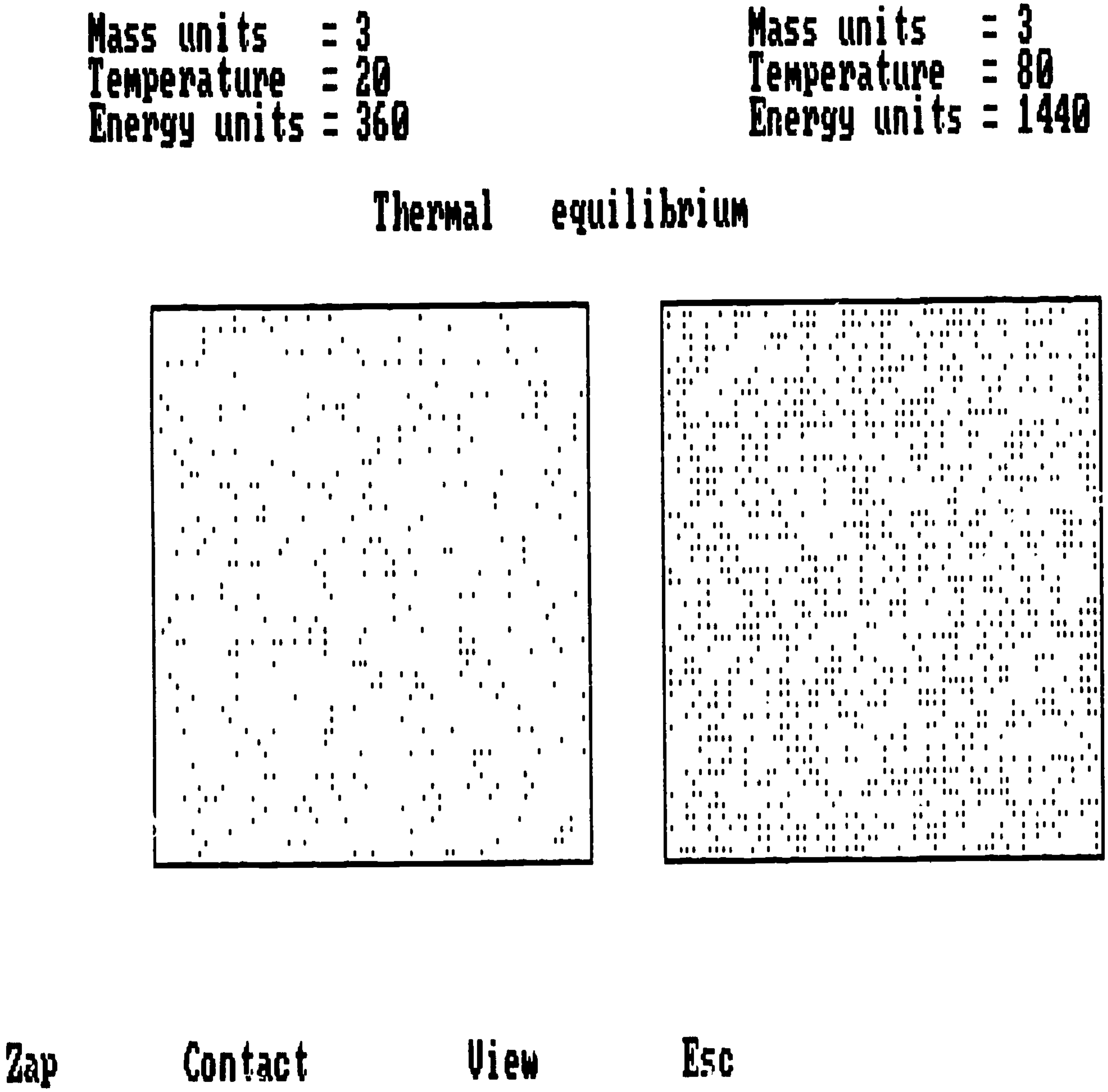
[7] All the molecules have the same speed. See above, "Simplified physics."

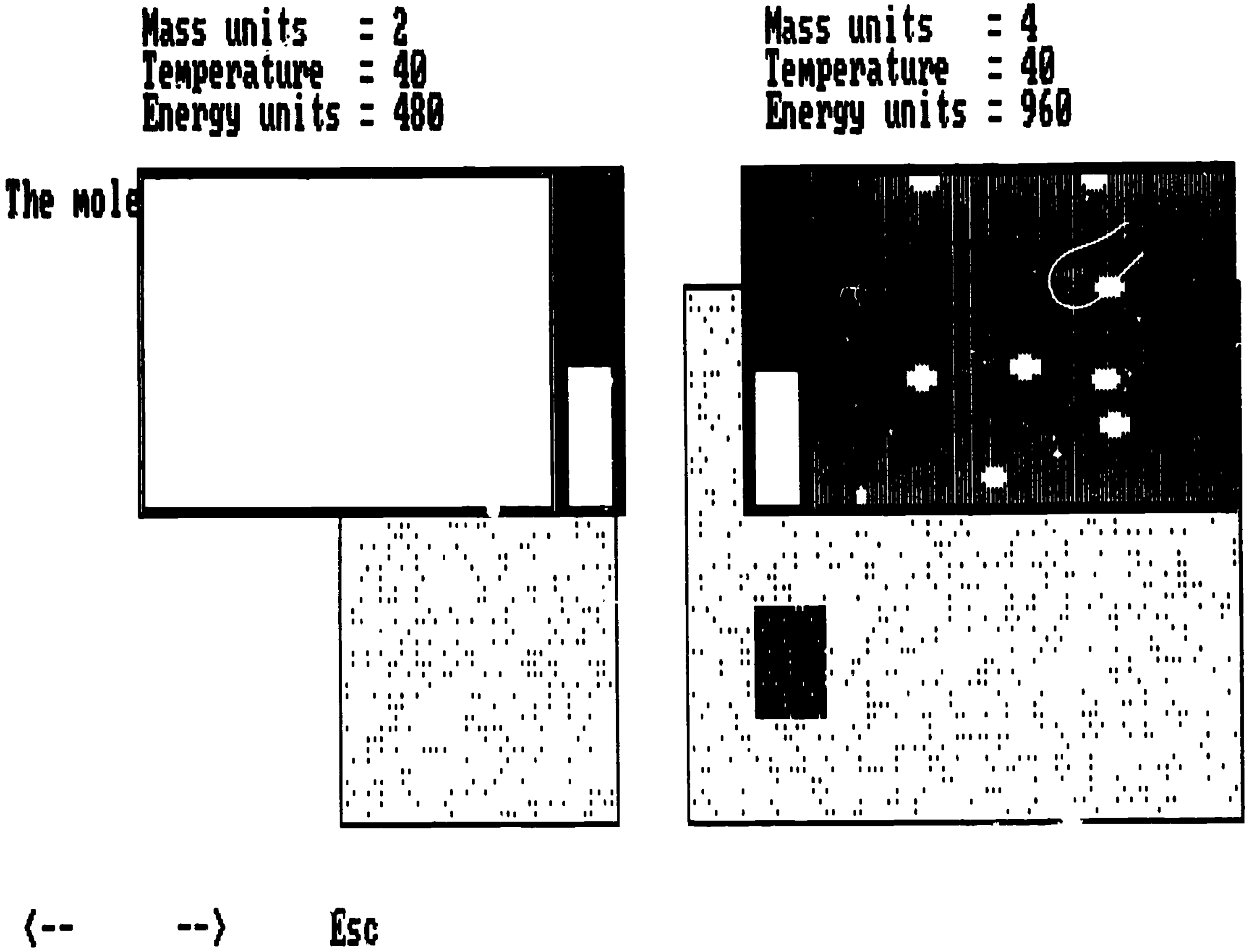


Mass units = 3
Temperature = 20
Energy units = 360

Mass units = 3
Temperature = 80
Energy units = 1440

Thermal equilibrium

Figure 4. Screen from the CONTAINERS program. Two containers with the same mass. The container on the right has more heat (more energy dots) and a higher temperature (greater dot density).

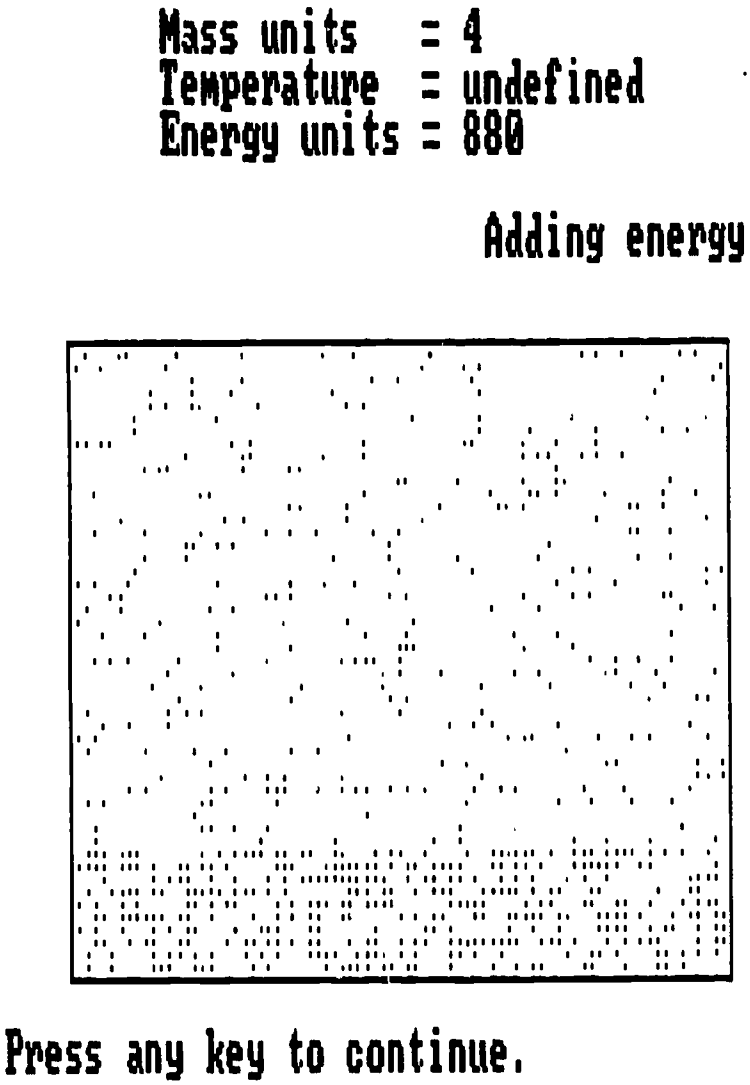


```
Mass units   = 2
Temperature  = 40
Energy units = 480
```

```
Mass units   = 4
Temperature  = 40
Energy units = 960
```

```
The mole
```

Figure 5. Screen from the CONTAINERS program, VIEW option. The big gray rectangle represents a blowup of the small black rectangle, and the white circles inside it represent molecules. The height of the small white rectangle adjacent to the gray rectangle is proportional to the kinetic energy of the molecules.



```
Mass units   = 4
Temperature  = undefined
Energy units = 880

                 Adding energy

Press any key to continue.
```

Figure 6. Screen from the CONTAINERS program, ZAP option. Initial stage: energy dots are added at the bottom.

gradually spread upward (representing the energy exchanges between the fast-moving molecules at the bottom and the slow-moving molecules at the top) until thermal equilibrium is established (the dot distribution is homogeneous), at which point the new temperature replaces the old one on the screen. During the equilibration process the temperature is labeled "Undefined" (Fig. 7) and the user can VIEW the molecules (e.g., to compare velocities at the top and bottom) or choose the option QUICK, which by-passes the equilibration process and represents the container directly in the final state of equilibrium.

The CONTACT option allows the user to demonstrate thermal conduction (Fig. 8). A solid bar appears between the two containers, to simulate contact, and the energy dots are redistributed, moving from the container at the higher temperature to the one at the lower temperature, until equilibrium is reached. During this process, the temperature and number of energy units in each container are constantly updated in the captions over them. Again, the user can select the QUICK option, which presents both containers in final equilibrium. In a future version of the software, the rate of energy exchange will be a function of the temperature difference between the two containers, and of the conductivity of the substance.

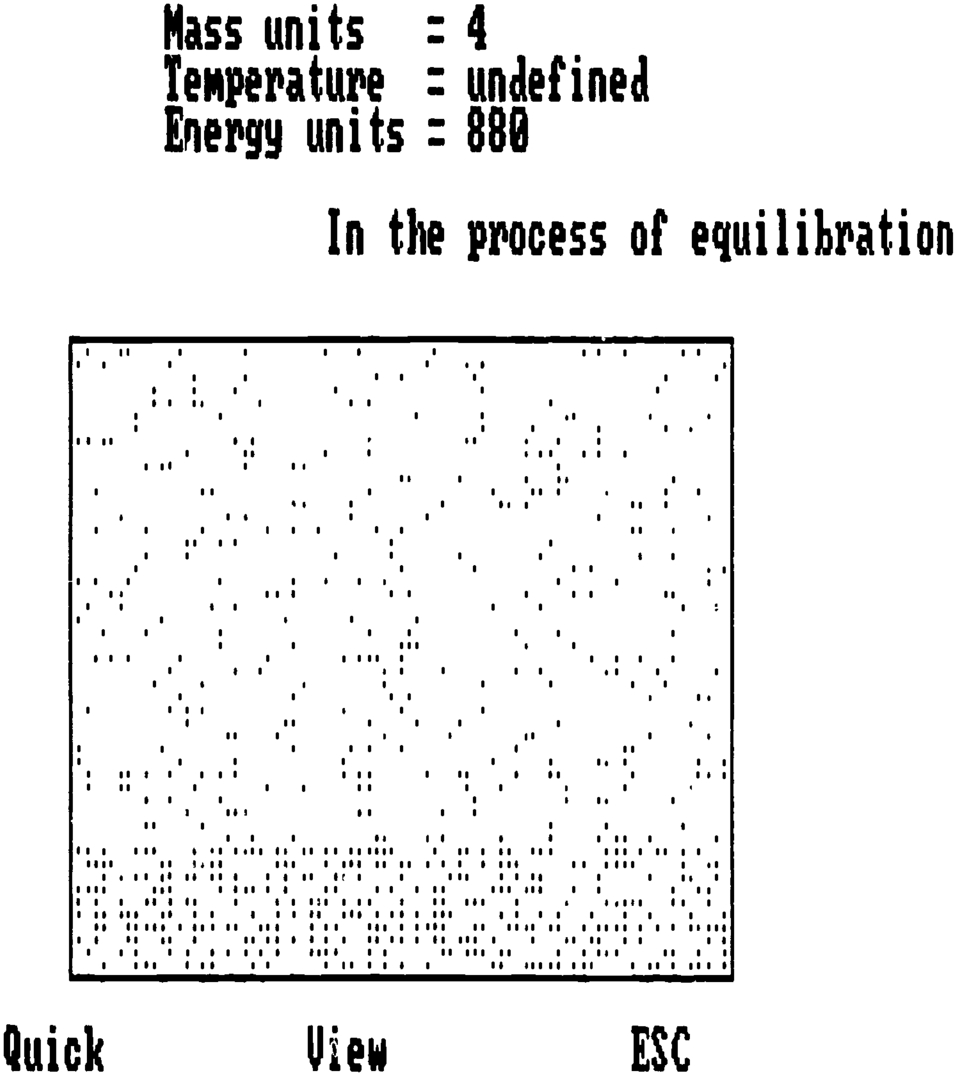
In the "Different substances" option, each container contains a different substance with a different specific heat; the user can choose among substances A, B, C, or D. The size of a mass unit on the screen differs for each container, because different substances are likely to have different densities. The density of the dots is no longer proportional to temperature. When the temperatures in the two containers are equal, the number of energy dots per molecule is different (the kinetic energy of the centers of mass of molecules is the same, but the energies of their internal modes of motion are different). Further, the number of molecules per mass unit differs for each substance, and on the screen the mass units have different sizes. Consequently, at this point the density of the dots is no longer proportional to tempterature, and the model has lost much of its usefulness because there is no pictorial representation of temperature. The consequences of this loss offer a subject for fruitful class discussion of the usefulness of models and their revisability.

Tasks option

This option consists of a series of exercises about the relations of amount of heat, mass, temperature, molecule velocity, dot density, and so on. Eight types of exercises have been developed so far, all involving identical substances in the two containers. Tasks for different materials (i.e., about specific heat) are under development. After selecting a type (e.g., Task 1), the user can generate an infinite number of exercises of that type, each with different parameters (Fig. 9).

Task 1. Watch two containers. See Figure 10. Two containers filled with dots, with different masses and different temperatures, appear on the screen. The user decides by looking at them which has more energy units and which a higher temperature. When the user presses RETURN, the data (temperatures, numbers of energy units) appear on the screen.

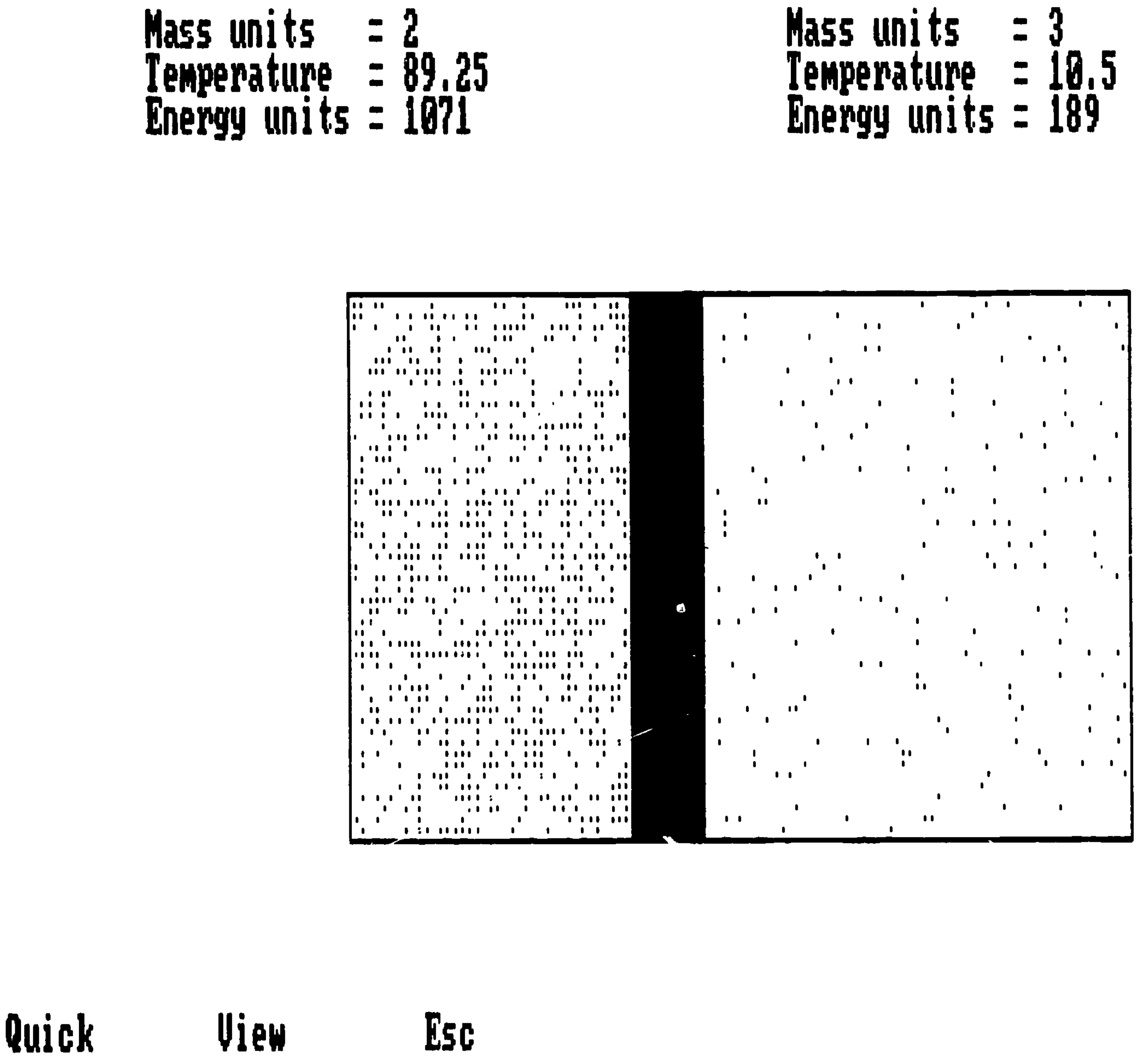
Task 2. Choose energy for fixed temperatures: Same mass. See Figure 11. The container on the left is filled with dots. The caption over it gives its mass, temperature, and the number of energy units it contains. The container on the right is empty. The caption over it gives only its mass (which is the same as that for the one on the left). The user is given a



```
Mass units    = 4
Temperature   = undefined
Energy units  = 880

        In the process of equilibration
```

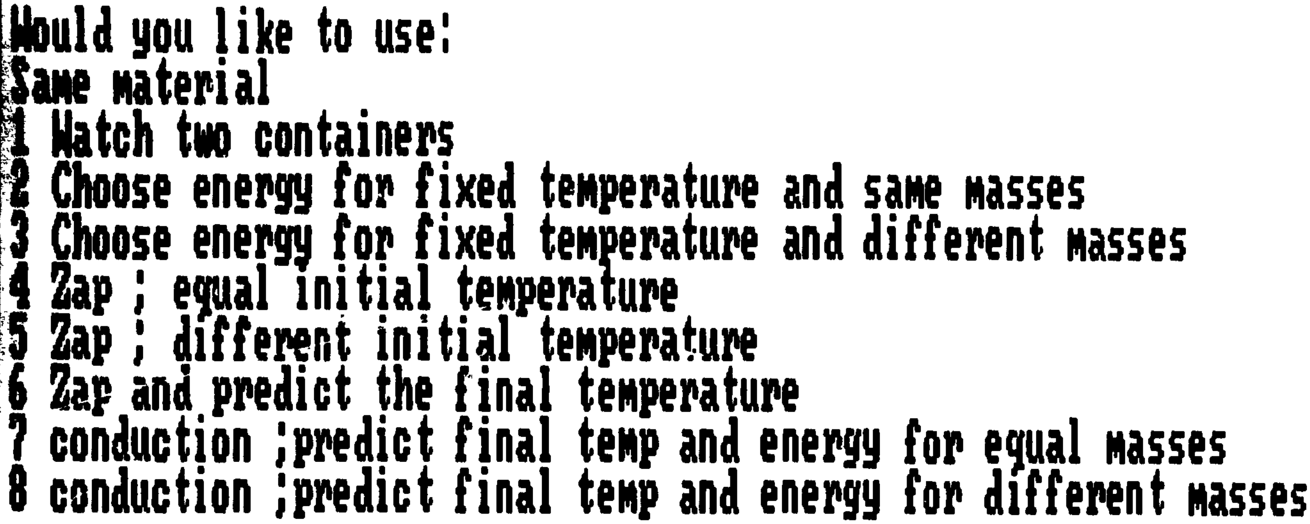
Figure 7. Screen from the CONTAINERS program, ZAP option. Intermediate stage: dots migrate upward.



Mass units = 2
Temperature = 89.25
Energy units = 1071

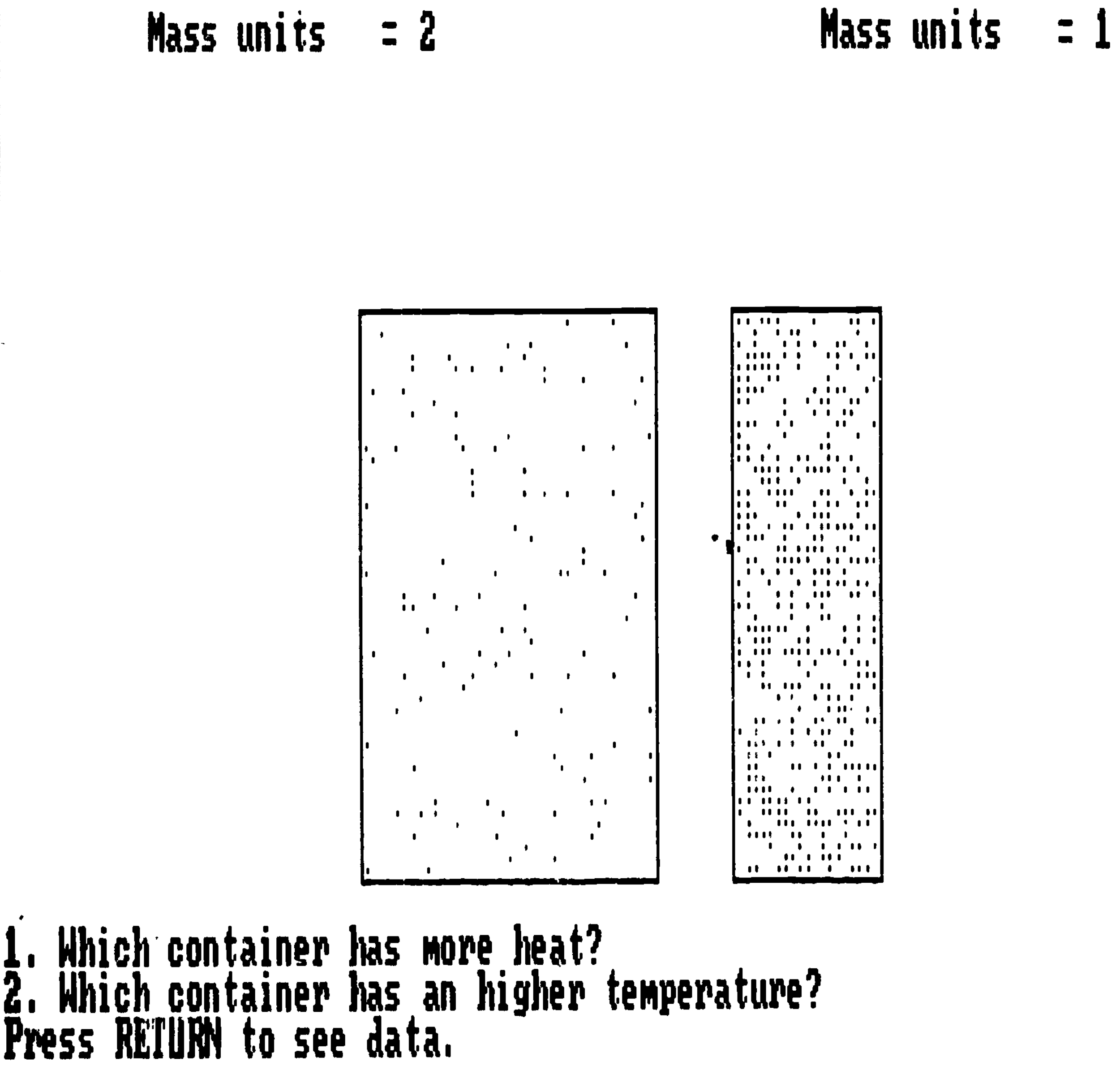
Mass units = 3
Temperature = 10.5
Energy units = 189

Figure 8. Screen from the CONTAINERS program, CONTACT option. The black bar symolizes thermal contact between the two containers.



```
Would you like to use:
Same material
1 Watch two containers
2 Choose energy for fixed temperature and same masses
3 Choose energy for fixed temperature and different masses
4 Zap ; equal initial temperature
5 Zap ; different initial temperature
6 Zap and predict the final temperature
7 conduction ;predict final temp and energy for equal masses
8 conduction ;predict final temp and energy for different masses
```

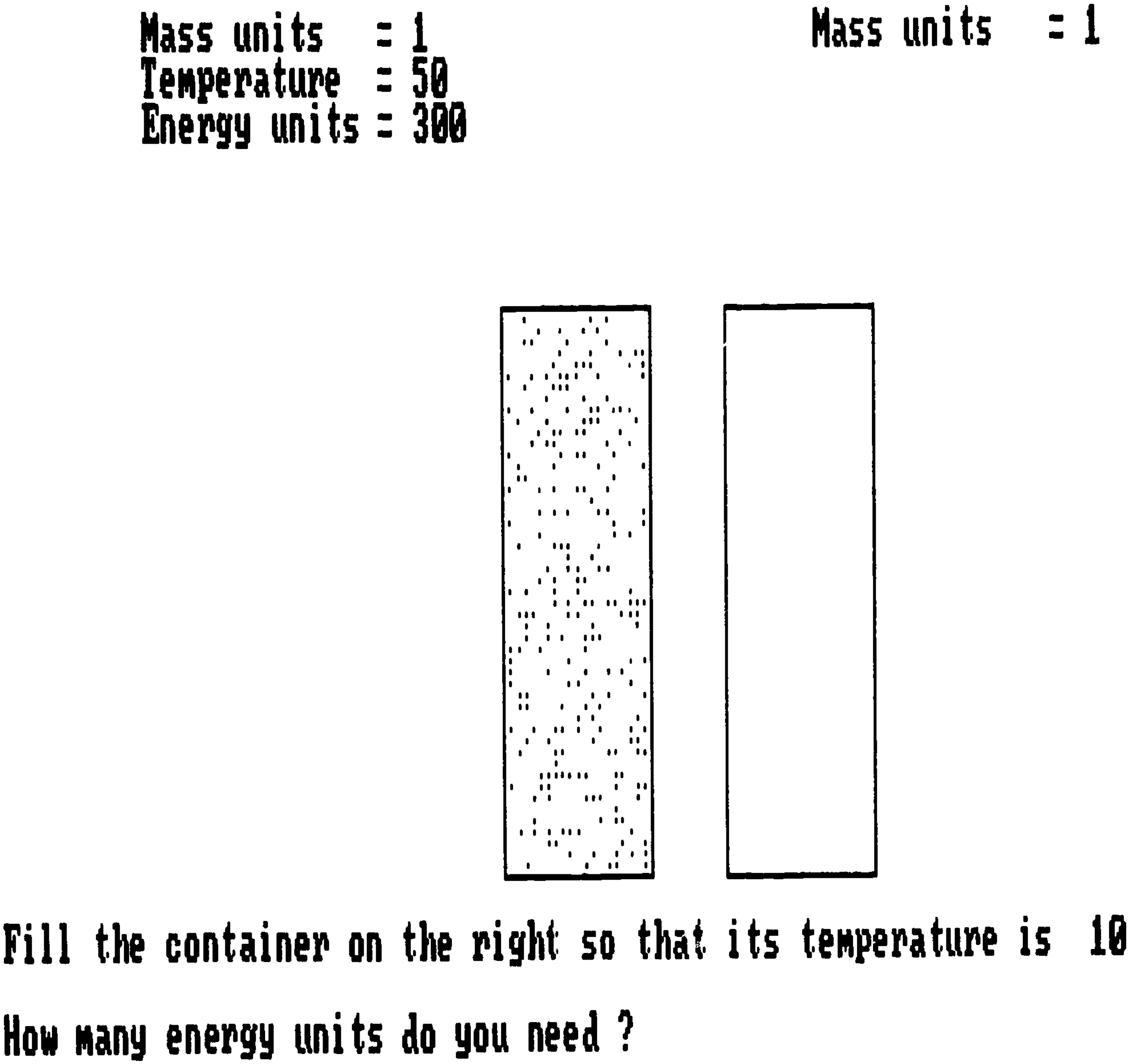
Figure 9. Screen from the CONTAINERS program. Menu for Tasks.



```
Mass units   = 2                      Mass units   = 1

1. Which container has more heat?
2. Which container has an higher temperature?
Press RETURN to see data.
```

Figure 10. Screen from the CONTAINERS program, Task 1.



Mass units = 1
Temperature = 50
Energy units = 300

Mass units = 1

Fill the container on the right so that its temperature is 10

How many energy units do you need ?

Figure 11. Screen from the CONTAINERS program, Task 2.

temperature value for the container on the right (always different from that of the one on the left) and the task is to choose the number of energy units that will bring the container on the right to the that temperature. The container fills up with the number of dots chosen. If the user "does not like it" (i.e., if, from comparing the dot densities in the containers, the user concludes that the container on the right will not have the specified temperature), the user can press the SPACE BAR and choose a different number of energy units. This can be repeated as many times as necessary. Once satisfied with a choice, the user presses RETURN to view the temperature corresponding to the number of energy units chosen, thus seeing whether it is close to the value aimed at.

Task 3. Choose energy for fixed temperature: Different masses. See Figure 12. This task is similar to Task 2, except that here each container has a different mass.

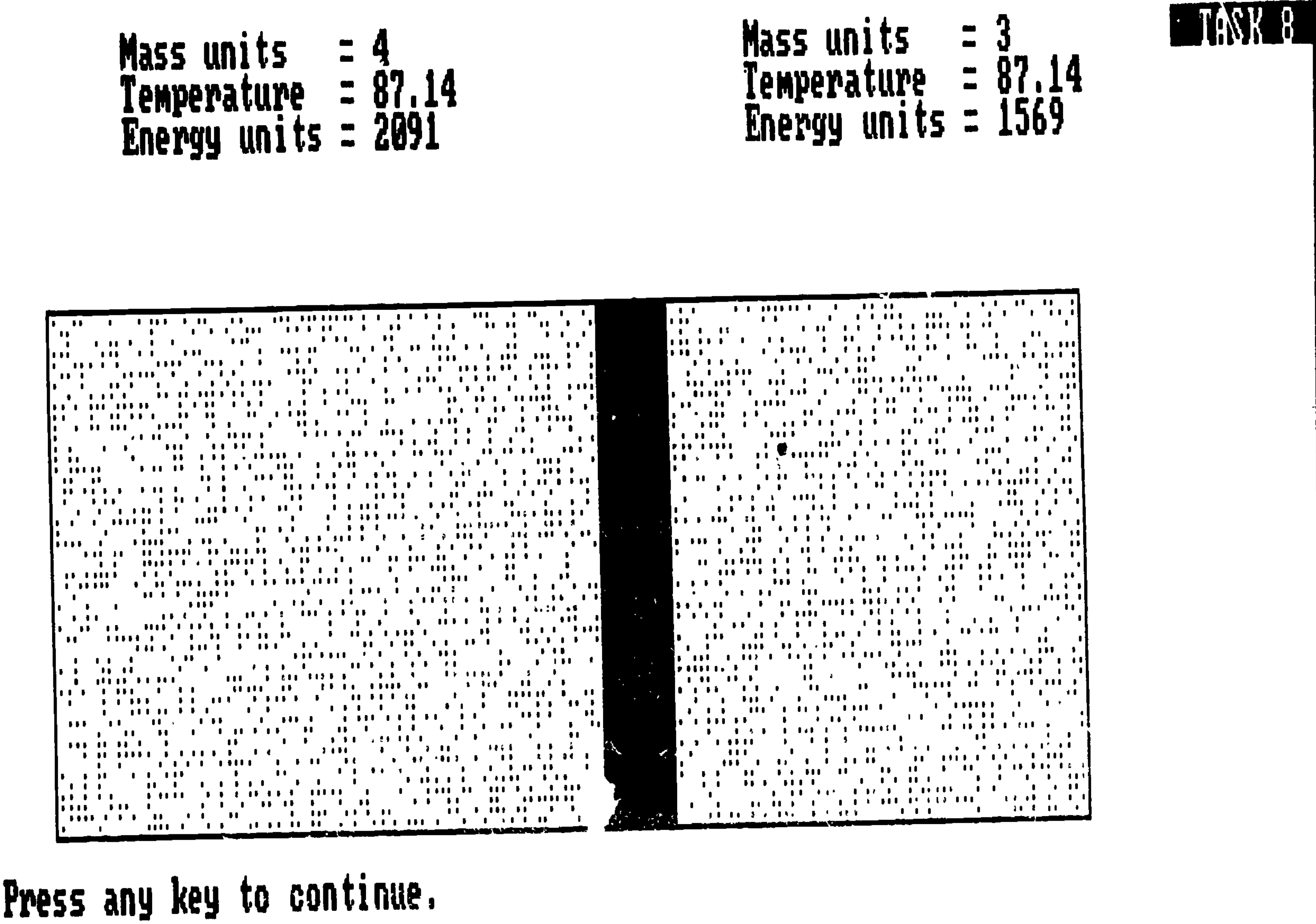
Task 4. ZAP: Equal initial temperatures. Two containers each with a different mass but the same initial temperature (thus differing amounts of energy dots) appear on the screen (Fig. 13). The container on the left gets a certain number of ZAPs, e.g., 3. While it undergoes equilibration, the user can select the options VIEW and QUICK. After equilibrium is reached, the user is asked how many ZAPs the container on the right needs in order to reach a temperature close to that of the container on the left (Fig. 14). The container on the right receives that number of dots, and equilibrates (but its final temperature does not yet appear on the screen). As in Task 3, the user may "not like" the result and choose a different number of ZAPs. Once satisfied with a choice, the user can view the final temperature of the container on the right and compare it to that of the one on the left.

Task 5. ZAP: Different initial temperatures. See Figures 15 and 16. This task is similar to Task 4, except that here the initial temperatures of each container differ.

Task 6. ZAP and predict final temperature. Two containers each with a different mass and a different initial temperature appear on the screen. The one on the left receives a certain number of ZAPs, e.g., 3, undergoes equilibration (Fig. 17), and its new amount of energy and final temperature appear on the screen. The container on the right receives the same number of ZAPs, and the user has to predict its final temperature (Fig. 18).

Task 7. Conduction: Predict final temperature and energy content: Equal masses. Two containers with equal masses but each with a different initial temperature appear on the screen, with a conducting bar between them (Fig. 19). The user is told: "After equilibration is reached, the container on the left will have a temperature of, e.g., 55° and a number of energy units, e.g., 990. Predict the temperature and number of energy units in the container on the right." After making a choice, the user presses RETURN to see conduction occur. The captions above the containers are constantly updated until equilibrium is reached. The user can also choose the QUICK option, to verify the temperature and energy content predictions. See Figure 20.

Task 8. Conduction: Predict final temperature and energy for different masses. This task is similar to Task 7, except that here the masses of the containers differ. See Figures 21 and 22.



```
TASK 8

Mass units   = 4                  Mass units   = 3
Temperature  = 87.14              Temperature  = 87.14
Energy units = 2091               Energy units = 1569

Press any key to continue.
```

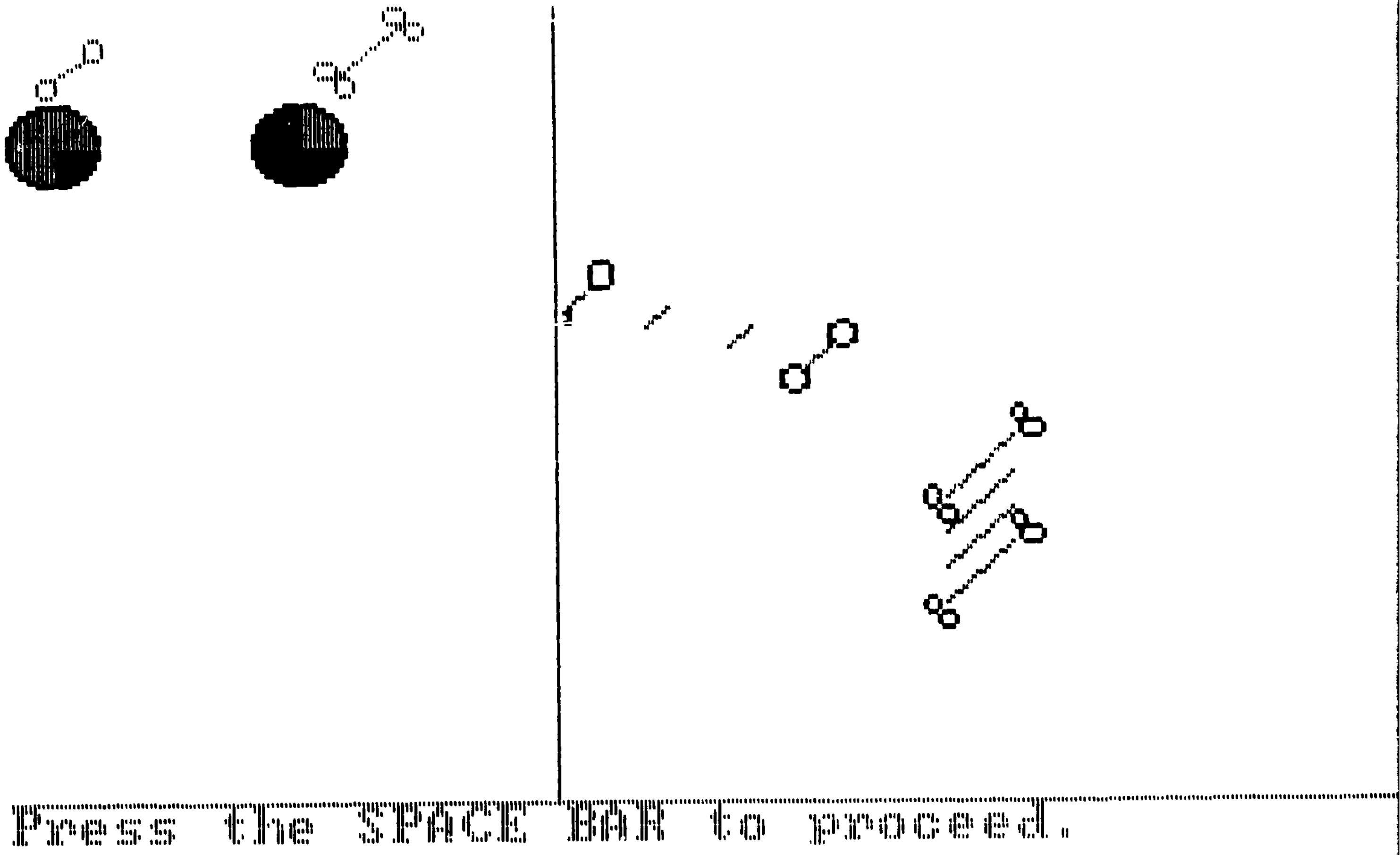
Figure 22. Screen from the CONTAINERS program, Task 8. After equilibration.

KINETIC & INNER ENERGIES program

This program, like the COLLISION progam, deals with collisions between two molecules, but it takes into account two types of energy, the kinetic energy of the center of mass motion of the molecules and the vibrational and rotational energy inside the molecule (which we call inner energy). Its purpose is to explicate the concept of specific heat. When identical masses of two different substances receive or lose the same amount of thermal energy, their temperature changes are not the same. For example, if 1g of water and 1g of alcohol each receives 1 calorie, the temperature of the water will increase by 1° C but the temperature of the alcohol will increase by a little more than 2° C. The property of substances that makes them respond differently to heat input/output is called their specific heat; water has a higher specific heat than alcohol. One of the factors underlying differences in specific heat is molecular structure. A molecule has a certain number of *degrees of freedom*, or independent modes of motion, depending on the number of atoms it is made of. A diatonic molecule, for example, has six degrees of freedom: the three degrees of freedom of its center of mass (which can translate in the three directions of space) and three internal degrees of freedom (it can rotate around one of two spatial axes and vibrate along the axis joining the two atoms). The more atoms per molecule, the more internal degrees of freedom; the center of mass of the molecule, however complex the molecule, always has three degrees of freedom. According to classical physics, when a molecule receives energy, equal shares of energy are distributed among the degrees of freedom; some energy is also used to increase the potential energy related to the internal motions. The ratio of the amount of energy added to the inner energy to the amount of energy added to the kinetic energy of the center of mass motion is therefore a function of the structure of the molecule: a molecule containing many atoms has more internal degrees of freedom and, thus, a higher ratio than a molecule containing few atoms, because relatively less energy is added to its center of mass motion and more to its internal motions.

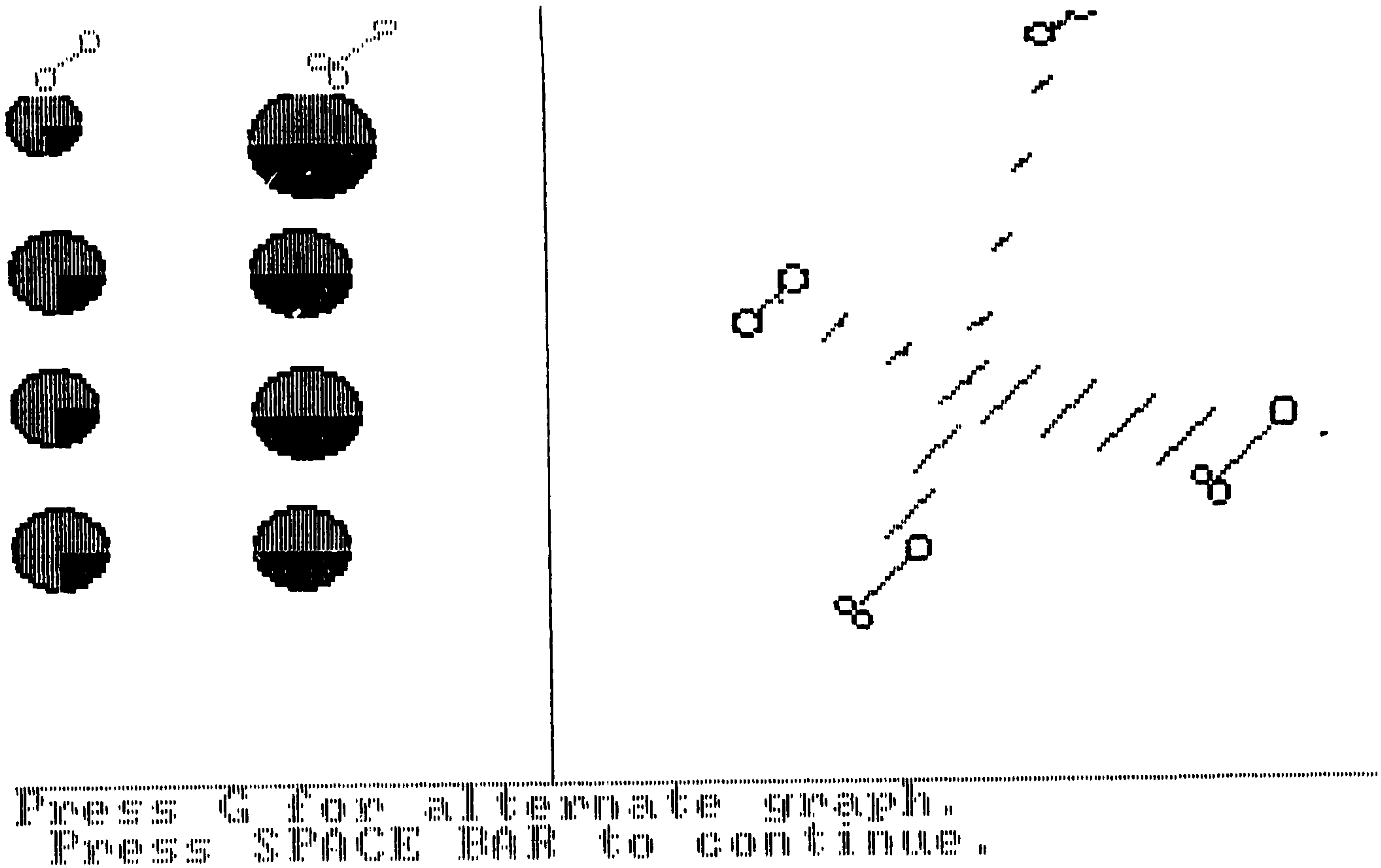
The KINETIC & INNER ENERGIES model illustrates the distribution of heat energy between two different molecules. See Figure 23. As in the COLLISION model, two molecules, one green, the other red, converge, collide, then diverge (on the right side of the screen). Users are told that the molecules have different structures (e.g., one could be a molecule of water, the other alcohol). The user chooses the initial speed of the molecules (very slow, slow, medium, fast or very fast). Their initial positions are randomly determined. Every time the user presses the SPACE BAR, the molecules move one step, their trajectories represented by dotted lines. On the screen the molecules have a barbell shape, the length of the bar being proportional to their internal energy (symbolic of the fact that atoms vibrate farther from each other when internal energy increases). The size of the steps (the distance between two successive dots) is proportional to their speed.The user can verify that the size of the step (proportional to the kinetic energy of the molecule's center of mass motion) and the length of the bar covary; if one increases due to the collision, the other also increases. When the user presses the RETURN BAR, the molecules start from new random positions, with the energies achieved at the end of the previous collision, and collide again (Fig. 24), continuing as long as the user wishes.

As that occurs on the right side of the screen, on the left the energies are represented by both circles and dots; the total energy for each molecule is the area of an "energy circle."



Press the SPACE BAR to proceed.

Figure 23. Screen from the KINETIC & INNER ENERGIES program. The circles on the left represent the energy of the two molecules. The area of each circle that appears light gray in the figure (green on the screen) represents the kinetic energy, and the dark gray area (red on the screen) represents the inner energy of the molecule. On the right are the trajectories of both molecules.



```
Press G for alternate graph.
 Press SPACE BAR to continue.
```

Figure 24. Screen from the KINETIC &INNER ENERGIES program. The two molecules have collided three times. On the left circles represent the original energy of the molecules (top) and their energy after successive collisions. On the right are their trajectories before and after the third collision.

After each collision, the circle expands or shrinks, depending on whether the molecule received or lost energy. If the circle for one molecule expands, the circle for the other shrinks, because energy is conserved. Each circle is divided into two parts: a green area, or rather an area containing green dots, representing the kinetic energy of the center of mass motion, and a red area representing the inner energy of the molecule. The ratio of these areas stays constant (i.e., the same from one collision to the next, irrespective of the size of the circle). This constant ratio is the focus of the model, which shows users that energy is always divided in the same ratio between kinetic and inner energies but varies with the structure of the molecule. For example, the ratio of inner to kinetic energy for the molecule on the left is 1:3 while for the molecule on the right the ratio is 1:1.

Users are asked next to imagine a container filled with molecules like "the one on the left" and another filled with the same number of molecules like "the one on the right." The sizes of the green areas in the two circles would be proportional to the temperatures in the two containers, by virtue of the definition of temperature. If the same total thermal energy were given to both containers (resulting in an equal increase in the size of the energy circle of each molecule), their temperature increases would be different (because the increase in the green areas will be different).

POTENTIAL ADVANTAGES OF OUR CONCEPTUAL MODELS

Our models confront directly students' lack of differentiation between heat and temperature. The representations for heat and temperature – number versus density of energy dots (when a single substance is used) – capture the essential difference between these concepts – extensivity versus intensivity – and embody their essential relation quantitatively (total number of dots = dot density x mass). A student who always thought of heat as intensive may learn that the total number of energy dots is an important variable and, we hope, may end by mapping "amount of heat" on that variable, while a student who was confused about the extensive/intensive aspects of thermal variables may be able to apprehend easily the distinction and relation between them. The COLLISION program should help students understand that heat is mechanical energy and that *it is exchanged, not created*, by molecular collisions. Finally, the shortcomings of the CONTAINERS model applied to two different substances can engage students in metaconceptual learning about models.

PILOT STUDY

The goal of the pilot study was to test our computer models. We wanted to know whether they made sense to subjects, helped them differentiate heat and temperature, and whether the Tasks could be solved easily after exposure to the main program. We wanted to gather information about the process of reconceptualization (or its absence) from subjects' comments, spontaneous questions, difficulty or ease in understanding particular points, and prediction errors, to help us where necessary to revise the programs and plan the curriculum.

We presented the first two models, COLLISIONS and CONTAINERS, to our subjects. With most subjects, interview time was limited, so we rarely had time to introduce the topic of specific heat. Our approach was a mixture of didactic and Socratic methods: we conversed with the subjects, showing them the computer programs and then asking them to use them themselves. We gave them some information directly, answered their queries, and tried to lead them to discover some of the principles embodied in the program, e.g., that temperature is represented by the density of the dots.

SUBJECTS

Fifteen subjects, males and females, participated in the study. Some were ninth- and tenth-grade students recruited from science classes in two middle-class suburban high schools. They were selected by their teachers from among volunteers to represent a range of ability in science from grade C to grade A. They were interviewed at their schools, in groups of three (who knew each other). Others were eighth- and ninth-grade students who had volunteered to take part in a study run by Technological Education Research Centers (TERC), Cambridge, Mass., about the use of microcomputers in science education; they were paid for their participation. These subjects were interviewed at TERC, also in groups of three. Finally, five adult subjects were paid volunteers, college students, and Harvard employees, with no formal science education beyond general high school science.

PROCEDURE

The taperecorded interviews required one or two sessions, each one-and-one-half to two hours in length, depending on the subjects' availability. The subjects were posed a series of preliminary questions and problems about heat and temperature:

> "Do you know what heat is?"
>
> "Is there a difference between heat and temperature?"
>
> "What is cold?"
>
> "A certain quantity of heat raises the temperature of 100g of water by 10°; if the same quantity of heat is given to 200g of water, what will the temperature rise be?"
>
> "Imagine that we pour hot water into a small beaker and a big one. Does it make sense to say that one beaker has more heat than the other?"
>
> They were posed the steel problem (p. 8).
>
> "Imagine a flask of alcohol with a long, narrow neck. You put it into a bath of hot water. What will happen to the alcohol level? Why?"
>
> "How does the alcohol get hotter? If you had a very powerful microscope and could observe the water heating the alcohol, what would you see?" Some subjects were asked to draw a model of the heating process.

The subjects who did not know about the molecular basis of heating were told that molecules in a hot body have more energy than those in a cold one. When the molecules collide, energy is redistributed: the more energetic molecules slow down and the less energetic ones speed up, until all the molecules have the same energy.

The COLLISION model was presented first to illustrate the redistribution of energy that occurs through the collision of two molecules. The concept of *energy dot* was introduced, to represent a unit of motion energy. We emphasized that dots are not molecules; that they are not "really" inside molecules; that they are an abstraction. The subjects' attention was drawn to the conservation of energy during the collisions.

Next, they were introduced to the CONTAINERS model. The order in which the concepts were presented, examples given, and questions and problems posed, varied from group to group, because the experimenter adapted the presentation to the subjects' reactions, questions, and comments. The ideas discussed in this section included the following. (1) Amount of heat is represented by number of dots while temperature is represented by the density of the dots. (2) Temperature measures the energy of each molecule[8]. (3) To understand the relation between dot density and energy per molecule, one should consider two containers with different dot densities (e.g., Fig. 4, above) Each "region" of the container on the right, for example, has more dots than each region of the container on the left; both regions contain the same number of molecules, however, so that a molecule in the container on the right ends with more dots than a molecule in the container on the left and thus moves faster. (4) Of two pieces of the same substance, one big, the other small, at the same temperature the big one has more heat. Same temperature means same dot density, so if two containers differ in size and have the same dot density, the bigger one has more dots. At the molecular level, same temperature means same energy per molecule; the bigger container has more energy dots because it has more molecules. (5) Conversely, if the same amount of heat is put into two containers of different sizes, the smaller one will have a higher temperature because its dot density will be greater. At the molecular level, the molecules in both containers share the same amount of energy; since the smaller container has fewer molecules, each molecule in it receives more energy and thus moves faster.

The options ZAP and CONTACT were introduced after the students understood the quantitative relation of heat, mass, and temperature. They were told ZAPping represents heating. If the container were placed, e.g., on a hot plate, it would receive heat: the molecules of the hot plate have a lot of energy; when they collide with the molecules of the container, they give them some of their energy. In terms of dots: the hot plate molecules have a lot of dots each; when they collide with the molecules in the container, they give them some of their dots. ZAPping is a representation of the influx of dots that results. At first the dots are concentrated at the bottom of the container, because the molecules in the hot plate hit the molecules at the bottom of the container. Then, the molecules at the bottom start sharing some of the energy of the hot plate with the molecules above them, and so on, until all the molecules in the container have the same energy (same density of dots), i.e., thermal equilibrium. Until equilibrium is reached, the temperature is "undefined" because it is a measure of dot density, and, on the scale of the container, dot density is not constant. One ZAP causes a smaller temperature change in a bigger container, because the energy of the hot plate is shared by a greater number of molecules.

When two containers are brought into contact, conduction takes place. Dots move from one container to the other, although molecules "stay on their own side." The molecules on

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[8] See above, "Simplified physics."

both sides of the surface of contact exchange energy: those in the colder container speed up, those in the hotter one slow down. Then, those molecules close to the surface exchange energy with molecules farther from the surface of contact until all the molecules have the same energy (number of dots), i.e., until both containers are at the same temperature. At equilibrium, the densities of the dots in the containers are the same, but the total number of dots is different (except when the containers have the same mass). Similarly, the total number of dots exchanged during equilibration depends on the masses of the containers: if the masses are doubled but the initial temperatures are the same, the final temperature will be the same but the number of dots exchanged will double.

After the subjects gave evidence of having mastered the CONTAINERS program, they were asked to solve one or two problems from each Task. If time allowed, the topic of specific heat was introduced.

RESULTS

First, the interviews with each group are summarized, without any attempt to distinguish systematically among the members of a group, except in the case of: Harry, the only one in his group willing to talk. We "collapsed" the subjects in each group because our goal was, not to study individual learning progress, but, as stated earlier, to obtain feedback about our models. Next, general conclusions about the usefulness of the models are drawn, and about their flaws. Our analysis of Interviews 1-3 will be more detailed than the others, because the subjects were junior high and high school students and, therefore, better "indicators" than the adult subjects of what to expect in our classroom studies.

Interview 1: Harry: entering eighth grade. See Appendix B. Initially, Harry had no idea about the nature of heat, the difference between heat and temperature, the mechanism of heating, and so on, but he knew about molecules. He easily accepted that molecules are faster when temperature is higher and the molecular mechanism of heating. His understanding was robust: he could describe the mechanism of heat transfer in new cases, without needing to be reminded, in terms of both molecule collisions and dot exchanges. He never confused dots and molecules and spontaneously commented that the molecules were still colliding at equilibrium, although not exchanging energy.

As long as the examples chosen by the experimenter (using the CONTAINERS program) involved the same mass containers (thus did not require differentiation of heat and temperature), Harry grasped the information very easily. When the experimenter introduced different size containers, for a short time Harry expected temperature to be proportional to the total number of dots (therefore, in the conduction examples, that the number of dots would be equal at equilibrium); but he caught on quickly. When he was shown that, although he had put the same number of dots into the two (unequal size) containers, their temperatures were not the same, he immediately came up with the correct justification in terms of dots, dots per molecule, energy per molecule, molecule speed, and temperature. His initial confusion reappeared from time to time, but he always corrected himself spontaneously. He applied his new knowledge to the ZAPping case without error. He also solved all the Tasks without a mistake and understood the topic of specific heat perfectly.

Needless to say, Harry's case is unusual. Little can be learned from it, except that the models can be understood easily by bright, young students. It is interesting to note that at first even he thought temperature was correlated to the total number of dots, presumably because at that stage he still thought temperature measured heat.

Interview 2: The Newton North High School students: tenth grade. See Appendix C. These students had been previously exposed to the topic of heat and temperature (using MBL), and, not surprisingly, had a richer set of beliefs about thermal phenomena than Harry, including more misconceptions. They knew that heat is energy ("It is molecules moving around," "It is what is given off by the moving molecules"), that molecules move faster when the temperature is higher, and they had some understanding of the heating process. They knew that when a hot body is placed in contact with a cold body, the more energetic molecules in the former collide with the less energetic molecules in the latter and make them move faster. One student, Jonathan, showed a very prevalent misconception. He believed that as the molecules in the cold body started to move faster, they collided more, generating heat (by friction) and raising the temperature of the cold body. He was to bring up this collision/friction schema many times during the interview.

All the students said that temperature measured heat; the lack of differentiation was also apparent in their ideas about the nature of heat, which they saw as a property of individual molecules instead of taking the whole mass into account. They responded to the steel problem accordingly (i.e., they thought the two pieces would get equally hot because they received the same heat), except one subject, who intuited that the two pieces absorbed and released the same amount of heat. Jonathan's answer to the steel problem was particularly interesting: "The small piece will get hotter because it is more crowded, so there are more collisions and therefore more heat [is generated]." It is not clear what "it" is that is more crowded. He was probably (mistakenly) imagining an equal number of molecules in both pieces which hit each other more in the smaller piece because they are closer together. Here as well as in previous studies we have noted that a smaller space suggests a kind of nondifferentiated (between molecules, heat, energy...) crowdedness; subjects seem not to realize that, for something to be more crowded in a smaller, rather than bigger, space, that something must have the same value in both cases (e.g., the molecules will be more crowded in a smaller space if the same number are in both it and a bigger space; if the number of molecules were proportional to volume, the spaces would be equally crowded).

This issue arose again later (Appendix C, pp. 3–4), when the steel problem was presented in terms of containers and dots instead of pieces of steel and heat. Jonathan knew that the temperature would be higher in the small container because the dots were more crowded and the molecules were moving faster. He attempted, once again, to apply his collision schema: "There are more collisions in the small one...." How is that? It must be that "there are fewer molecules in the big container," which, he realized, did not make sense. One source of his confusion was applying the wrong analogy: he was thinking of a mass of gas. When a certain mass of gas expands, its molecules move farther apart and its temperature drops. This is another case of new information creating more misconceptions because its domain of application has not been internalized (see a similar case, in CLASSROOM STUDIES, pp. 8–9). Jonathan had retained: "Bigger = more widely spaced molecules = lower temperature," because that conceptualization fitted his collision schema, without understanding the physical mechanism behind the rule or wondering about the limits of application (gas in adiabatic expansion).

As in Interview 1, the subjects assimilated information easily as long as equal mass containers were used. When the case of unequal mass containers with the same total energy (same number of energy dots) was introduced, the subjects did not agree on whether the two containers had the same heat (see Appendix C , pp. 5-6). Unlike Harry, this group resisted the notion that the number of energy dots represented amount of heat, in the extensive sense, for a long time. They understood quite well that dot density was proportional to temperature (probably because it fitted the misconception "more crowded = hotter, " just discussed), but they were faced with a paradox: If the dot crowdedness is temperature and temperature measures heat, then what does the total number of dots represent? Or, put another way, the total number of dots could not represent the measure of heat: dot crowdedness must measure heat (because it measures temperature and temperature is the measure of heat), and obviously dot crowdedness and total number of dots are different.

This group appears to have evolved slowly toward the understanding that the total number of energy dots represented the heat, and, therefore, that temperature was not the measure of heat. It is not easy to determine exactly how the change happened, nor is that the purpose of this analysis; but several interconnected trends are apparent. First, two aspects of the models fitted the subjects preconceptions and helped anchor the idea that the dots represented the heat. One was ZAPping. They immediately related ZAPping to "dolloping" (why the analogy was so obvious is itself an interesting issue), which allowed the following steps in reasoning: ZAPping is like dolloping, dolloping is delivering heat, therefore ZAPping is delivering heat and the energy dots are heat. For reasons not entirely clear, establishing that energy dots added to the containers were heat was not sufficient to establish either that the dots already in the containers also were heat or that the amount of heat was measured by the number of dots. Nevertheless, understanding ZAPping was a step in the right direction.

A second element of the model that fitted into the students' preconceptions was the concept of "crowdedness" already discussed. Part of many students' conceptualization is the "dilution/concentration" schema. They explain why a small object gets hotter than a big one when heated for the same amount of time by saying that the heat gets more concentrated in the small object. In the model, they easily accepted that dot crowdedness was the temperature (see above). Little by little, the students made the connection between the two crowdednesses: more crowded dots means higher temperature, more crowded heat means higher temperature, therefore dots = heat.

A second factor contributing to reconceptualization was the relation between the dots and the molecules. The subjects understood that temperature is proportional to the number of dots per molecule because a molecule with more energy (dots) moves faster. Repeated encouragement to relate the total number of dots to the total number of molecules fostered in the subjects a sense of extensivity for energy, because the number of molecules is obviously extensive. Visualizing all the molecules, each with a certain number of dots, seemed to lead them to consider the total energy dots as a variable in its own right.

A third factor was the constant probing by the experimenter: What is heat? What do the dots represent? and so on.

The combination of these factors seems to have built up a sense that total number of dots had an explanatory role to play in the model not unlike the role heat sometimes played in their own theory. Their acceptance of the idea that the total number of dots represented amount of heat resolved some paradoxes in their theory and may have contributed to reconceptualization. Once established by one of the students, the differentiation was easily understood by the others and was "there to stay." They spontaneously, and correctly, described a series of two-container examples in terms of heat and temperature (e.g., the temperature in both is the same because dot crowdedness is the same, but in the bigger one there is more heat). Further proof of their understanding came in the spontaneous query: "But, then, how do you measure *amount of heat*?" and in their correct solution to the steel problem using the model.

Interview 3: The Braintree High School group: ninth grade. See Appendix D. These students were taking a science class and had just studied heat and temperature. In the preliminary questions, they showed little understanding of thermal expansion, no idea about the nature of heat or its extensivity, and they were confused about the steel problem. In the course of the interview, the students easily understood the molecular basis of heat exchange; they had a confused notion of crowdedness at first, and showed a slow progress toward differentiation, starting with the understanding that temperature was represented by the crowdedness of the dots.

These students showed greater confusion than the previous subjects between dots and molecules. Initially they thought that two containers of equal size but different numbers of energy units contained different numbers of molecules and, conversely, that two containers of different sizes but the same amount of energy contained the same number of molecules. It seems that, for them, same mass of same substance did not necessarily imply same number of molecules. They also resisted for a longer time differentiating between heat and temperature, that is, accepting that the total number of energy dots represents amount of heat, showing deeper confusion. Consider the following excerpts.

> **Student:** There's the same number of energy units but the heat is how fast they [the molecules] move.
> **Experimenter:** Temperature does not measure heat.
> **Student:** It measures the amount of energy.
>
> **Experimenter.** Consider a 2-mass unit container at 50° and a 4-mass unit container at 60°. What will the energy dots look like?
> **Student:** The first container will be more crowded because you put in [only] 10 more degrees in the other one, which is twice as big
> **Other student:** The bigger one will have more energy dots because it is at 60°.
>
> **Experimenter:** Consider the same containers; they have the same number of energy dots. Which one will have more crowded dots?
> **Student:** The one on the right, because it has more dots.

The students struggled not only with a lack of differentiation between heat and temperature but also with a lack of understanding of intensive and extensive quantities. They were not clear about the difference between the total number and the density of the dots (the previous group was always clear about this). It is as if "more dots," with the undifferentiated meaning "greater amount of dots/more crowded dots," corresponded to "more heat,'with the undifferentiated meaning of 'more heat/higher temperature."

In spite of their serious and prolonged confusion, in the end, these students, too, seemed to have understood the model, in particular, the correspondence between heat and number of energy dots on one hand and temperature and dot crowdedness on the other. Like the previous group, at the end of the interview, they were able to reconceptualize the steel problem.

Interview 4: Andrea, adult. See Appendix E. Andrea, of all the subjects interviewed, had the least background in physics. She also showed the least progress. Inititally, she did not differentiate between heat and temperature. In the course of the interview, she easily understood the molecular mechanism of heat exchange and that higher temperature means faster-moving molecules and maintained this understanding throughout the interview, but she had difficulty remembering that the dots were not molecules.

At first she reasoned in purely intensive terms; for example, she thought that two ZAPs would make the molecules move twice as fast. As the teaching progressed, her understanding of total number of dots, dot crowdedness, number of dots per molecule, and their relation to heat and temperature all developed. She built up an understanding of the relations between them: that, when temperatures are equal, the number of dots in two containers is proportional to the masses of the containers and that the total number of dots in a container is proportional to its temperature and its mass.

Like the students in Interview 3, she struggled both with a lack of differentiation between heat and temperature and with intensive versus extensive (total number of dots versus dot crowdedness), indeed with quantitative relations in general. Although she succeeded in solving the Tasks, her grasp of the model did not appear so complete as that of the previous subjects. She seemed to have a more local understanding, to establish fewer relations among the different concepts and ideas, and to be less comfortable manipulating variables.

Two factors may have contributed to Andrea's difficulties. First, the style of the interview was different: more didactic, less Socratic. Her "mistakes" were quickly corrected, rather than challenged or probed; it is likely that. given more time to reflect upon the model and her difficulties with it, she would have made more striking progress. Second, unlike the other subjects, who were taking science classes at that time and, except for Harry, had already studied heat and temperature, Andrea had never taken a science course in school and had little mathematical training. Thus, she had to become familiar not only with the model but also with a novel way of thinking and with concepts the others already had (molecules, energy) or had been thinking about (heat and temperature, molecular collisions).

Interviews 5: Four adults. See Appendix F. All the subjects thought that temperature was the measure of heat, all understood thermal expansion at the molecular level, none knew what heat was, and one said that "heat is when molecules move faster, thereby increasing the temperature, and cold is when they slow down." As explained in STUDENTS' CONCEPTUALIZATION OF THERMAL PHENOMENA (above), the subjects believed that heat *gave* energy to the molecules, not that heat was *itself* motion energy. Opinions were divided about the beaker and the steel questions. One subject solved problems correctly; while he mentioned *amount of heat* in the proper context, he was also open to the possibility that heat and temperature were the same thing.

All these subjects easily understood the COLLISION program and the mechanism of heat transfer and were able to use that explanation in several new contexts (e.g., an object on a flame). They had no trouble distinguishing dots and molecules and had good questions about the dots: one subject wondered how the dots got in and out of the molecules, and another asked why the dots moved at equilibrium, since they were not molecules.

The CONTAINER program posed no problem as long as equal masses were used, a familiar finding by now. The subjects easily grasped the concepts of energy dot and number of energy dots per molecule and how the latter was directly correlated with the speed of the molecules and thus to temperature. They understood immediately that adding energy dots into a container increased its temperature because it increased the number of dots per molecule. Unequal masses brought up the usual prediction errors (if the same energy is put into the two containers, the temperatures will be the same) and misconceptions (the heat is correlated with the speed of the molecules; the temperature is lower because there are fewer collisions). One subject solved the unequal masses problems correctly, stating, e.g., that "the amount of heat is the same, but there are fewer molecules in the small [container], so each molecule gets more energy, so the temperature is higher" and "if the containers you put in contact are bigger [but the initial temperatures are the same], they have more molecules and more energy units, so [although the final temperature is the same in both cases] more energy dots are exchanged in the case of the bigger containers." The other subjects seemed to learn, progressively, the quantitative relation of total number of dots (representing heat), dot crowdedness (representing temperature), and mass. Again, their acquisition of the concept of the extensivity of heat (represented by the total number of dots) appears to have been aided by envisioning the energy of all the molecules.

CONCLUSIONS

Comparison of the different groups

Our teaching was most successful in Interviews 1 and 2, for different reasons. Harry's easy mastery of the model was due, on one hand, to his ability in scientific reasoning, and, on the other, to his lack of strongly entrenched misconceptions, which he might have developed had he received any formal training about heat and temperature. Although, like any other novice, he initally believed that temperature measured heat, he lacked related knowledge, and thus had few other misconceptions. Owing to his capacity for abstraction and reasoning, he made sense of the model very quickly, adopting it easily because he only needed to reject the notion that temperature measured heat.

In contrast, the students in Interview 3 had already learned a lot about heat and temperature, and, by assimilating that knowledge into their pre-existing framework, had ended up with a rich network of misconceptions, including a reinforced belief that temperature measured heat. Owing to their logico-mathematical difficulties (they could not distinguish between an intensive quantity and an extensive one and did not know how to set and test between two rival hypotheses), they did not assimilate the model as well; pitting a weaker (internal) model against stronger misconceptions resulted in poorer learning.

Although the students in Interview 2 also had a strong network of misconceptions, perhaps because they were somewhat older or because they had more background knowledge to help them (e.g., familiarity with molecular model from the study of chemistry), they understood the model easily. They were much clearer about what they did not understand, including tensions in their own conceptualization. A strong (internal) model finally defeated their misconceptions, because they were metaconceptually aware of a need for revisions.

What the interviews revealed about the strengths and flaws of the programs and suggested about future curriculum

Overall, the results were very encouraging. Most subjects could, in a few hours, differentiate between heat and temperature, explain the molecular basis for heat transfer, conceptualize a variety of problems, and solve them, and so on. That the models could accomplish in a few hours what traditional teaching fails to do in several days is certainly a positive result.

One major difficulty, which can be remedied, was confusion between energy units represented as dots and molecules represented as moving circles. The remedy is a program in which the energy dots are drawn inside the circles that represent molecules. The VIEW option allows the user to verify that the speed at which the molecules are moving is correlated with the number of energy dots per molecule. The molecules can be erased, leaving the dots (as now in the CONTAINERS program). When necessary, the molecules can be made to reappear (i.e., when students show signs of confusion between the dots and molecules). Such a model is described below, in the section on SOFTWARE.

Certain aspects of the dots puzzled some students: Why do they move at equilibrium? Do they actually go in and out of molecules? We need to clarify both that the dots are not really *in* the molecules but symbolize energy units and what the motion of a dot actually represents. Such clarification is best accomplished by integrating it into a general discussion about the nature of models.

Several groups showed difficulty distinguishing between and relating intensive and extensive quantities, which adds to the difficulty of distinguishing between heat and temperature, and it may be worthwhile devoting classroom time to this issue. The case of weight and density may be a good training topic (see ETC Technical Report TR 87–11, *Teaching for conceptual change using a computer-based modeling approach: The case of weight/density differentiation*. November 1987).

All the interviews showed consistently that some aspects of the models were easy to grasp and others hard. Among easy topics was that higher temperature means faster molecules and that adding heat results in faster moving molecules. Similarly, the molecular account of dilation was easily assimilated. We believe that most subjects underwent a similar progression in their reconceptualization. These topics were easy because they fitted into the students' own framework. The hardest topic, of course, was the concept of amount of heat represented by the total number of energy dots. Most subjects needed time, repeated challenges, reminders, prompts, and exercises before they accepted total number of dots, first, as a variable and, then, as the measure of heat; they understood more easily that number of dots per molecule represented temperature. This differential rate of acquisition is not surprising; in the case of temperature, the subjects were simply adding to their knowledge (more dots per molecule means more energy per molecule, which they already knew means faster moving molecules and therefore hotter substance); but in the case of amount of heat they had to adopt a new concept that violated their initial beliefs.

How the subjects came to give up their own beliefs (especially that temperature measures heat) and instead adopt the computer model was discussed in the analysis of Interview 2. To reiterate, it appears that the subjects first established a purely abstract relation between total number of dots, dot density, and rectangle size that quickly became an "intermediary" relation of total number of dots, dots per molecule, and mass, and then more slowly, a relation of heat, temperature, and mass. We see two major threads leading to final reconceptualization. One was the realization that the concept of total number of dots had an explanatory role in understanding the model. This realization was accomplished by mentally visualizing all the molecules, each with a certain number of dots, and recognizing that raising the temperature of an object involves giving every molecule extra dots. In the beginning, the subjects mapped the energy dots onto their undifferentiated concept of heat: the COLLISION program showed them that dots represented energy transmitted from a hot body to a colder one but did not attempt to establish the differentiation between heat and temperature, which they interpreted as "the dots have something to do with heat." Later, at least for MBL subjects, ZAPping evoked "dolloping," reinforcing the notion that heating was represented by adding more dots. The subjects had no difficulty understanding that more ZAPs meant more heat and that more ZAPS consisted of more energy dots. At this point, more or less readily, they had to accept that amount of heat was represented by the total number of dots. Having already come to believe that temperature was represented by dot density, they were forced to accept that temperature does not measure heat. Once this mapping was complete, the subjects adopted the model as a representation of heat and temperature: they had undergone conce ual change.

If this account of the process of differentiation correctly depicts our subjects' progress and if it applies to the reconceptualization we hope to foster on a large scale in the classroom, then particular attention must be paid to students' understanding of intensive versus extensive qualities: the differentiation between heat and temperature relies crucially on a prior differentiation between total number of dots and dot density. As already noted, in the pilot study the subjects who had difficulty with the distinction between intensive and extensive proved least successful in assimilating the heat and temperature model. For that reason we will consider devoting time to this distinction, perhaps, as mentioned above, by using the case of weight and density as a training topic.

The pilot study gives us little information about students' understanding of our KINETIC & INNER ENERGIES program, because we were rarely afforded sufficient time to introduce it to the subjects. Those to whom it was presented appeared to grasp the topic easily and to appreciate understanding a concept that until then had remained opaque.

Overall, we intend to base our curriculum on the models, following an order similar to the one used in the pilot study. Some findings from this study as well as some aspects of the models themselves (see "Simplified physics") suggest incorporating metaconceptual points about models into the curriculum.

SOFTWARE: MODIFICATIONS AND NEW PROGRAMS

Two of the inital models, CONTAINERS and KINETIC & INNER ENERGY, were modified, and two new programs, SPECIFIC HEAT and SPECIFIC GRAM, were created.

MODIFICATIONS TO THE *CONTAINERS* PROGRAM

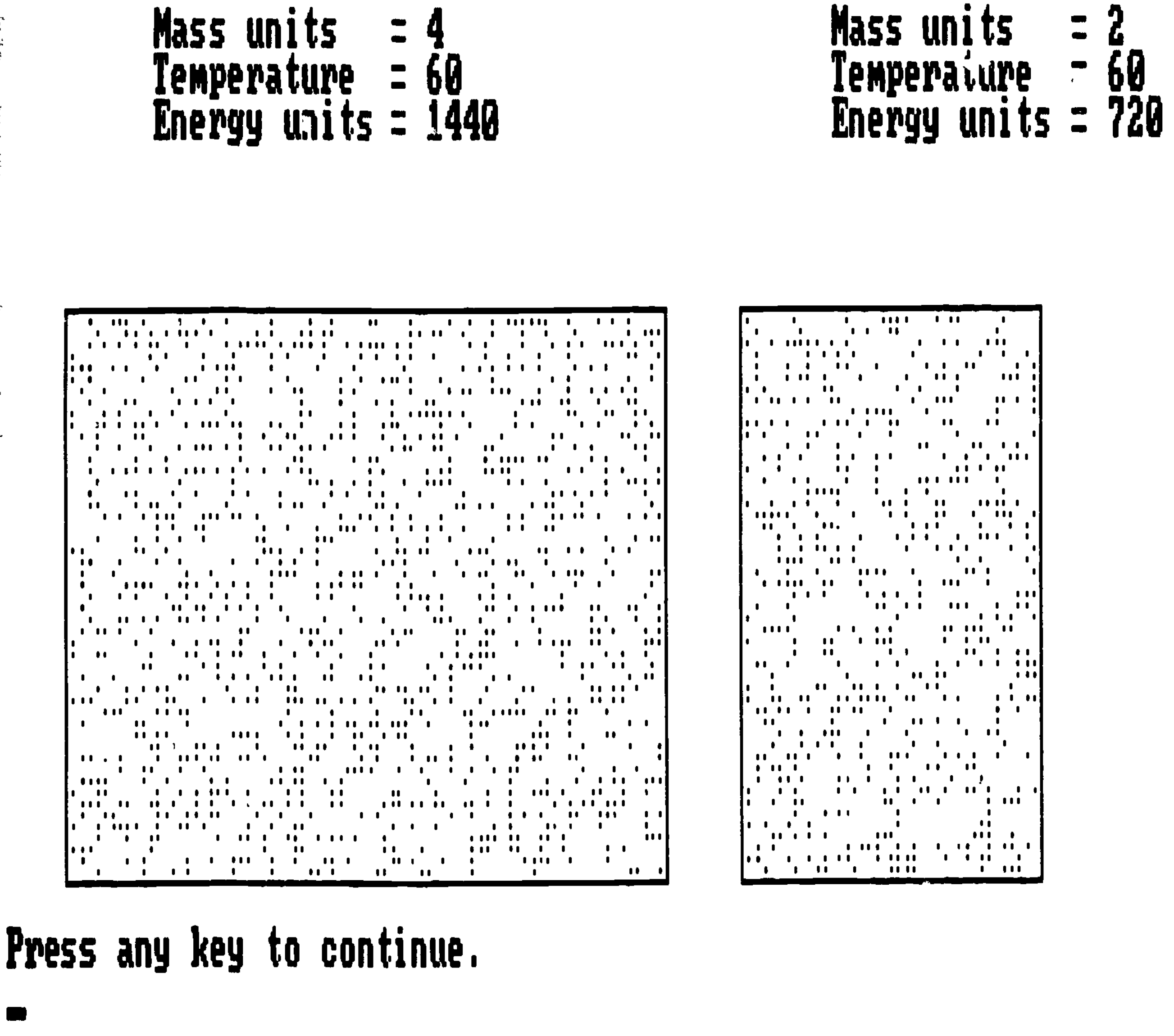
To enrich CONDUCTION, a new option, contact with an infinite source at a fixed temperature, was added, in which the container on the left is connected to a source, or sink, of energy that maintains it at a constant temperature, thereby modeling a hot plate or refrigerator. If the container on the left is at a higher temperature than the one on the right and is to be maintained at that temperature, as with a hot plate, then when these containers are brought into contact, energy dots move from the container on the left to the one on the right, which then increases in temperature (Fig. 25). The temperature of the container on the left is kept constant by a steady input of energy which compensates for the loss of energy dots. Dot transfer, from the container on the left to the one on the right and into the container on the left from the source, continues until the container on the right reaches the temperature of the container on the left and thus of the source.

The option VIEW was modified so that now, using the arrow keys, the user can switch back and forth between two windows to compare the velocities of the molecules in both containers.

Figure 25, referred to above, is also part of a new Task, Task 9, similar to Tasks 7 and 8. The difference between the previous Tasks and the new one is that in Task 9 the container on the left is an infinite source (hot plate or refrigerator). Two containers with different masses and different initial temperatures appear on the screen with a conducting bar between them. The user is told "The container on the left is an infinite source. Predict the temperature and the number of energy units in the container on the right." After making the prediction, the user presses RETURN to see conduction occur.

MODIFICATIONS TO THE *KINETIC & INNER ENERGIES* PROGRAM

The physical reason for the different ratios of inner energy to kinetic energy in different substances is the difference in molecular structure. We represented that notion

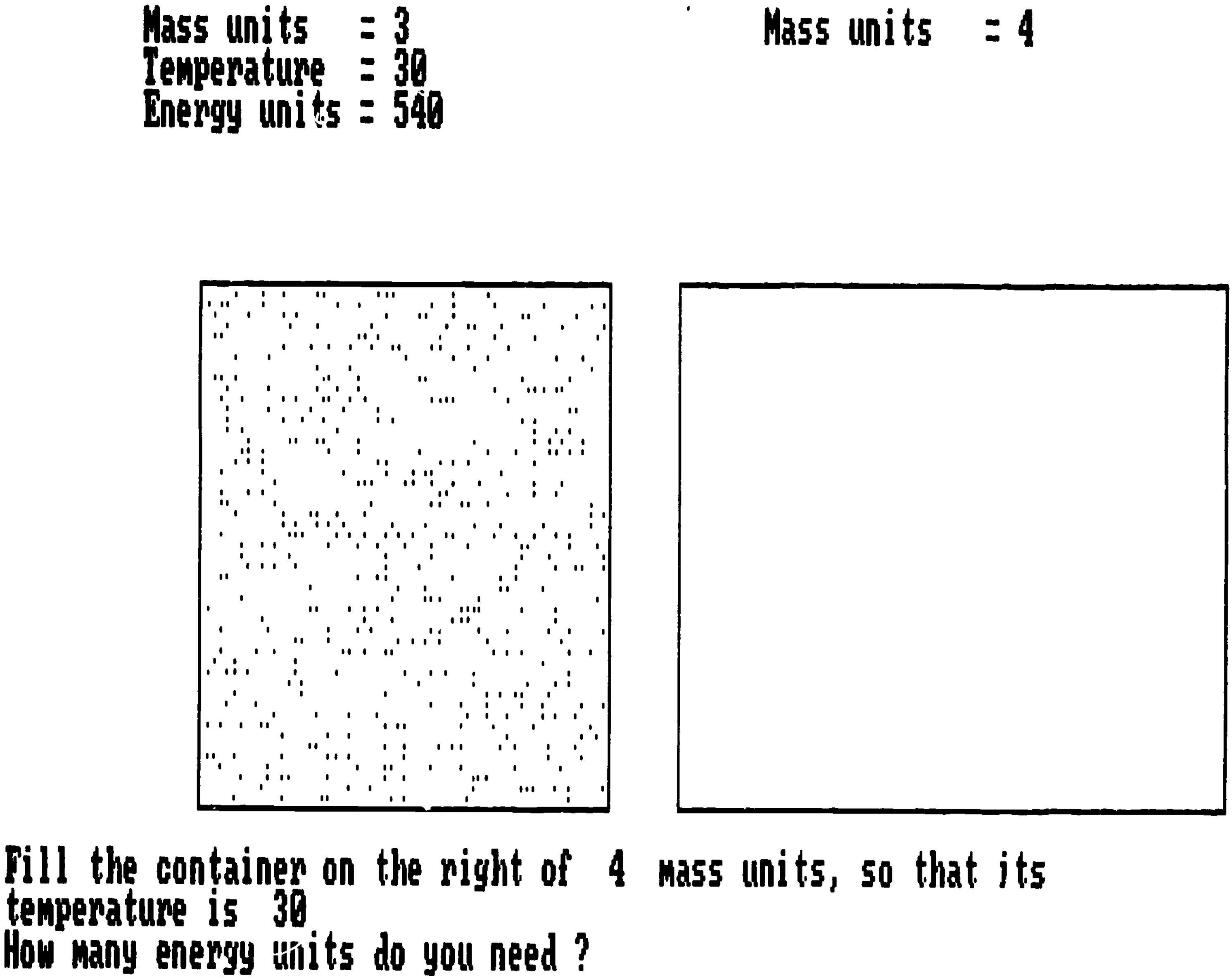


```
Mass units   = 4                    Mass units   = 2
Temperature  = 60                   Temperature  = 60
Energy units = 1440                 Energy units = 720




Press any key to continue.
```

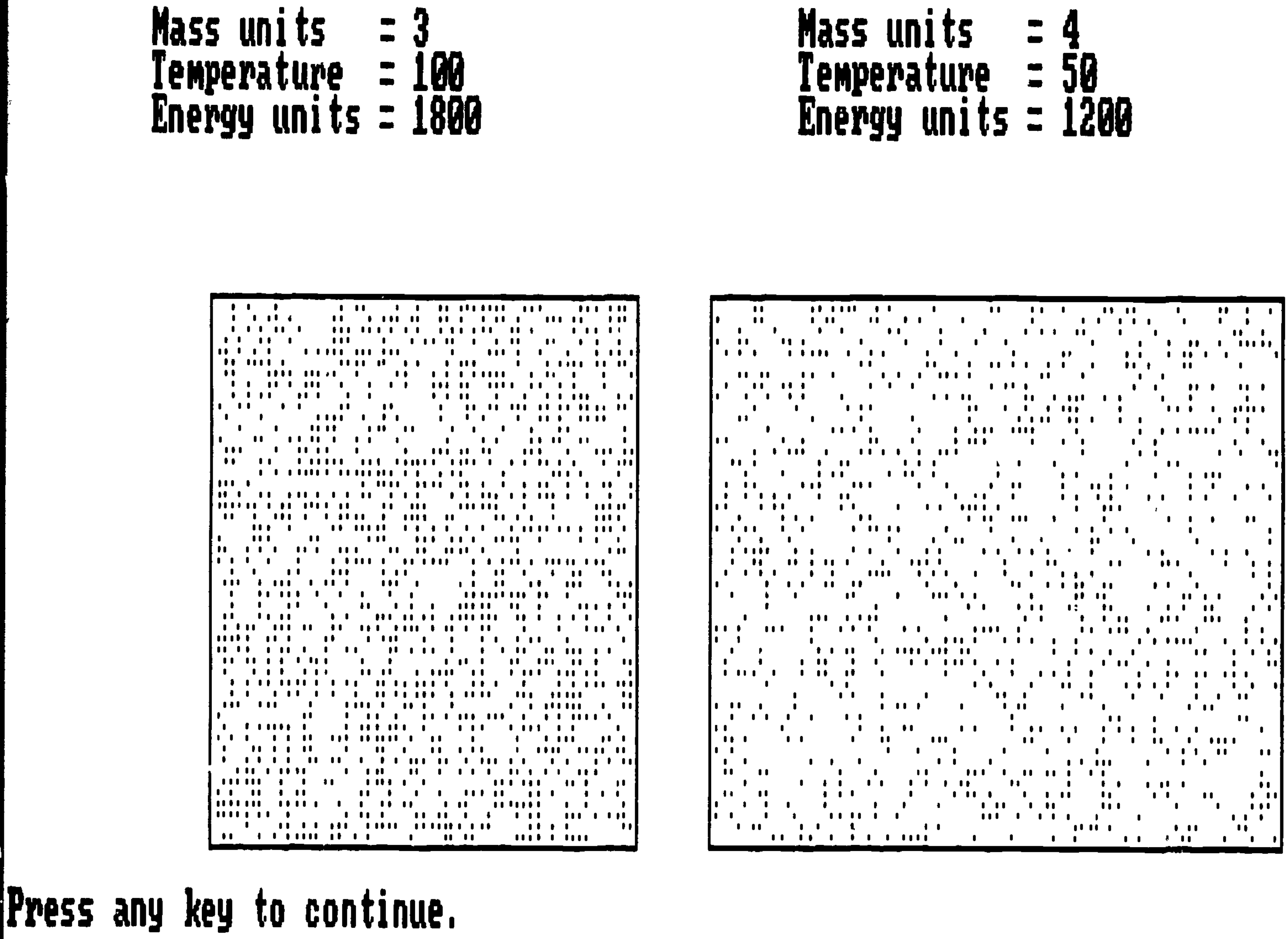
Figure 13. Screen from the CONTAINERS program, Task 4. Initial state.



```
Mass units    = 3                    Mass units    = 4
Temperature   = 30
Energy units = 540

Fill the container on the right of  4  mass units, so that its
temperature is  30
How many energy units do you need ?
```

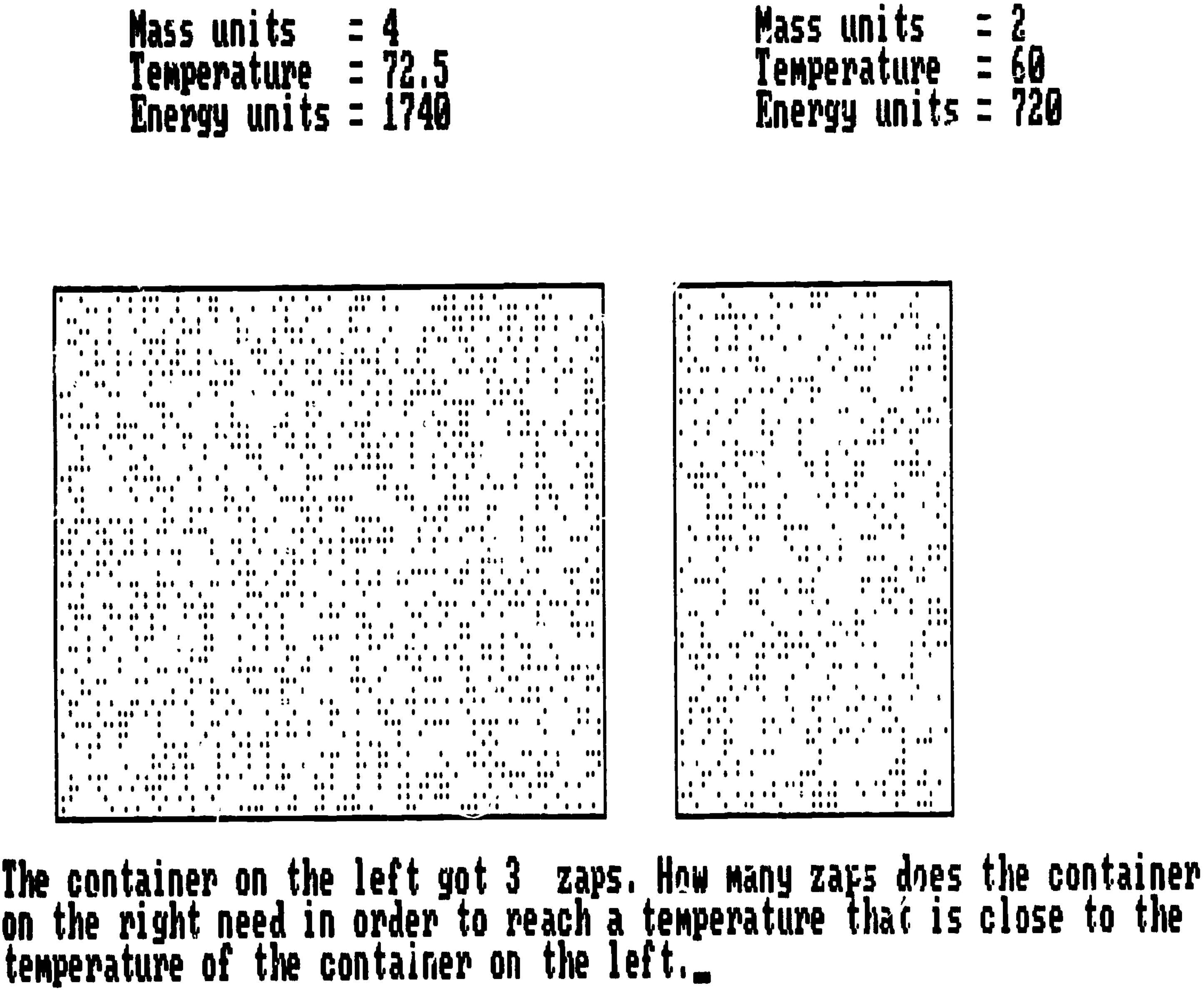
Figure 12. Screen from the CONTAINERS program, Task 3.



```
Mass units   = 3                      Mass units   = 4
Temperature  = 100                    Temperature  = 50
Energy units = 1800                   Energy units = 1200

Press any key to continue.
```

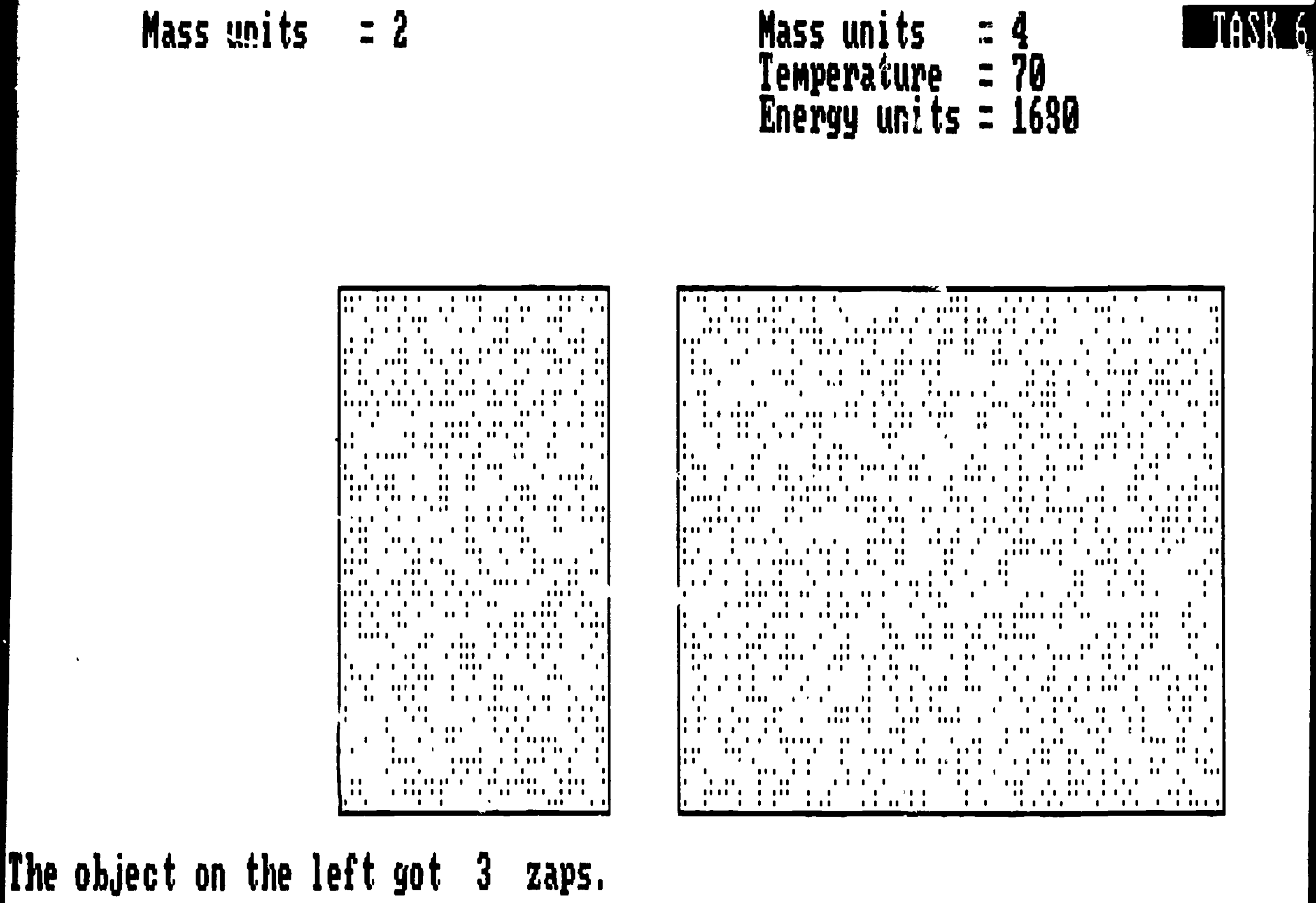
Figure 15. Screen from the CONTAINERS program, Task 5. Initial state.



```
Mass units   = 4                       Mass units   = 2
Temperature  = 72.5                    Temperature  = 60
Energy units = 1740                    Energy units = 720
```

```
The container on the left got 3  zaps. How many zaps does the container
on the right need in order to reach a temperature that is close to the
temperature of the container on the left.
```

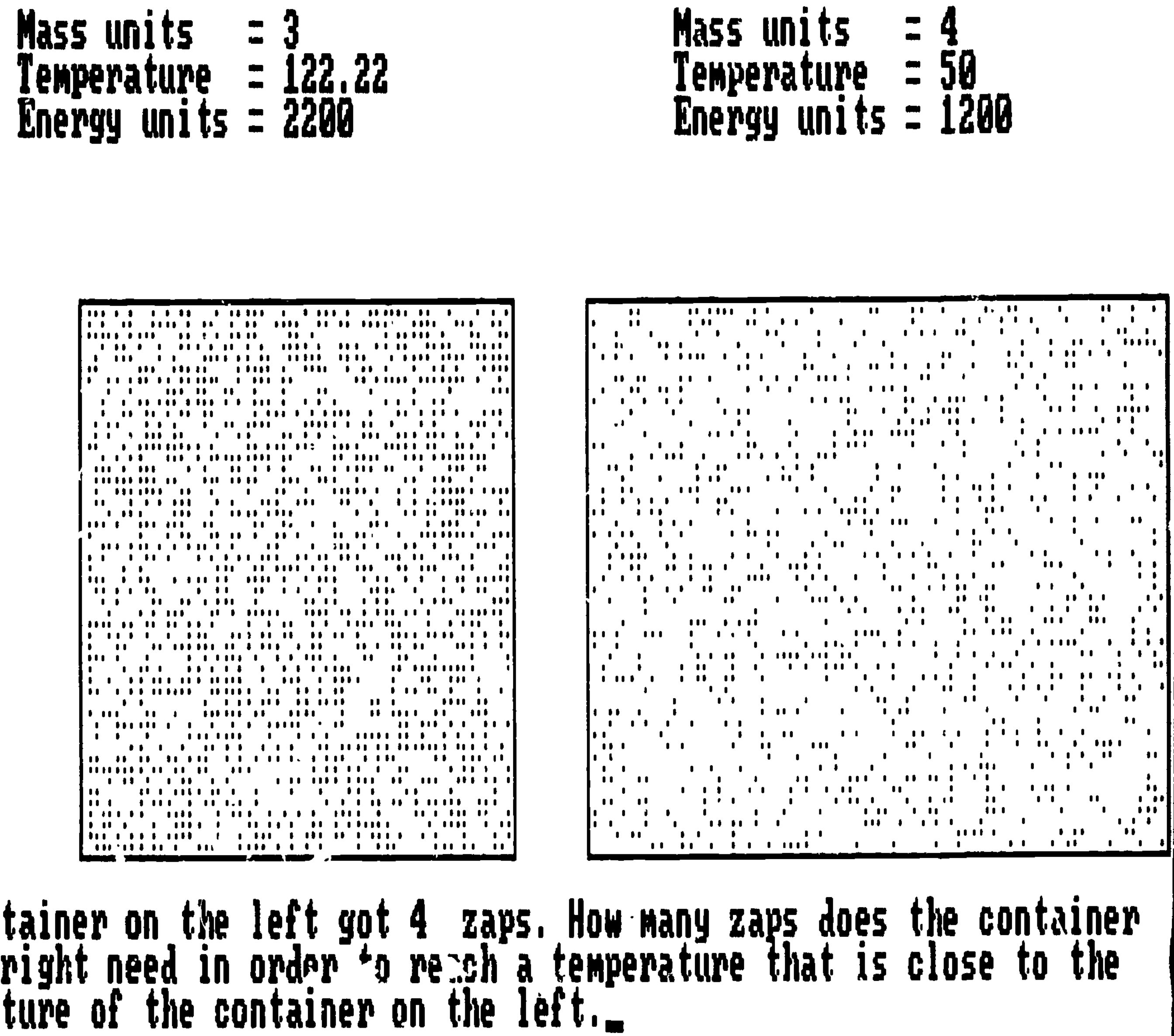
Figure 14. Screen from the CONTAINERS program, Task 4. The container on the left received 300 energy units.



```
Mass units   = 2                     Mass units   = 4        TASK 6
                                     Temperature  = 70
                                     Energy units = 1680

The object on the left got  3  zaps.
```

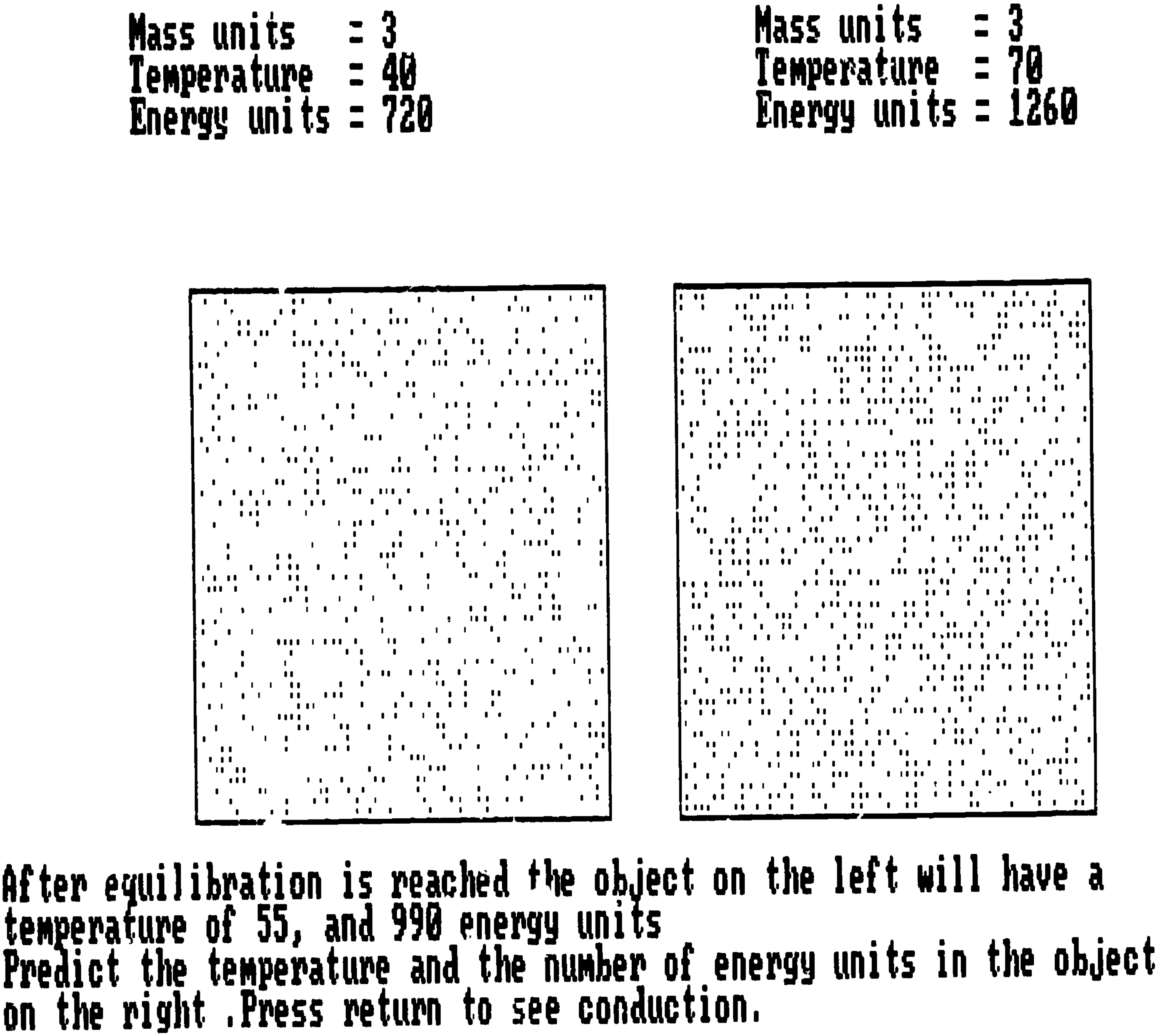
Figure 17. Screen from the CONTAINERS program, Task 6. Initial state: the container on the left received 300 energy units.



```
Mass units   = 3                    Mass units   = 4
Temperature  = 122.22               Temperature  = 50
Energy units = 2200                 Energy units = 1200
```

```
The container on the left got 4  zaps. How many zaps does the container
on the right need in order to reach a temperature that is close to the
temperature of the container on the left._
```

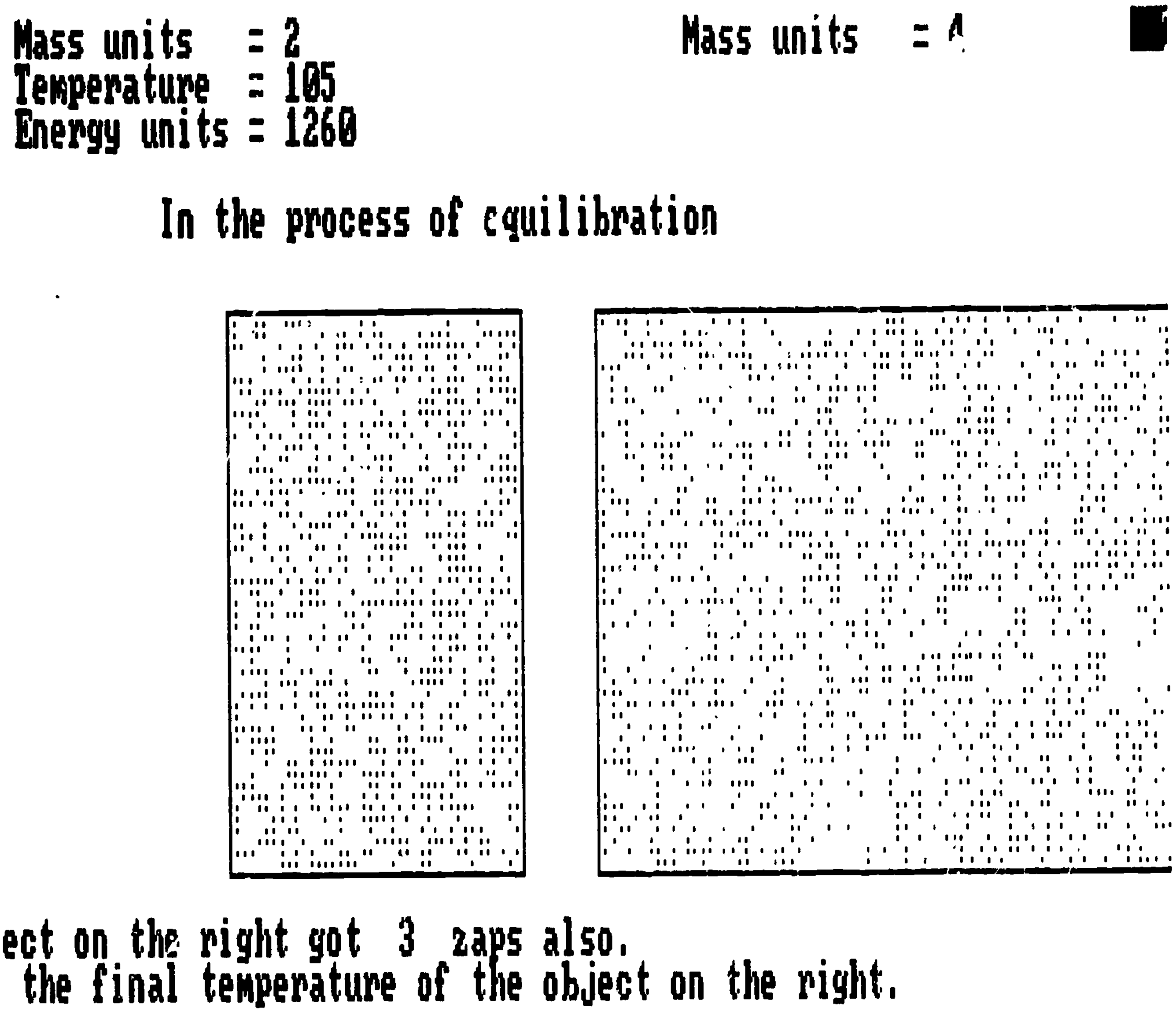
Figure 16. Screen from the CONTAINERS program, Task 5. The container on the left received 400 energy units.



```
Mass units   = 3                    Mass units   = 3
Temperature  = 40                   Temperature  = 70
Energy units = 720                  Energy units = 1260

After equilibration is reached the object on the left will have a
temperature of 55, and 990 energy units
Predict the temperature and the number of energy units in the object
on the right .Press return to see conduction.
```

Figure 19. Screen from the CONTAINERS program, Task 7. Initial state: before the containers are put in thermal contact.



Mass units = 2
Temperature = 105
Energy units = 1260

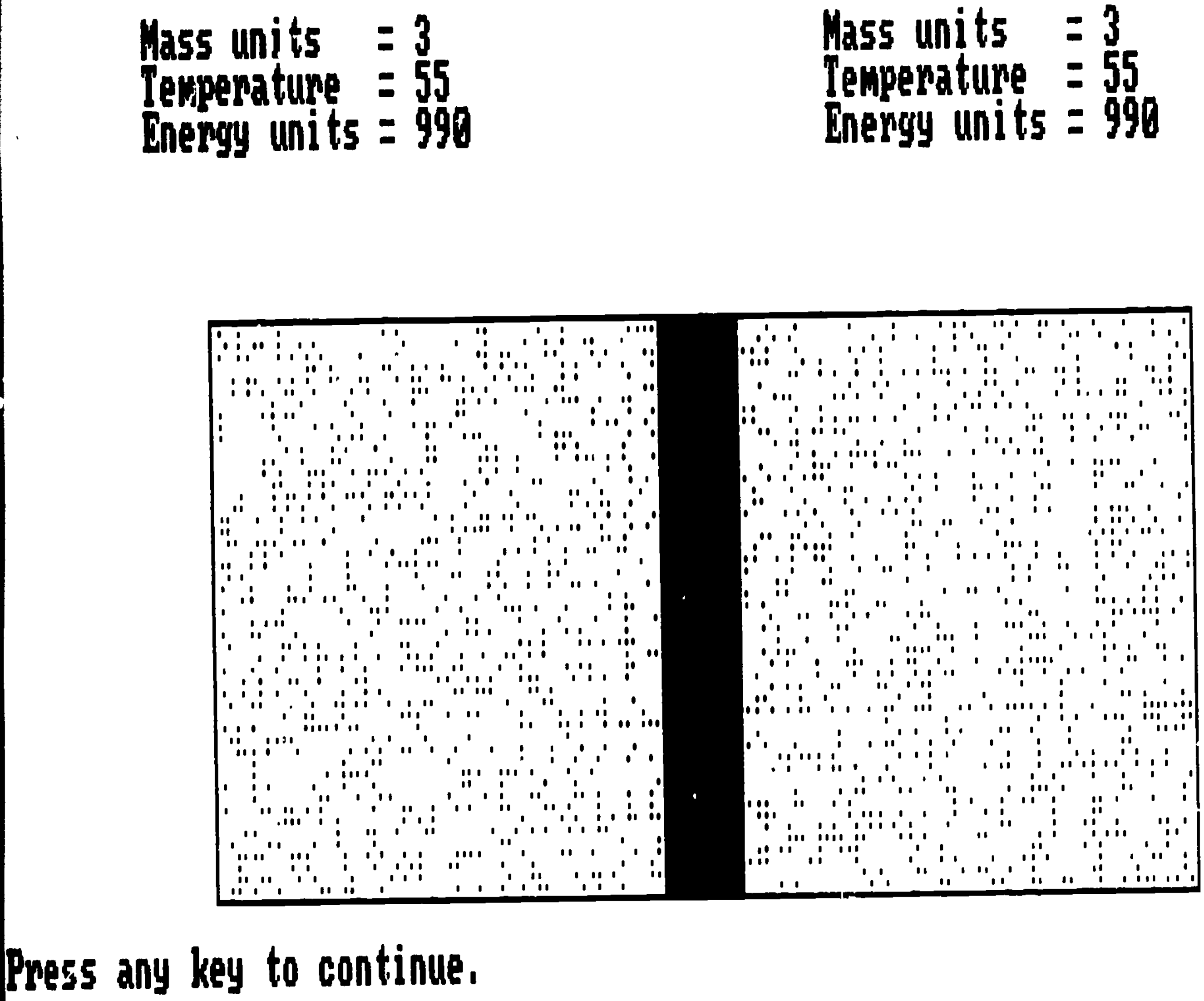
Mass units = 4

In the process of equilibration

The object on the right got 3 zaps also.
Predict the final temperature of the object on the right.

Figure 18. Screen from the CONTAINERS program, Task 6. The container on the right received 300 energy units.

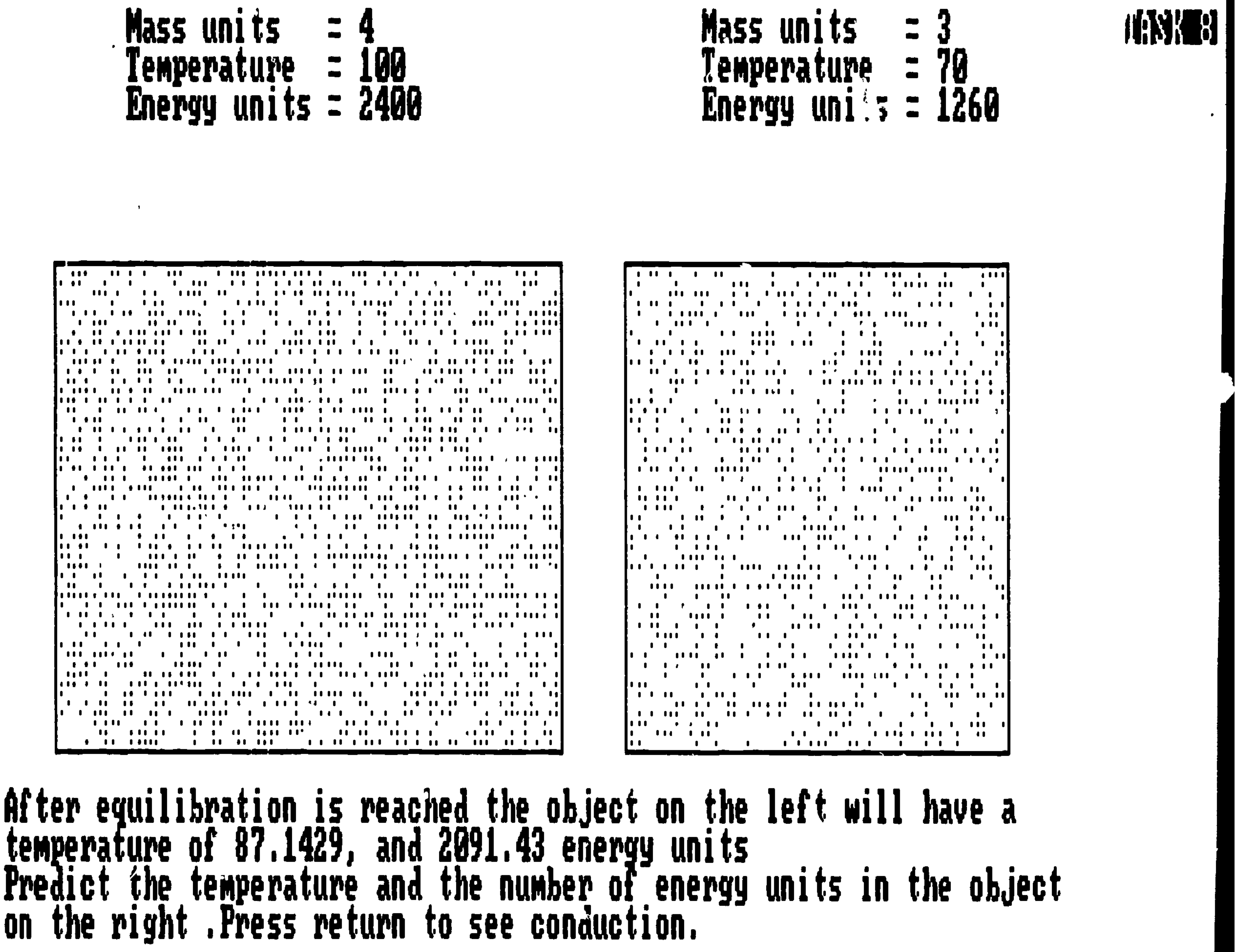
TASK 7



```
Mass units   = 3                    Mass units   = 3
Temperature  = 55                   Temperature  = 55
Energy units = 990                  Energy units = 990

Press any key to continue.
```

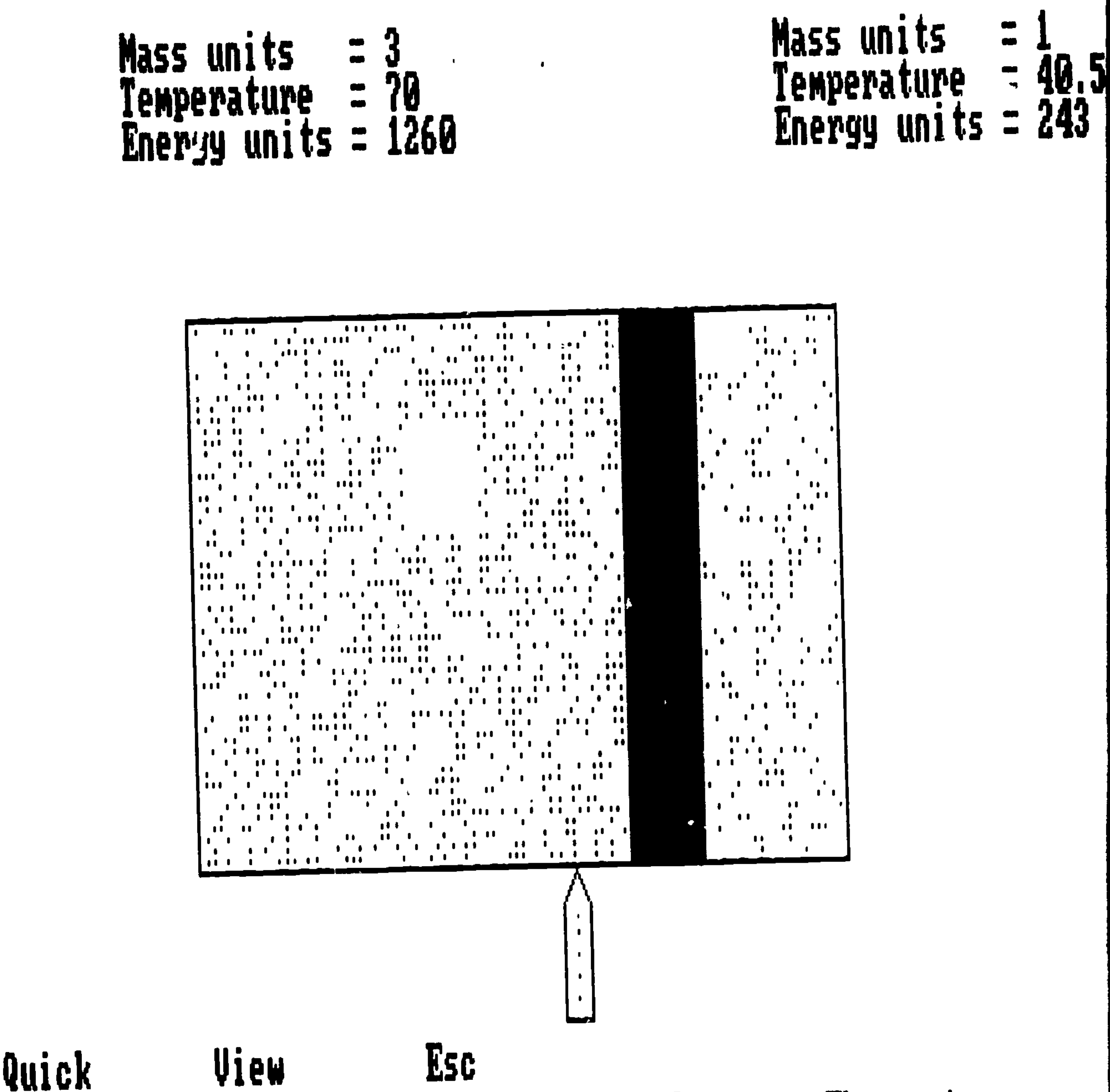
Figure 20. Screen from the CONTAINERS program, Task 7. After equilibration.



```
Mass units   = 4                    Mass units   = 3
Temperature  = 100                  Temperature  = 70
Energy units = 2400                 Energy units = 1260
```

```
After equilibration is reached the object on the left will have a
temperature of 87.1429, and 2091.43 energy units
Predict the temperature and the number of energy units in the object
on the right .Press return to see conduction.
```

Figure 21. Screen from the CONTAINERS program, Task 8. Initial state.



Mass units = 3
Temperature = 70
Energy units = 1260

Mass units = 1
Temperature = 40.5
Energy units = 243

Figure 25. Screen from the revised CONTAINERS program. The container on the left is in contact with an infinite source of heat at a constant temperature (here, a hot plate).

visually by using two molecules that look different. The choices are: two, three, or four atoms, with ratios in the energy circles that vary accordingly. Both molecules now are orange; the red and green colors used previously may have been confusing, since red and green were also the color code for inner and kinetic energies, respectively.

We now have multiple representations for the energy circles: areas, dots, and numbers (of energy units). The representations as dots and numbers of energy units were needed, because areas are not always easily compared visually (Fig. 26).

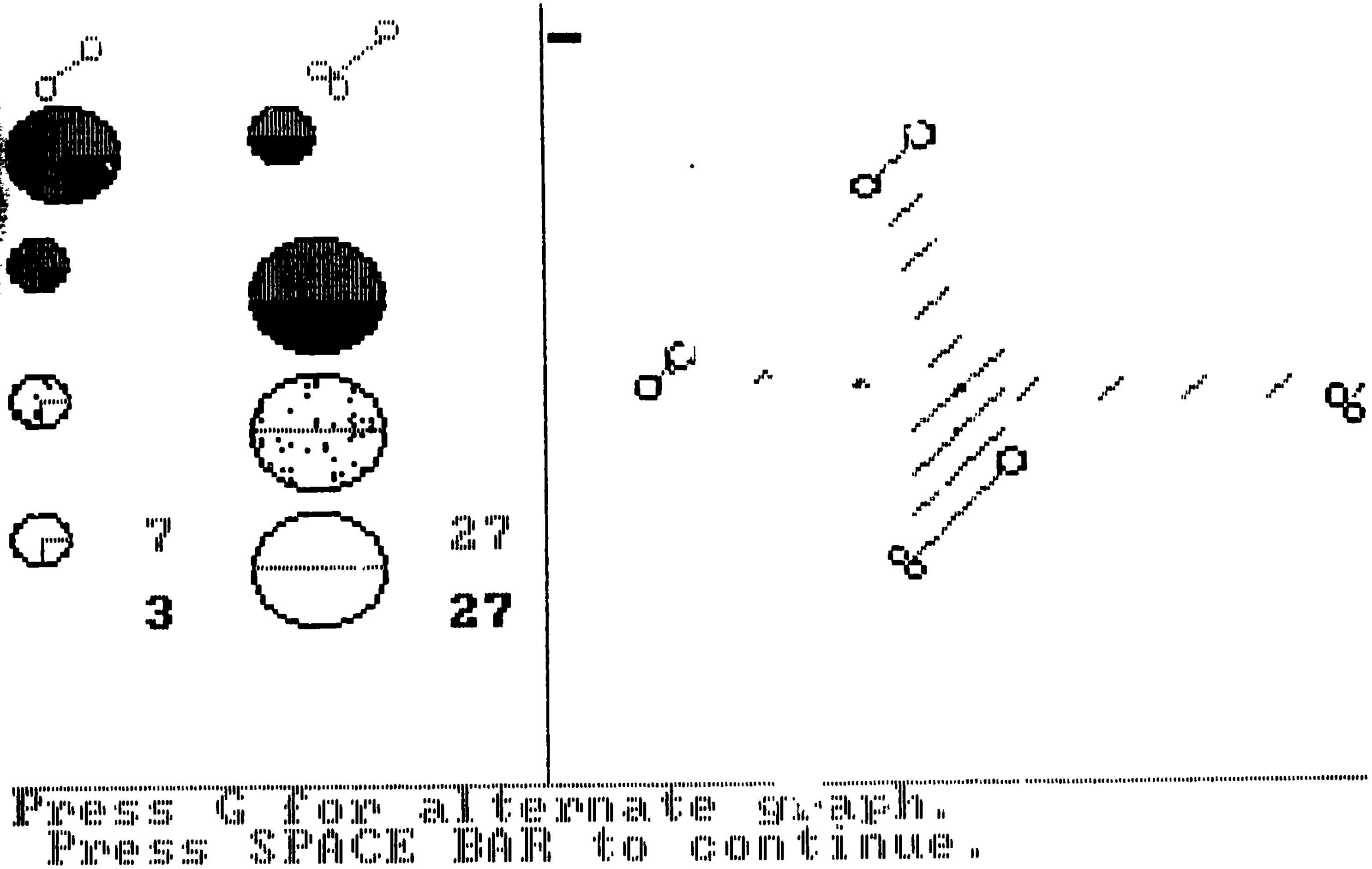
TWO NEW PROGRAMS: *SPECIFIC GRAM* AND *SPECIFIC HEAT*

One aspect of specific heat that textbooks tend to ignore, and we also hoped not to have to include in our curriculum and our computer models, is its dependence on molecular mass. In the KINETIC & INNER ENERGIES program we concentrated on the standard account of specific heat phenomena: different substances require different amounts of heat for equal temperature increases, because different proportions of the energy their molecules receive become kinetic energy of the center of mass (manifested as temperature rise); the rest of the energy received becomes what we call inner energy (with no effect on temperature). That account, while correct, is not the whole story. Even if all molecules in the world had the same structure, and thus the same ratio of inner to kinetic energy, different substances would still have different specific heats so long as their molecules have different masses, for the following reasons. Consider 1g of substance A, which is made of light molecules, and 1g of substance B, made of heavy molecules. When both substances are given the same amount of thermal energy, one molecule of A will receive much less energy than one of B, because in A more molecules share the same amount of energy than in B. If we assume that the proportion of energy that becomes kinetic energy is the same for both A and B, then one molecule of A ends up with less kinetic energy than one of B and the temperature rise in 1g of substance A will be less than in 1g of substance B.

To sum up, there are two "molecular" reasons for differences in specific heat: molecular mass and molecular structure. When the masses of the molecules of two substances differ, the number of molecules per gram differs, so that each molecule receives a different share of the energy. When the structures of the molecules are different, the part of the energy received that becomes kinetic (contributing to temperature rise) differs; even if each molecule in both substances had received the same amount of energy, each would have different kinetic energy and the temperature increases in the two substances would be different[9].

---

[9] Like our initial account of specific heat, our present model is based on the kinetic theory of gases, itself based on classical mechanics. The model would have to be modified considerably to account for the specific heat of liquids and solids. Even for gases, the specific heat values it predicts are generally wrong. A correct understanding of the subject requires quantum mechanics. However, we believe that our model, as it stands, captures the general meaning of specific heat and can be used, particularly by novices, to understand the thermal behavior of a substance in any state. Should students pursue the study of thermodynamics, our initial model would provide a stepping stone, rather than an obstacle, to further learning.



```
Press G for alternate graph.
 Press SPACE BAR to continue.
```

Figure 26. Screen from the revised KINETIC & INNER ENERGIES program. Multiple representations (areas, dots, and numbers) of energy content in a collision. On the right, in the top row two circles represent the energy of the molecules before the collision; in the next row the circles represent their energy after the collision. Alternative representations of their energy after the collision are shown by the circles in the third and fourth rows.

The KINETIC & INNER ENERGIES program deals only with the ratio of inner to kinetic energy (the second factor) as the explanation for specific heat. Unfortunately, in the students' laboratory experiments molecular mass or number of molecules per gram (the first factor) is "dominant." For example, alcohol molecules are more complex and have a higher inner/kinetic ratio than water molecules, yet, alcohol has a lower specific heat than water because alcohol molecules are heavier. If students had tried to use our KINETIC & INNER ENERGIES program in its original form to account for the relative specific heat of alcohol and water on the basis of molecular structure, the explanation would have contradicted the students' experimental findings. We therefore decided to include both factors in a new conceptual molecular model: SPECIFIC GRAM. The KINETIC & INNER ENERGIES program would be used to explain the second factor.

SPECIFIC GRAM program

This program explicates the concept of specific heat in a *dynamic* fashion. Unlike amount of heat and temperature, which can be apprehended visually in each static display (number versus crowdedness of dots), specific heat becomes meaningful only with a succession of screen images. In other words, we could not create a static graphic representation for specific heat.

The SPECIFIC GRAM program represents the energy content of molecules in 1g of different substances. The user can choose from among four substances[10] that differ either in number of molecules per gram or ratio of inner to kinetic energy in a molecule, or both (Fig. 27). Substance A has 6 molecules per gram and a ratio 1:1; substance B has 6 molecules per gram and a ratio of 2:1; substance C has 18 molecules per gram and a ratio 1:1; and substance D has 12 molecules per gram and a ratio 3:1 (Fig. 28). As before, kinetic energy is represented by green dots and inner energy by red. In this program, one green dot per molecule corresponds to 1°. The user selects two substances, and two rectangles of equal size appear on the screen representing 1g of each substance. Depending on which substances were chosen, the rectangles are filled with 6, 12, or 18 ovals (representing the molecules). When the T (temperature) key is pressed, energy dots fill the molecules and the temperature increases by 1° in both substances: each molecule receives one green dot and a certain number of red dots, depending on the substance (one red dot for substance A, two for B, one for C, and three for D; compare Figs. 27 and 29, which represent an increase of 1° in substances A and B). The same information – temperature, kinetic energy, inner energy, and total energy – is represented numerically in captions below the rectangles. The user can press V (VIEW) and then R to see only the red dots (Fig. 30) or V and then G to see only the green ones (Fig. 31) in the different substances. For instance, the user can verify that when substances A and B have the same temperature they have the same number of green dots but that B has twice as many red dots as A.

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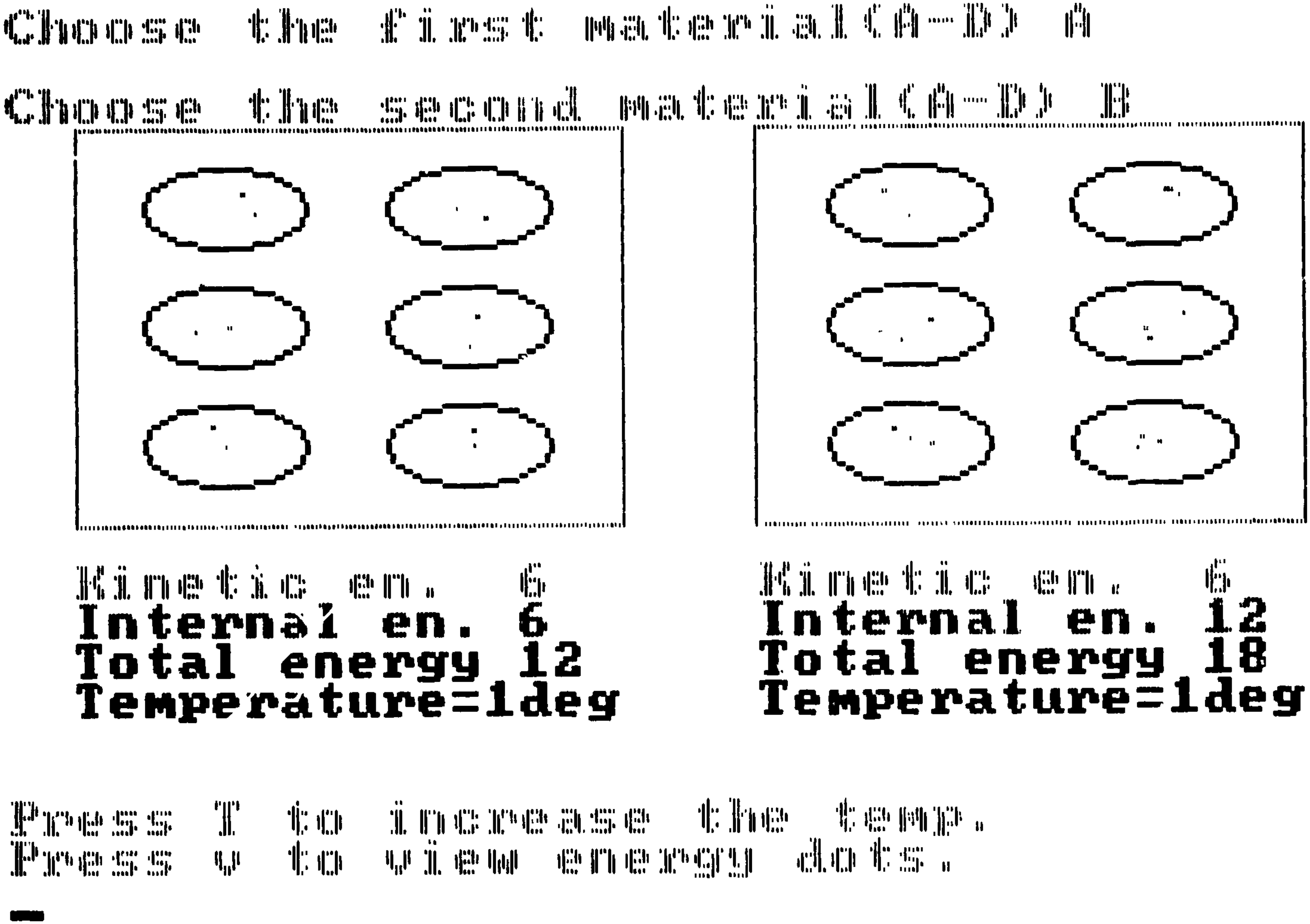
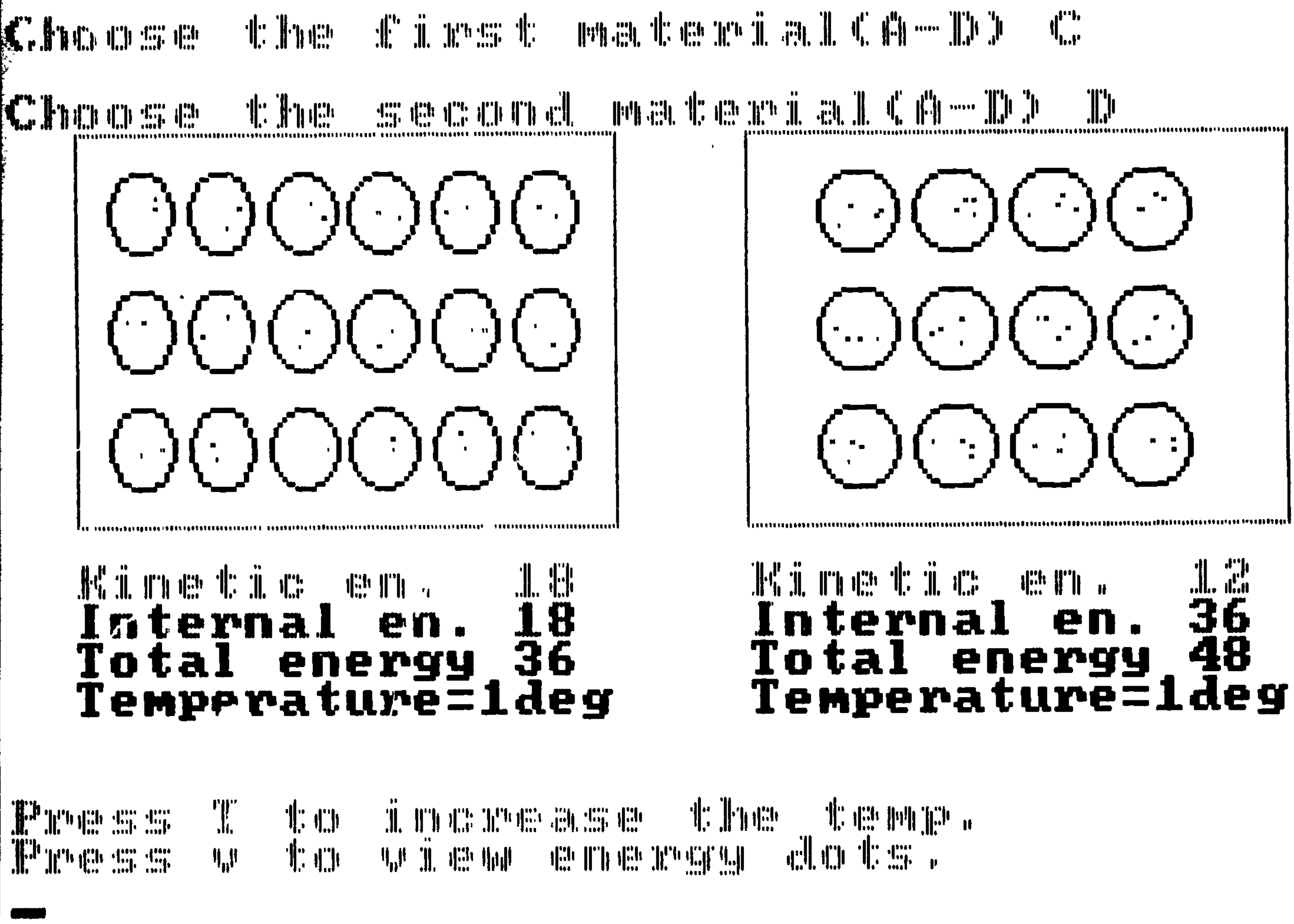
[10] Students are warned that these substances are entirely fictional; 1g of any real substance actually contains millions of molecules. We chose to represent only a few molecules to make concepts easier to grasp.



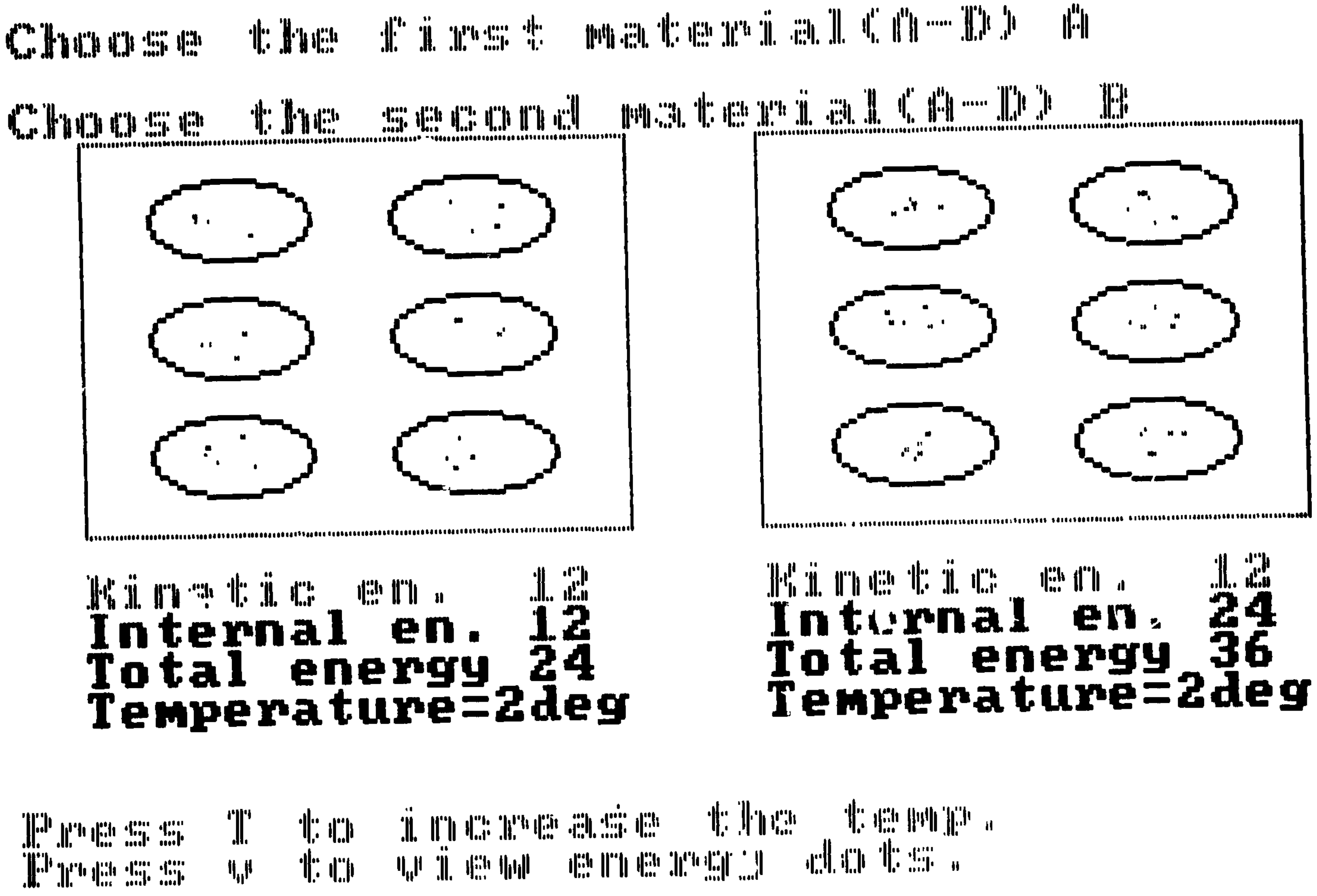
```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.    6            Kinetic en.    6
Internal en. 6              Internal en. 12
Total energy 12             Total energy 18
Temperature=1deg            Temperature=1deg

Press T to increase the temp.
Press v to view energy dots.
```

Figure 27. Screen from the SPECIFIC GRAM program. Substances A and B differ in their ratio of inner to kinetic energy. The big dots (red on the screen) represent inner energy. The small dots (green on the screen) represent kinetic energy.



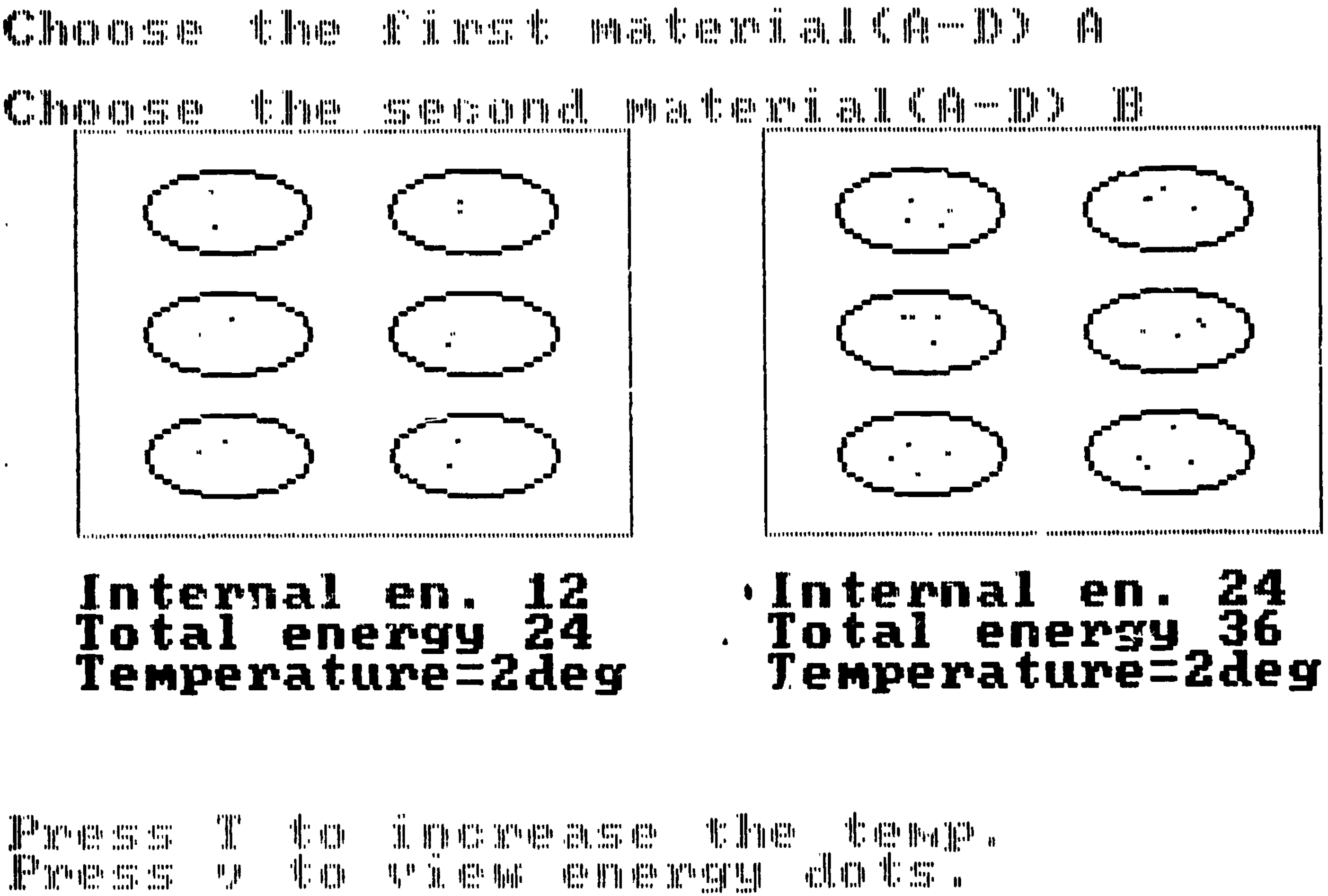
```
Choose the first material(A-D) C
Choose the second material(A-D) D

Kinetic en. 18                 Kinetic en. 12
Internal en. 18                Internal en. 36
Total energy 36                Total energy 48
Temperature=1deg               Temperature=1deg

Press I to increase the temp.
Press V to view energy dots.
```

Figure 28. Screen from the SPECIFIC GRAM program. Substances C and D differ in their ratio of inner to kinetic energy. The big dots (red on the screen) represent inner energy. The small dots (green on the screen) represent kinetic energy.



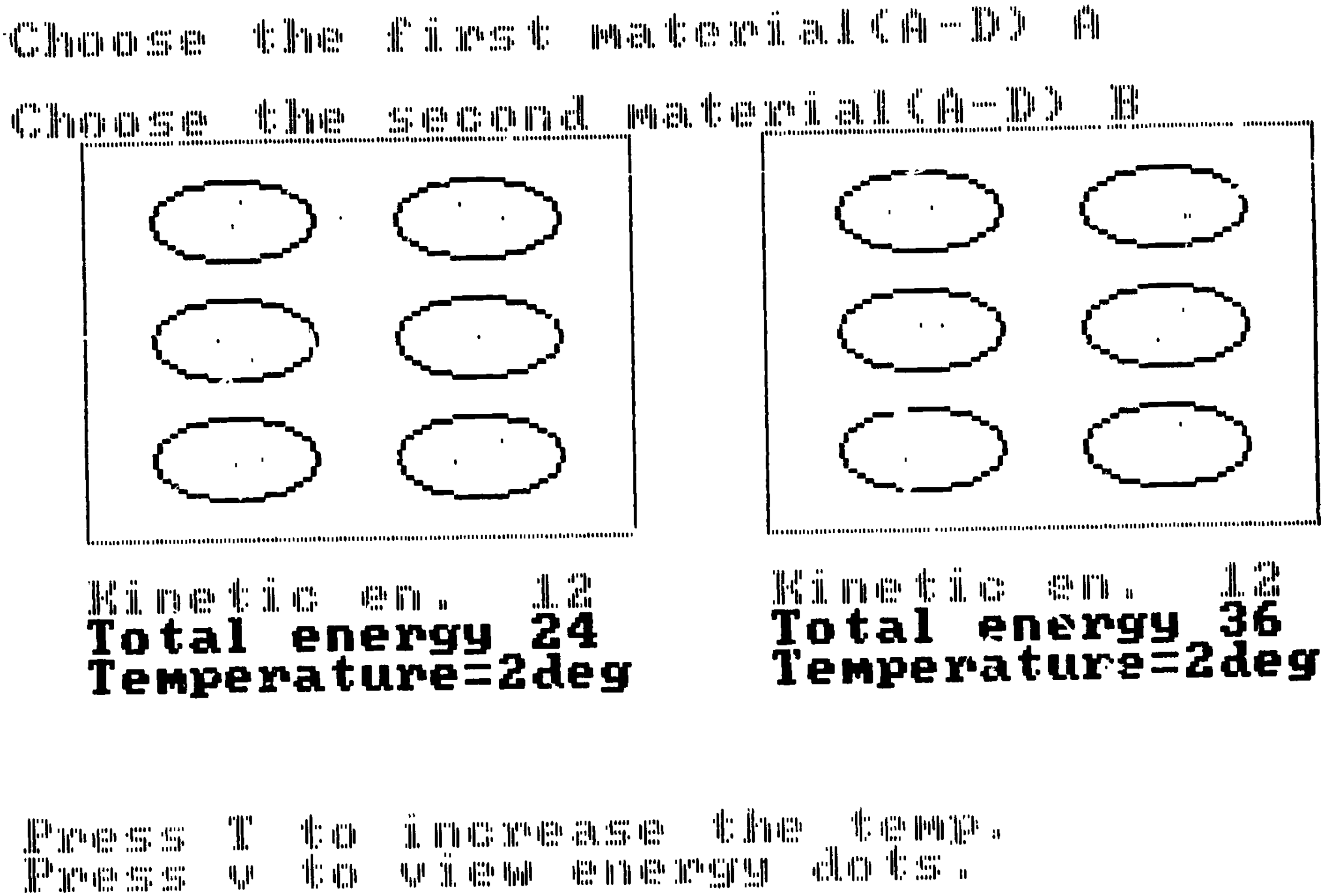
```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.   12            Kinetic en.   12
Internal en.  12            Internal en.  24
Total energy  24            Total energy  36
Temperature=2deg            Temperature=2deg

Press T to increase the temp.
Press V to view energy dots.
```

Figure 29. Screen from the SPECIFIC GRAM program. The temperature of both substances has been increased by 1 degree. (Compare with Fig. 27.)



```
Choose the first material(A-D) A
Choose the second material(A-D) B

Internal en. 12              Internal en. 24
Total energy 24              Total energy 36
Temperature=2deg             Temperature=2deg

Press I to increase the temp.
Press y to view energy dots.
```

Figure 30. Screen from the SPECIFIC GRAM program. Only the dots (red on the screen) representing inner energy appear. (Compare with Fig. 29.)



```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.  12          Kinetic en.  12
Total energy 24          Total energy 36
Temperature=2deg         Temperature=2deg

Press T to increase the temp.
Press v to view energy dots.
```

Figure 31. Screen from the SPECIFIC GRAM program. Only the dots (green on the screen) representing kinetic energy appear. (Compare with Fig. 29.)

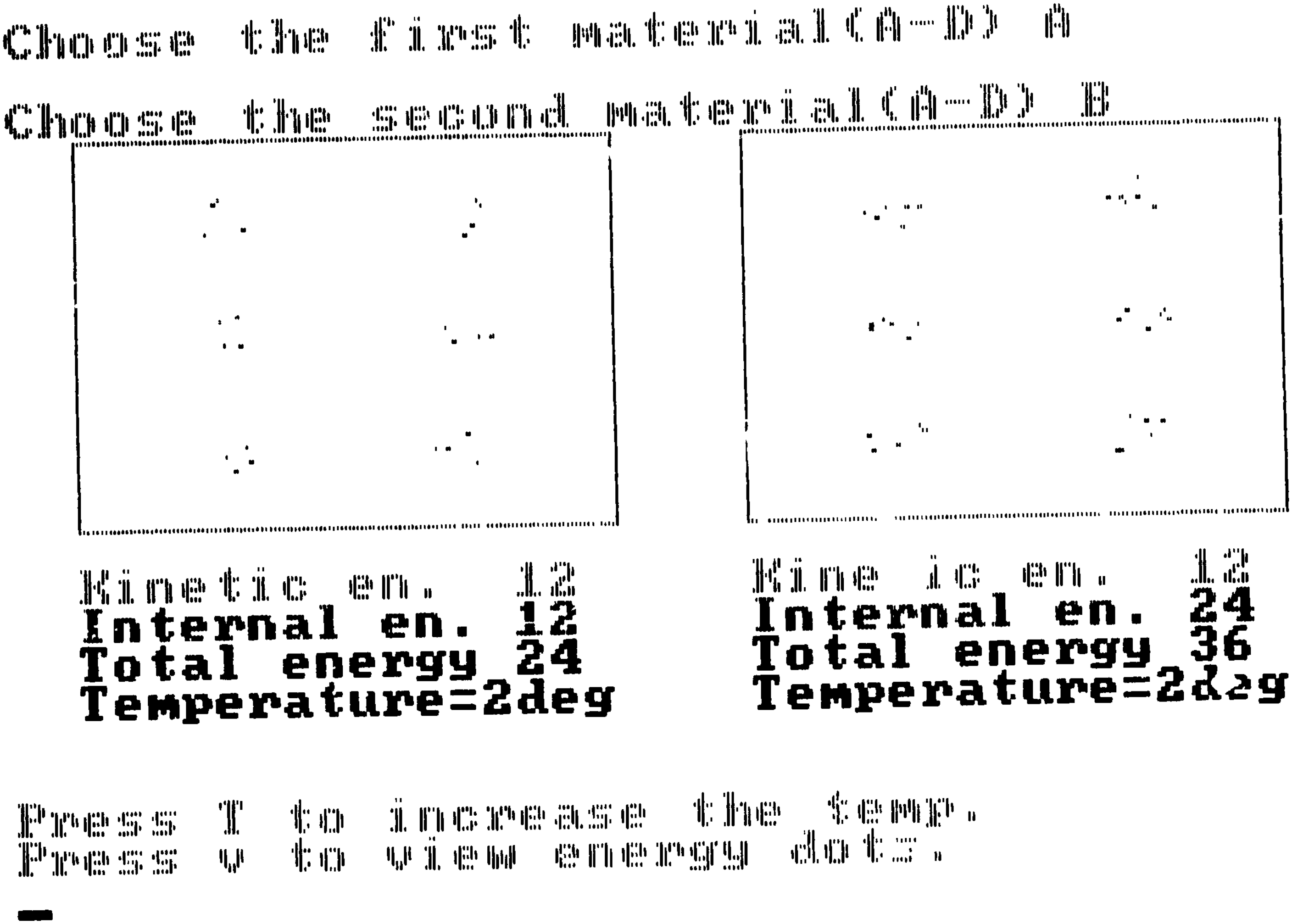
We added an option called CIRCLES ON/OFF. When the user presses C (CIRCLES) the ovals representing the molecules disappear; pressing C again makes them reappear. Without ovals, the screen looks like the CONTAINERS program, so that the CIRCLES ON/OFF option helps establish the link betweeen the molecular explanation of specific heat (CIRCLES ON) and the thermal properties of a substance at the macro-level (CIRCLES OFF) (See Fig. 32).

SPECIFIC HEAT program

This program is the macro-level version of SPECIFIC GRAM. As in CONTAINERS, the user chooses the masses and either the temperatures or the energy contents of two "containers," which here represent different substances chosen from among A, B, C, and D (and correspond to the substances in SPECIFIC GRAM). When the parameters are set, the containers fill with red dots (the inner energy) and green dots (the kinetic energy of the center of mass motion of the molecules). The proportion of red and green dots is constant for a given substance (Fig. 33). The number of dots depends on the temperature and on the specific heat of each substance and obeys the following numerical relation: (M*C*T), where C has been calculated according to the ratio of inner to kinetic energy and the number of molecules per gram for that substance. As in CONTAINERS, the user can choose to VIEW (the molecules in motion) or ZAP (energy into the containers). For example, when one ZAP is delivered into a container, 100 dots appear at its bottom, distributed between green and red dots, according to the specific heat of the substance. The values for the mass, temperature and total energy for each container are represented numerically at the top of the screen.

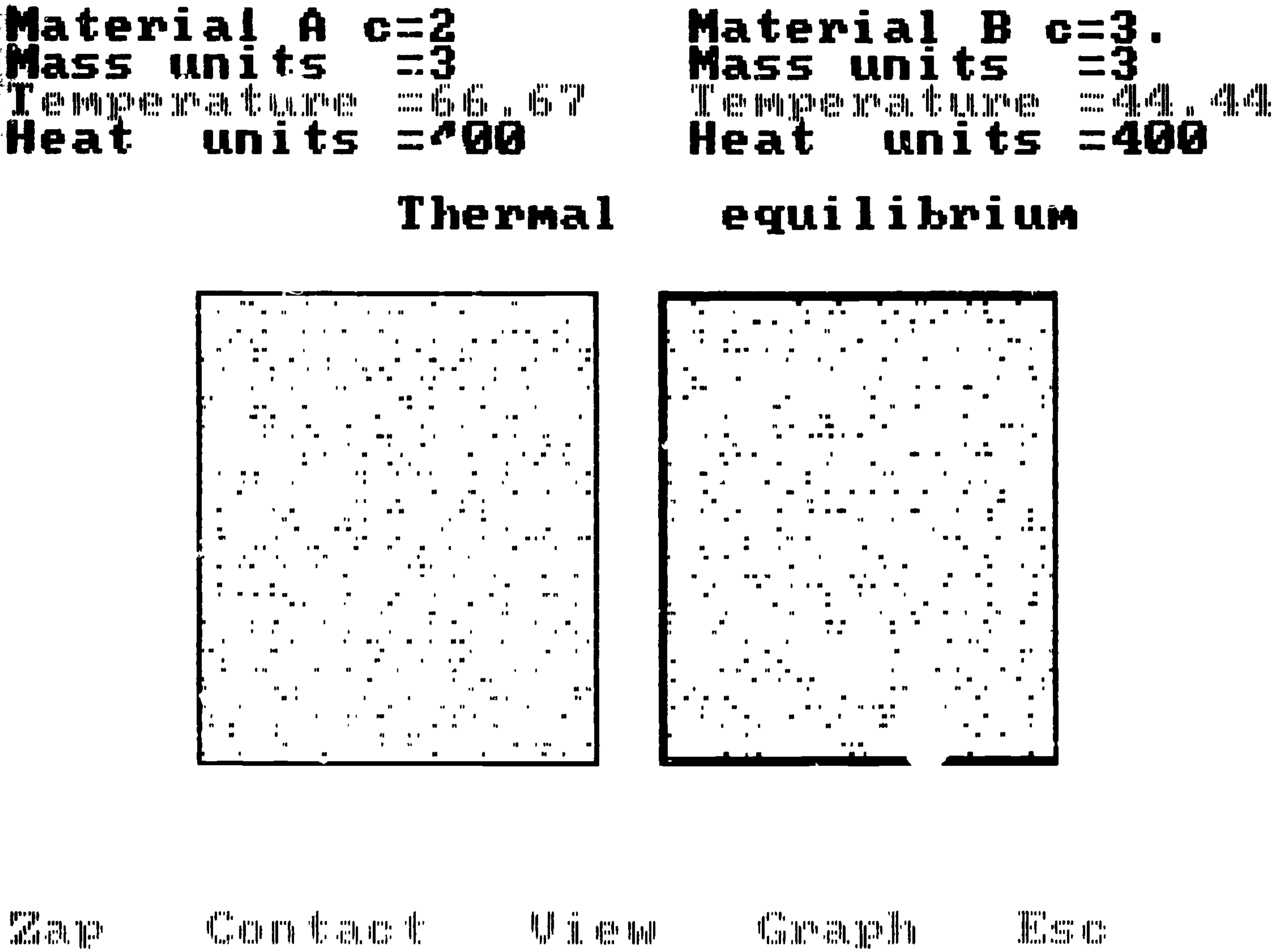
A new option called GRAPH can be accessed by the user by pressing G. Two insets summarize the information for each container visually and numerically. The upper inset represents the kinetic energy, the inner energy, and their sum (total energy) in the whole container, both numerically and in a bar graph. Green signifies the kinetic energy content, red the inner energy. The lower inset represents the kinetic, inner, and total energy in one molecule, both numerically and in a pie graph (to suggest the link with the pie graph representation in the KINETIC & INNER ENERGIES program). The size of the circle is proportional to the total energy of the molecule. The circle is divided into green and red areas, according to the ratio of inner to kinetic energy for that substance. The green area in the pie graph (not the angle), represents the kinetic energy in each molecule and is proportional to the temperature of the container (Fig. 34). If ZAP is used to increase the energy in a container, the option HISTORY can be used to compare the energy content of one molecule before and after ZAPping. Pressing the H key makes the insets appear or disappear. After adding a few ZAPs (e.g., 3), the user can compare the data from before and after ZAPping (Fig. 35).

This program combines CONTAINERS and SPECIFIC GRAM; it embodies the quantitative relation of mass, heat, specific heat, and temperature; and it relates macroscopic events (total energy input, temperature rise) to molecular events.



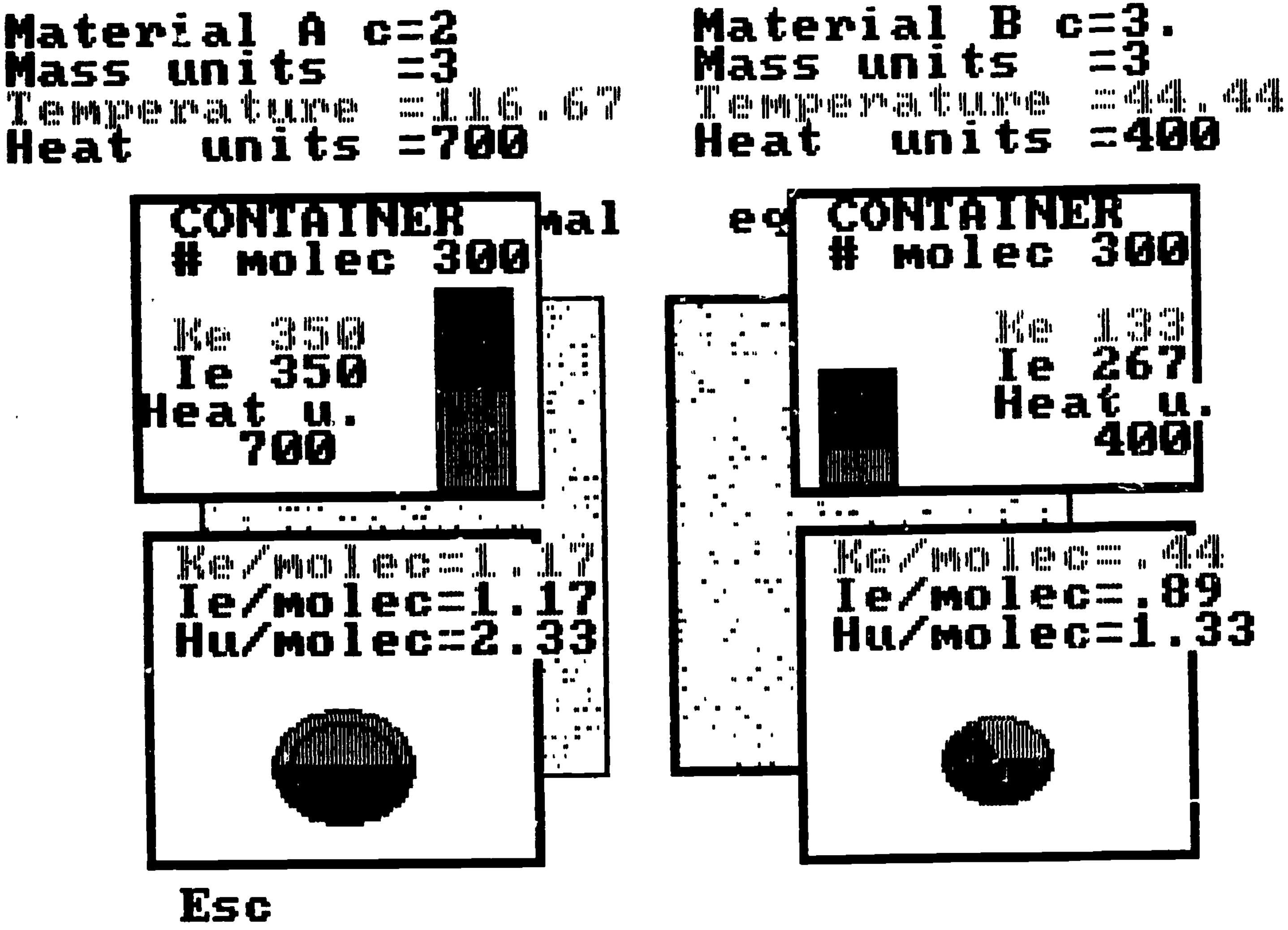
```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.  12            Kinetic en.  12
Internal en. 12            Internal en. 24
Total energy 24            Total energy 36
Temperature=2deg           Temperature=2deg

Press T to increase the temp.
Press v to view energy dots.
```

Figure 32. Screen from the SPECIFIC GRAM program. The ovals representing the molecules have been removed; only the energy dots appear on the screen. (Compare with Fig. 29.)



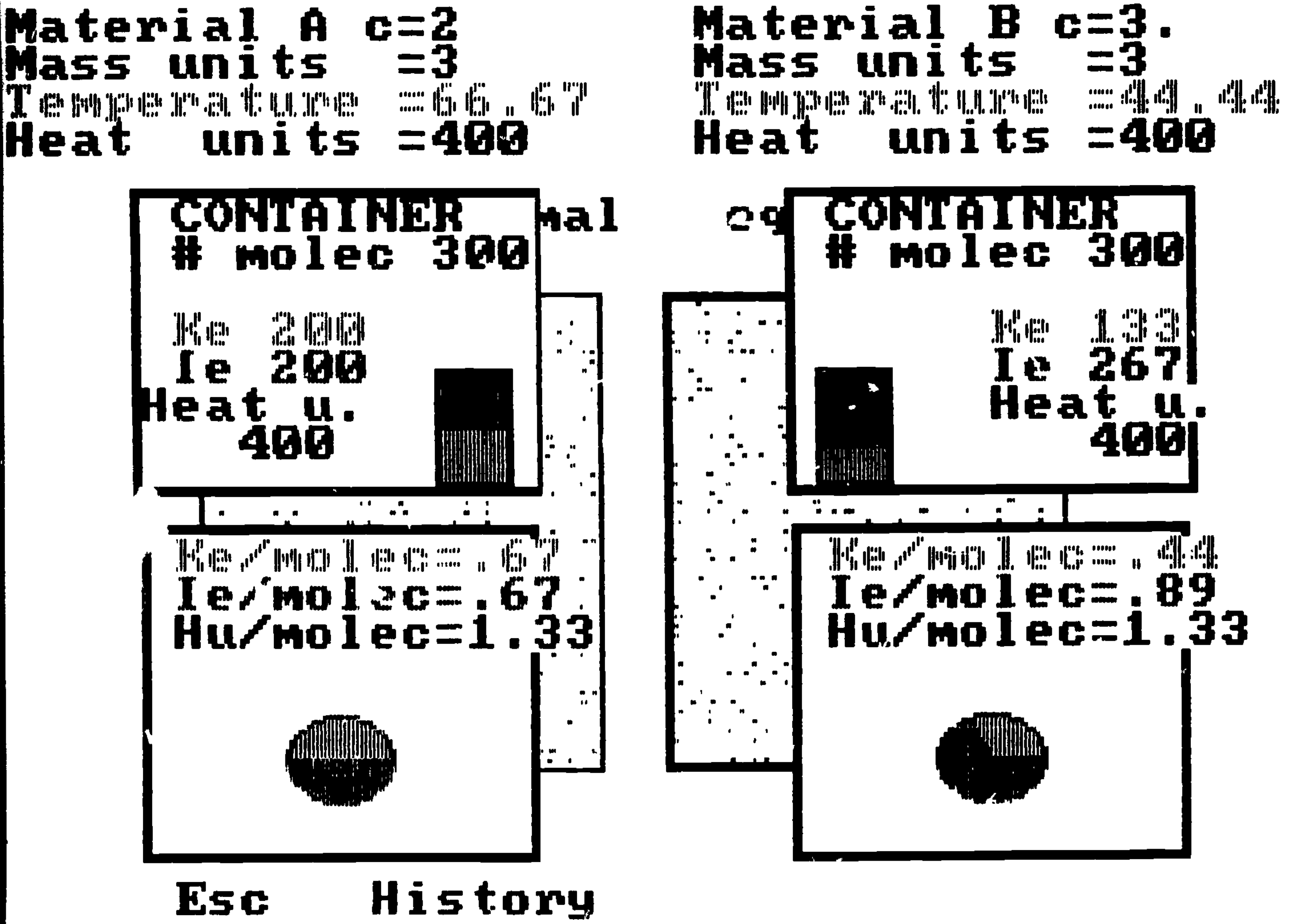
```
Material A c=2            Material B c=3.
Mass units   =3           Mass units   =3
Temperature =66.67        Temperature =44.44
Heat  units =400          Heat  units =400

           Thermal   equilibrium
```

Figure 33. Screen from the SPECIFIC HEAT program. The dark dots (red on the screen) represent inner energy and the light dots (green on the screen) represent kinetic energy.



```
Material A c=2              Material B c=3.
Mass units   =3             Mass units   =3
Temperature =116.67         Temperature =44.44
Heat   units =700           Heat   units =400

CONTAINER        mal     eq CONTAINER
# molec 300                 # molec 300

Ke 350                           Ke 133
Ie 350                           Ie 267
Heat u.                          Heat u.
  700                              400

Ke/molec=1.17               Ke/molec=.44
Ie/molec=1.17               Ie/molec=.89
Hu/molec=2.33               Hu/molec=1.33

Esc
```

Figure 34. Screen from the SPECIFIC HEAT program, GRAPH option.



```
Material A c=2              Material B c=3.
Mass units   =3             Mass units   =3
Temperature =66.67          Temperature =44.44
Heat   units =400           Heat   units =400

CONTAINER        mal        eq CONTAINER
# molec 300                    # molec 300

Ke 200                                Ke 133
Ie 200                                Ie 267
Heat u.                            Heat u.
  400                                   400

Ke/molec=.67                   Ke/molec=.44
Ie/molec=.67                   Ie/molec=.89
Hu/molec=1.33                  Hu/molec=1.33
```

Figure 35. Screen from the SPECIFIC HEAT program, GRAPH and HISTORY options.

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APPENDIX A

Heimler, C.H. and Price, J. S., 1984. *Focus on Physical Science.* Columbus, Ohio: Charles E. Merrill, Chapter 19.

Activity 19–1. Can kinetic energy produce heat?

Materials: 2 drinking cups, sand, tape, thermometer, clock

Fill a cup one-third full of dry sand that is at room temperature. Place the end of a thermometer in the sand and record the temperature. Now invert the second cup over the first cup. Seal by wrapping a piece of tape around the seam between the two cups. Shake the sand back and forth inside the cups for five minutes. Punch a hole in the top of one of the cups. Insert the thermometer through the hole into the sand. Record the temperature again. What causes the change in temperature of the sand?

Making Sure

1. Explain how each of the following examples of potential energy changes to kinetic energy.
   - a. wound watch
   - b. stretched rubber band
   - c. diver on a diving board
   - d. a drawn archer's bow

19:2 Temperature and Heat

All matter is made of particles in constant motion. They have kinetic energy. Temperature is a measure of the average kinetic energy of the particles in matter. Two objects are at the same temperature when the average kinetic energy of the particles in each is the same. For example, an orange and milk in a carton are at the same temperature in a refrigerator. The average kinetic energy of the particles in the orange is the same as the average kinetic energy of the particles in the milk.

How is heat different from temperature?

Temperature and heat are not the same. Temperature is a measure of the average kinetic energy of the particles in an object. **Heat** is the energy transferred between matter as a result of differences in temperature. The ability of matter to transfer heat energy depends on its mass and temperature. Imagine a swimming pool and a bathtub of water. The water in each is the same temperature. Which has more heat energy? The mass of water in the pool is greater than in the bathtub. A large mass of water has a higher total energy than a small number of particles at the same temperature.

What affects the direction of heat transfer?

You will learn in Section 19:4 that temperature is used to calculate heat energy. Temperature also shows the tendency of a material to gain or lose heat. For example, when you put a thermometer in a glass of ice water, the column of mercury drops. The thermometer lost heat to the ice water. If you put the thermometer in boiling water, the column of mercury rises. The thermometer gained heat from the boiling water. Heat flows from regions of higher temperature to regions of lower temperature. Heat is similar to work because both quantities are forms of energy. Heat is a transfer of energy between matter rather than being a part of matter. In studying work, you saw that it also involved a transfer of energy. You consider the work done on an object, but the work is not the property of that object. Like other forms of energy, heat energy is measured in joules.

Making Sure

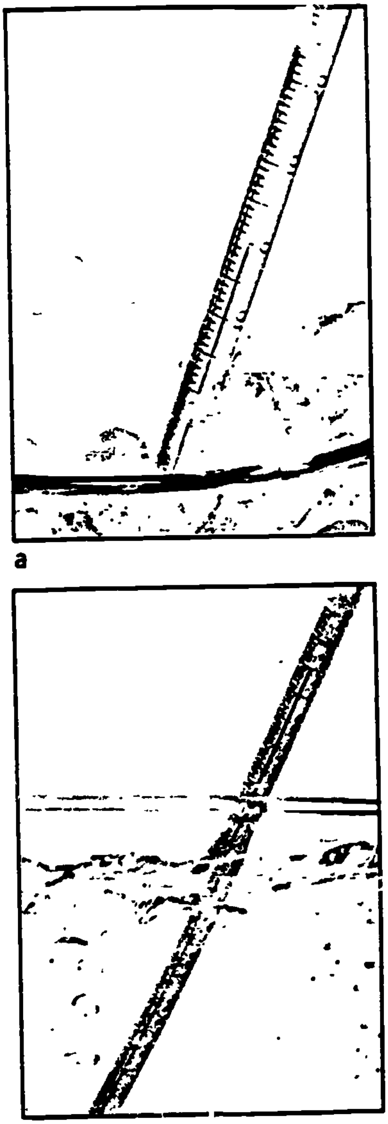
2. What does temperature measure?
3. Which will have more heat energy, a cup of boiling water or a pot of boiling water?
4. What other physical quantity is expressed in joules?

19:3 Specific Heat Capacity

Heat and temperature are related. When the total energy of a substance is increased, its particles move faster. The kinetic energy of the particles increases and the temperature rises. As a material loses heat to its surroundings, its particles move more slowly, and the temperature of the material falls.

Specific heat capacity (C_p) is the ability of a material to absorb heat. It is measured using the unit joule per gram Celsius degree (J/g·C°). For example, water has a specific heat capacity of 4.18 J/g·C°. This value shows that 4.18 joules of heat energy are absorbed in raising the temperature of one gram of water one Celsius degree.

Different materials have different specific heat capacities. Iron has a specific heat capacity of 0.45 J/g·C°. It takes 0.45 joules to raise the temperature of one gram of iron one Celsius degree. Table 19–1 shows the specific heat capacities of several substances.



a

b

FIGURE 19–1. The thermometer shows 0°C in ice water (a). The mercury rises showing 100°C in boiling water (b). Heat energy is transferred from the water to the thermometer.

What units are used to express specific heat capacity?

TABLE 19–1

Specific Heat Capacities of Common Substances (in J/g·C°)

water	4.18	iron	0.45
aluminum	0.92	copper	0.38
carbon (graphite)	0.71	mercury	0.14

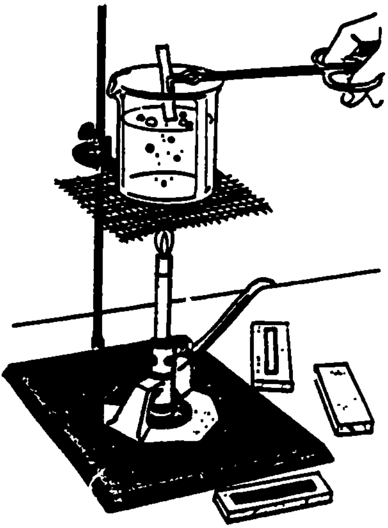


FIGURE 19-2.

Activity 19–2. Which metal holds more heat?

Materials: pieces of aluminum, copper, iron, beaker, ring stand, ring, laboratory burner, tongs, wire screen, paraffin, goggles, apron

Each metal piece used should be the same mass. Place the metal pieces in boiling water for five minutes. With tongs, remove each piece from the water and set it on a block of paraffin wax. Allow the pieces of metal to stand until they are cool.

Which metal melts the most paraffin? Which metal has the most heat energy? How are your results related to the specific heat of each substance?

Making Sure

5. How does a gain in heat affect the particles of an object?
6. What is specific heat capacity?
7. What is the symbol for specific heat capacity?
8. Metals are good conductors of heat. How does this property relate to specific heat values for metals?

19:4 Measuring Heat Energy

What measurements are made when calculating the gain or loss of heat?

Changes in the heat energy of a material can be measured. To find the change in heat energy, we measure the mass and temperature of the material. Another temperature reading is taken when the material is heated or cooled. Using the specific heat capacity of the material, we can find the amount of heat energy absorbed or released. The change in heat energy equals the temperature change multiplied by the mass and the specific heat capacity of the material.

Heat absorbed or released = *Change in temperature* × *Mass* × *Specific heat capacity*

$$H = \Delta t \times m \times C_p$$

Δ means change, so Δt means change in temperature. Δt equals $t_2 - t_1$ when heat is gained. When heat lost Δt equals $t_1 - t_2$.

Example Heat Calculations

Ten grams of water are heated from 5°C to 20°C. How much heat energy is absorbed by the water?

Solution:

(a) Write the equation for the change in heat energy.

$$H = \Delta t \times m \times C_p$$

(b) Substitute the values given in the problem for the temperatures and mass. The specific heat capacity of water is 4.18 J/g·C°.

$$H = (20°\text{C} - 5°\text{C}) \times 10\text{ g} \times 4.18\text{ J/g·C°}$$
$$= 15\text{ C°} \times 10\text{ g} \times 4.18\text{ J/g·C°} = 627\text{ J}$$

Example Heat Calculations

An iron pipe with a mass of 5 kg cools from 20°C to 10°C. How much heat is lost by the pipe?

Solution:

(a) Write the equation showing heat released.

$$H = \Delta t \times m \times C_p$$

(b) Since the specific heat capacity value contains grams as the mass unit, convert 5 kg to g.

$$5\text{ kg} = 5000\text{ g}$$

(c) Substitute the values for the temperatures and mass given in the problem. The specific heat of iron is 0.45 J/g·C° from Table 19–1.

$$H = (20°\text{C} - 10°\text{C}) \times 5000\text{ g} \times 0.45\text{ J/g·C°} = 22\ 500\text{ J}$$

Making Sure

9. Calculate the heat lost when a 100 g sample of aluminum foil cools from 75°C to 20°C. Use Table 19–1.
10. If the foil in problem 9 was cooled in 150 g of water, what is the heat gained by the water?

APPENDIX B

Pilot Study. Interview 1. Harry: entering eighth grade

Interview I. Harry, entering 8th grade

INTRODUCTION

L: Show you a model about heat phenomena. Do you know what a model is?

L: Could a map be a model?

B: Yes.

L: Why?

B: I think a model is something...smaller version something.

PRELIMINARY QUESTIONS

L: Do you know what heat is?

B: It's something hot. Something like hot.

L: Do you know what cold is?

B: Like ice, snow.

L: Do you know what temperature is?

B: It's a measure of heat. A measure of how hot.

L: Is there a difference between heat and temperature?

B: You can measure heat with the temperature.

PROBLEMS

L: I imagine you put a certain amount of heat into 100g of steel. The temperature increases by 10 degrees. If you put the same amount of heat into 200g of steel, what will the temperature rise be?

B: 20 degrees? I don't understand.

L: (repeat problem)

B: I think it might be the same.

L: Why?

B: I don't think it matters how big it is.

L: Take two containers, one big and one small; fill them with hot water. Does one have more heat than the other?

B: It's about the same.

L: Why?

B: Because you put the same water.

L: Imagine two pieces of steel, one twice as high as the other, but with the same cross section. You hold them, for a brief moment, on the same hot plate. If you had thermometers in them, what would they read?

B: I think the small one will be hotter. Because I think the bigger one takes more time to heat up.

L: Now imagine you drop them into identical cold water baths. You have thermometers in the water. What will they read?

B: The one that will have the smaller block will be hotter.

L: Why?

B: Because the small one is hotter.

PROBING CONCEPTUALIZATION

L: Could you draw a model of what happened when we heat the pieces of steel, and then cool them in the water?

[No response]

L: Imagine a flask of alcohol in a warm water bath.

L: What will happen to the level of the alcohol?

B: The temperature will go up. It might evaporate.

L: Will anything happen to the level of the alcohol in the pipe?

B: There will be steam.

L: What is that steam?

B: Alcohol that gets hot.

L: Do you think the level in here is going to rise? Have you seen what happens to thermometers?

B: The level rises

B: Is there a thermometer in there?

L: No but the alcohol in the pipe can work as a thermometer. Let's suppose that the level is going to go higher. Do you know why?

B: Because the heat is pushing it.

L: Anything else?

B: [No response]

L: Imagine you had a microscope and you could see what happens inside the alcohol. What would you see?

B: [No response]

L: What does the alcohol consist of?

B: Bubbles.

L: Have you heard of molecules?

B: Yes.

L: Do you think alcohol has molecules in it? What's going to happen to the molecules, seeing that the level will go higher?

B: They will grow bigger.

L: Actually they don't grow bigger. They just move faster and pushing each other further. That's why the alcohol expands. Do you know why they move faster? Is there anything in them that makes them move faster?

B: The same is going to happen in the warm water?

L: Can you make a model to show what happens in the molecules. Would you say that the water molecules have more heat?

B: Yes.

L: How does the energy of the water go to the molecules of the alcohol?

[No response]

L: Molecules collide with each other and redistribute their energies. Molecules with their speeds--this has more than that--they collide. Then that starts moving faster and this slower. After some time what do you think is going to happen?

B: All of them are going to move pretty fast.

L: Do you understand what energy is? What heat is? What it makes them do?

[No response]

MOLECULE ENERGY PROGRAM

L: Choose 1 fast and 1 slow. 2 circles collide. Then speeds are more or less same. Represent energies by a certain amount of dots in them. Draw a molecule with a lot of energy and one with a little. Then they collide. How will number of dots change?

B: More here (....)

CONTAINER PROGRAM

Heat and Temperature

L: Container. Has dots. What do they represent?

B: Energy.

L: OK. So, here we have many molecules--we don't see them because we are representing only the energy in them.

B: Is it possible to have a molecule with no energy?

L: Yes, it has to be in the absolute zero.

B: Will they still move?

L: No, they'll be like frozen--they will have no speed. No energy means they stand still. If you look with a microscope, you'll see the molecules. How will you know about the energy?

B: Speed.

L: So, in which substance will you have more energy?

B: In the hotter.

L: How can we in real life increase the temperature of an object?

B: Heat it.

L: What is going to happen in terms of energy?

B: Molecules are going to collide from the flame to the water.

L: How would you represent the energy in the molecules of the flame?

B: With the dots. They'll have many dots. And when...

L: And when they collide with the molecules of the water what will happen to the energy dots of the water?

B: They will increase.

L: What are we adding from the plate to the water?

B: Heat.

L: Which is?

B: The dots.

L: This is ZAP. Let's give it 2 zaps like hot plate. Why do you think temperature is undefined?

[No response]

L: It's because the energy is not homogeneous all over--it will show you the temperature only when all molecules have the same energy. What will happen to the molecules here compared to these?

B: They move faster.

L: In terms of energy?

B: There's more energy here than up there.

L: Now it's starting to spread.

B: How much energy will the molecules have? Is there a limit?

L: I don't think so. A molecule can move very fast.

L: Heat a substance. Temperature undefined. What would happen if we waited long enough?

B: There would be the same amount of energy in all the molecules.

L: This is called EQUILIBRIUM. Same energy in all molecules, thus the same?

B: Speed.

L: Correct. Do you think molecules are still colliding?

B: Yes.

L: Very good. Then we go to 2 containers.

L: Let us choose equal size containers. Temperature on the left = 20 degrees and temperature on the right = 50 degrees. How will the energy dots be like?

B: The one on that side will have more energy dots.

L: OK. You see? Same number of molecules?

B: Yes. Except more energy dots.

L: So that means that every molecule here...

B: Will have more energy dots.

L: Also what else will be different?

B: The speed.

L: You can actually see the speed. That's how they move.

B: Why don't they collide?

L: Actually they do--it's not clear but they do. Now choose the energy.

B: 100
L: The other one same size. Smaller energy (50). What will their temperatures be?

B: That one's hotter, that one's cooler.

L: Bring them in contact and see how they will behave.

Conduction

B: After some time they'll all be the same.

L: Will the energy dots move?

B: Yeah.

L: [Different example of conduction: Same size containers.] Where are the dots going to move from and where to?

B: They will collide.

L: The molecules will collide.

B: The molecules will collide but the energy will move.

L: How are they going to end up in terms of temperature?

B: The temperature is going to be the same.

L: And the energy dots in this--are they going to be the same or not?

B: Don't understand.

L: Here we have a lot of energy dots and here a few. We let them touch. Temperatures are going to be the same. Do it (computer)

B: Oh, there's going to be more in that side and less in the other side.

L: So you think they are the same at the end?

B: Yes.

L: Different problem. 2 containers. Same mass. (Mass = 2 units) T = 30 , T = 70 . (Case #1). Put in contact. They'll end up ....

B: Same energy dots and same temperatures.

L: What do you think the temperatures will be?

B: Will be 50.

L: Very good. It's the average.
Now, let us select two smaller containers, both with mass = 1 unit. Same temperatures as before (30 degrees and 70 degrees). The one with higher temperature has more energy dots. What will happen when we put them in contact?

B: They'll be equal. In energy dots.

L: How about temperatures?

B: Same?

L: What will the temperatures be?

B: 50.

L: Very good. Let's do it. You were right. Remember the previous ones. Were there more energy dots exchanged then or here? Or the same?

B: The same.

L: OK. I'll repeat the question. In the previous one we saw 2 containers but they were much bigger. However, they had the same temperatures [as these]. OK. And of course they had more energy units. And the energy dots moved from the hotter one to the other. And now we have 2 smaller containers having the same temperatures, and after putting them together we saw some energy dots moving from this one (at 70 degrees) to the one that was at 50 degrees, and my question is "Were there more energy dots exchanged in the first or this case?" In both cases some energy dots moved from one to the other.

B: Were there the same energy units in the other one?

L: I don't want to answer this question. Let's see that. Make 2 containers. One container is: m = 3 units, T = 20 degrees. The other one: m = 1 unit and we'll put the same T = 20 degrees in both.

B: Before they were both the same.

L: Yes, but how I want you to see that even though they have the same temperature, they have different number of energy dots.

B: Last time at the end they both had 900 energy dots each.

L: But, to start with...Here they have the same temperature only this one has more energy dots. Why do you think this is the case? Each molecule will have a certain amount of...

B: Oh yes--energy dots and there's more molecules in there.

L: Now do you think there were more energy dots exchanged when there were 2 big ones or when there were two small ones?

B: When there were big ones.

L: Why?

B: Because there were more energy dots and more molecules.

L: Very good. Now unequal containers. Same number of dots in each. What will temperatures look like?

B: The same.

L: Let's look. Seems that this one has higher temperature. Can you say why?

B: Maybe because it has more energy dots in a smaller size (?)

L: Which one has fewer molecules?

B: This.

L: However, we put the same energy in both containers. So, what will the energy dots (per) molecule be?

B: There will be more energy dots/molecule in this one.

L: How can you tell just by looking at their temperatures? If you don't know how many energy dots they have.

B: This.

L: Correct, but why?

B: More energy dots.

L: As you see I put the same amount of energy dots.

B: In the other one they're all spread out. That means temperatures will be lower.

L: So, one way to tell the temperature is how crowded the dots are. Can you tell me now the different ways of thinking about temperatures, molecules?

B: Speed of the molecules.

L: And the other one?

B: How crowded the energy dots are.

L: How about the energy? How can we tell which one has more energy?

B: This one will be hotter.

L: So you said that temperature is a measure of heat, which is energy. But here this container then should have more energy. Does it? Although it has a higher temperature.

B: No.

L: So, maybe we need to make a change in our conceptualization of heat and temperature. This just proved that temperature is not a measure of energy. How can you tell the total energy of a substance? I'll help you. It has to do with energy dots. It's the total number of energy dots. Depending on how crowded they are we can tell the temperature.

L: 2 containers; one is twice as long as the other. Can you define energies so that the two are the same?

B: If this one were 50 energy dots, that one would be 100 energy dots.

L: Very good.

Review

L: Here we have 2 containers, 1 is twice as big as the other one and we have put the same number of energy dots (same energy) in them and we see that their temperatures are different. Which has the higher temperature?

B: The small one, because the other one has more molecules and less energy per molecule and the more energy dots per molecule the higher the temperature.

L: If they had the same crowdedness in terms of dots, that is, the same temperature, will one have more energy in it?

B: This one (the big) will have more energy.

L: Yes, explain.

B: Because you need more energy dots because there is a bigger amount of molecules in the big one.

L: Yes...and each molecule will have the same number of energy dots, thus more molecules...more energy in total. So, if we put them in contact (refer to the screen), what is going to happen?

B: They jump from this side (the more crowded) to this.

L: Until...

B: Until there is an even amount of energy in the 2.

L: So you mean we will have the same number of energy dots in here as in here?...

B: No...the same temperature in the two. The same amount of energy dots per molecule, however.

L: Exactly. So what will happen here (when in contact)?... Which is bigger?

B: The temperature will go higher.

L: How about total energy units? Which one will have more energy?

B: That one (the bigger).

L: Very good.

<u>Zapping</u>

L: Now, let's start from the beginning. We have 2 different sized containers. Let's put the same temperature (1) 50 degrees, (2) bigger, 50 degrees.

L: So they have the same temperature which means the same...

B: Same amount of energy. No, the same amount of energy dots per molecule.

L: Very good. If we did not know what it says up here, how would we know that they have more or less the same temperature from the way the energy dots look?

B: The crowdedness.

L: Very good. Now we are going to add a certain amount of energy or energy dots in each. Let's put 2 zaps in the first, so it immediately adds a lot of energy dots at the bottom. Temperature is undefined because...

B: Because the energy has not spread around.

L: OK. Now it was 300 energy units and we added 200 (2 zaps) and now it is 500. So, the temperature from 50 became 83.33. Now let's add the same amount of energy into the other one. What will happen in terms of temperature?

B: It will be undefined.

L: Yes, correct. But how will it compare to this one?

B: It will be a higher temperature over here (in the smaller).

L: Why?

B: Because there is more energy dots per molecule.

L: Thus, if this is 83.33 degrees, this one will be less.

B: If you want to make it the same temperature you have to add more energy dots.

L: Let's do something else. 2 different sizes (one twice as big as the other). Same number of energy dots, i.e., 500 energy dots in each. So the bigger one has a lower temperature. Why?

B: Because it is spread to more molecules.

L: An actually what happens here (small)?

B: The temperature is twice as much as in the other.

L: Very good.

L: And then we zap them again. (1 zap = 100 energy dots) The temperature will increase. So if we add here (in the other one), where will be the larger temperature rise?

B: I don't understand. Do you mean which one will have a high temperature?

L: No, if one (small) was 40 degrees and the other (big) was 20 degrees and this became 50 degrees.

B: Oh. The big will increase less than the small one.

L: Let's see it. Yes, you were right. Another problem: 2 different sizes (1 and 3), same temperature (e.g., 30 degrees in both). We see the one to the right (big) has more energy in it and in terms of crowdedness...

B: They are the same.

L: Now, what would you do to increase these two temperatures by the same number of degrees (to make them go higher in temperature by the same number of degrees).

B: I don't know how to make it exactly...

L: No exact numbers, but the same increase.

B: You have to give this one for example, 1 zap and this one 3.

L: Let's do it...OK, this one became 63.33 with 2 zaps. In order to make this (the other) 63.33.

B: We give it 3 zaps. No we give it 6 zaps.

L: Yes...63.33. Very good. Excellent!!!

TASKS

Task #1.

L: From the way they look, which one has the higher temperature?

B: The one on the left.

L: OK. That's the case. The left one had 40 degrees, the other had 20 degrees. Go to number 2.

B: I could do that.

Task #2.

L: Fill the container on the right so that its temperature equals 40 degrees. How many energy units do you need? They have the same size. I don't want the exact number but should we put more or less?

B: Less.

L: Correct. If this one has 720, maybe let's guess a number.

B: Let's stick in...600?

Task #3.

L: Very good! Great! Escape. Go to task 3, 1 mass unit, temperature equals 60 degrees; we need to fill the one on the right so that temperature equals 60 degrees.

B: (Does it)

Task #5.

L: Very good. So we go to task 5. Bigger one has higher temperature, lots of energy units. The container on the left got 5 zaps. The temperature was 40 degrees and became 540 degrees. So each zap was?

B: 100 energy dots.

L: So, let's see...It went from 90 degrees to 123.33 degrees.

B: I think there's something missing.

L: Something is missing. I guesss what it wants is the number of dots that we need to add to it to get to this temperature.

B: I think we need 1000 energy dots -- 10 zaps.

L: Let's try that. (does not work) One more try: Task #5.

Excape and go to number 6.

Task #6.

L: We have same mass. This one is higher [in temperature]. Before equilibrium container on left has temperature = 5.

This is for conduction, we're going to put them in contact and after a while the one on left will be 35 degrees. Since this one is hotter it will give energy to that one, so it will increase the temperature and the number of energy units.

B: Temperature will be 35 degrees and energy units will be 210. Because it's going to be the same.

L: Say this one was bigger and, after equilibrium, was 35 degrees, that one would have 35 degrees as well. Which one would have more energy units?

B: That one...wait...The bigger one.

L: So they have the same temperature because they're equilibrated but they also have the same number of energy units because they are the same mass. Let's see conduction... Very good. And the answer.

B: 35 degrees.

Task #8.

L: Let's see what number 8 is. Different masses. We might be able to do it. I don't want exact numbers. This one has higher temperature. After it contacts that one it will give some of its energy. This needs calculator.

B: How could it have...Is that 33.33 degrees? Oh yeah, it must be.

L: It must be between 30 and 40 degrees. Let's predict. If we put them in contact, what will the temperature on the right be?

B: 33.3 degrees.

L: How many energy units will there be?

B: This one will have less--will give 80 over here.

L: Very good. That's the end of this program.

SPECIFIC HEAT

L: Now we're starting something new that you haven't heard before. Each molecule has a certain amount of energy which we represent with dots. What does the molecule that has energy do?

B: It moves around.

L: The energy that makes it move is called kinetic energy. There is another kind of energy that makes it vibrate. If we give a certain number of energy dots to a molecule, some of it will be consumed to make it more and some to make it vibrate. However, different substances vibrate a lot and some vibrate very little. So, if we give a certain number of energy dots to a molecule that vibrates a lot, it will consume very little for its speed and most of it to make it vibrate ok. So, say we have 2 different molecules of 2 substances, one which vibrates a lot and one which vibrates a little and we give them say 100 energy dots, the one which vibrates a lot, will consume say 80 out of 100 energy dots. So, how much will remain for motion?

B: 20.

L: So if we see this molecule, what are we going to see? It's moving very slowly.

B: And vibrates a lot.

L: And the other one that vibrates a little will consume 40 for vibration and the remaining 60 will make it move. So it'll move very fast. So, their speeds will be different. Which we have in this model is 2 molecules and as you see, a molecule is not like a ball. Do you know about atoms? Here, set the speed. Kinetic energy is how fast it moves. We have 2 materials. Choose A, B, C, or D. Make it move very slow. The other one, make it move fast. We see 2 circles. They start moving. This makes big steps and that means it moves...

B: Very fast.

L: Right. Here they bounce and the green one...

B: They exchange energy.

L: OK. They redistribute, not exactly exchange, but the one that moves slowly will start moving much faster.

B: That one seems to have lost a lot of energy.

[problem with the program -- we quit]

L: Speed has to do with what?

B: Heat oh...temperature.

L: Right. So, if we add a certain amount of energy to a molecule that vibrates a lot, what will the temperature difference be?

B: Higher?

L: Are you sure? Let me put it differently. You have 2 molecules--one vibrates a lot and one vibrates a little, but they both have the same speed. So the total energy is different (if you add the energy that makes it vibrate and the one that makes it move). They move at the same speed, so they have the same temperature. If we give them, say, 100 energy dots, which one will increase in temperature more?

B: The one that....vibrates less?

L: Very good. Exactly. The one that vibrates less will spend more of the energy given to its speed. So it will move faster so the temperature will be higher. In reality, you have water and alcohol. If you heat the same amount of alcohol and water and heat them for the same amount of time, you start with both at the same temperature. Give them the same amount of energy. Alochol will go up more than the water. Do you know what's the explanation of that?

B: The molecules of the alcohol vibrate less so they move faster.

L: Very good. Most substances around us have different vibration and kinetic energies. So if you give them the same amount of energy they will consume them differently and the temperature will increase differently. Here (circle) the green part is the kinetic energy and the rest is vibration energy. Let's bounce them. What'll you see.

B: The green will be moving slower.

L: Yes, how in terms of total energy is this circle going to be the same size?

B: No, it'll be smaller.

L: It'll be smaller. Yes, and the other one will be bigger. However, the proportion of kinetic and vibration energy will be the same. What happened? We added some energy. The same amount here and here. The whole thing is smaller, but the proportion of kinetic and vibration energy is the same. Press S. The line represents the vibration energy. They hit and you see the green became bigger and the other one smaller. However, the proportion is still the same.

APPENDIX C

Pilot Study. Interview 2. The Newton North High School students: tenth grade

M: I want to ask you a few things about heat and temperature and I'll show you a model....Don't try to be scholarly or anything. So, the first question is: what do you see as the different between heat and temperature?

S: Temperature is like a measure.

S: Temperature is the measure of the heat, which is like the molecules moving around and how fast they do it. And then heat is energy. Temperature measures the change in energy.

M: You talked about the molecules moving around. Is that heat or temperature?

S: That's heat.

M: And the temperatures measures that?

S: No, it measures the more motion of the molecules.

M: So the hotter the substance the faster the molecules?

S: OK, all right.

M: And the temperature is related to the velocity of the molecules.

S: Yes.

M: What about heat? How does this relate?

S: Heat is the energy of the molecules.

M: The energy generated by the molecules?

S: By the collisions.

M: So, the molecules are colliding.

S: And they give out heat when they collide.

M: Now a little problem: If I put 200 cal. in 100 g of water and the temperature rises 2 degrees. Now if I put the same amount of heat (also 200 cal.) in 200 g of water, what will the increase in temperature be?

S: 1 degree.

M: Suppose that you have 2 pieces of steel and the only difference between the 2 is that one is twice as high as the other and I keep them on a hot plate together for the same amount of time. Not very long so that they don't get extremely hot. Then I take them and put them into 2 identical baths of cold water. Two questions: (1) If I put two thermometers in each piece of steel, what would the two thermometers read?

S: The smaller one will be twice as hot and the larger one will be less.

M: Why is that?

S: Because there is less steel to heat up.

S: And the collisions are in a closer surface, not as much of a surface. But there are more collisions, more heat energy (in the surface).

M: Now if I put them both into the same bath (2 baths) of cold water? And record the temperatures of the baths, what are those temperatures going to be?

S: The one with the smaller steel will be hotter.

M: Why is that?

S: Because the steel is hotter. Because it gives off more heat because it is hotter.

S: It would seem that they should be the same, since it is the same amount of heat going into them, right? So therefore the steel should be the same and the water should be the same, but maybe if it's a smaller space it wouldn't be the same.

S: Maybe the small bit of steel will be better than the larger piece of steel, but it's actually the <u>same amount</u> of heat, the water temperature will be the same because it's only the same amount of heat.

M: The next thing is: If I had a flask containing alcohol with a very thin neck and I put it into a hot bath and I watch the level of alcohol. Do you know what's going to happen?

S: It goes down like a little teeny bit, evaporating at the top.

M: No, suppose it's not evaporating.

S: Let's see, heat from the hot water would get into the alcohol. Alcohol would get hotter.

S: I think it'll get higher.

S: Heat would do something to the alcohol to make it rise. I don't know what.

M: What exactly does it mean when you say the heat goes from the water to the alcohol. If you look inside there with a microscope, what you would see?

S: OK, the water heats up the glass, then the glass molecules will speed up and they they'll hit the alcohol molecules, which will also speed up.

M: OK, very good. It is true that molecules collide but we don't have it on the model. Do you know what a model is?

S: An example. A non...

M: Yeah, it's not real. So it doesn't show everything. So, we chose not to show you one or two containers of liquid at a time. You can choose their mass. 1, 2, 3, or 4 units of mass. Dial 2 containers of equal masses. Then you have the choice of same material or different material. Let's say the same. Then we choose the total energy of the containers, let's say 400. Energy for the other 600. One confusing thing: these dots are not molecules. What they are is energy units. This represents the energy that the molecules have. Then if you choose the option "view" you can look at the molecules inside. Let's now switch to this container and look at the molecules. What is the difference going to be?

S: They'll be faster.

M: Faster, right. But they are the same number of molecules. What about temperature?

S: This one is going to be hotter, because it's moving faster and colliding more.

M: Which one has more heat?

S: The one with more energy.

M: OK. Now we're going to try 2 different masses. Go ahead! Same total energy. You've put the same number of energy units in both but this one is larger. When you're going to view things what's going to happen to the molecules?

S: This one will be hotter.

S: Faster molecules, more collisions, hotter.

S: ...'cause there's less space.

M: And you can see that [S presses view]. Does one have more heat than the other? You told me something like temperature measures the heat.

S: No, that's not true.

M: So, what's going on?

S: Temperature is a measure of ....

S: Temperature would be a measure of how fast the molecules are moving?

M: So, do you want to stick with that?

S: Yes, I suppose.

S: 'Cause they're moving faster here and it's higher. So, I think that sounds OK.

M: OK, so what about the heat then?

S: Then heat would be what was given off by the moving molecules...
[FIRE ALARM]

M: So we agreed that temperature is a measure of the speed, in fact the energy of the molecules. But are these related to the number of energy units?

S: No, because they're the same here and the temperature is different.

M: So, which one has more heat, or do they have the same heat?

S: Then it would make sense that heat would have something to do with the energy units.

S: I think that the small one would feel hotter. Although they have the same total energy. But it would feel hotter, because it's more concentrated, the temperature would be higher.

M: OK, so what is it that's more concentrated?

S: The energy.

M: Does one container have more molecules than the other?

S: Well, mass units, yeah--because you punched it m____.

M: So more mass units means more molecules.

S: Not necessarily.... (half finished sentence; collisions between a smaller and a larger object....)

M: When we are dealing with the same material, if you have more mass you have more molecules.

S: OK

M: Now let's have the same masses. 2 and 4 and program them to the same temperature. Now, what do you think the number of energy units would be like?

S: This would be more. 'Cause it's more space. And it has to have more to get it up to the same temperature.

M: Indeed you have more energy units. They have the same temperature. What is the same in the two containers?

S: The same amount of collisions.

M: I'm not sure. If we view the windows, what are we going to see?

S: The same speed?

M: So it's like the same kind of collisions? But what has more molecules?

S: This.

M: So, there are more molecules and there are more energy units and the molecules have the same speed. So, each individual molecule has the same amount of energy as each individual molecule here. But there are molecules so they need more energy units. So, in the one we did before we had the same energy units in a different number of molecules. So, they were more crowded here. So what about each individual molecule in the one before?

S: I guess if you like compress it into one that size, it would be twice as hot.

M: Yes, OK, because each molecule here would end up with more energy for itself than here. Now, what about heat?

S: Isn't heat like it's hot and cold?

M: Well, let me do one more thing. Let's try zapping. Same material, same mass units and choose the temperature. Press Z for zap. Zap means a certain amount of heat that you put in. Before you do it, what are we going to see here?

S: Increase in heat, increase in collisions.

S: Faster molecules, higher temperature.

S: More energy units?

S: More mass energy.

M: There would be more mass?

S. No, if heat would make it (other S's. No, no....) expand.

M: Does expanding mean more mass?

S: No, more space. But the same amount of heat and same amount of energy.

M: So can you ever increase the mass of anything by heating it?

S: No, unless you add something to it but not by heating.

M: So, what is heat?

S: It's the energy to raise 1 g of something by 1 calorie or something.

M: No... that's calorie. Calorie is the heat to raise 1 g of water by 1 degree. But what *is* heat?

S: The thing I'm confused about is the energy units.

M: So, would that be related to temperature at all?

M: Yes and no. Think of it as little packages of energy of motion. Each molecule has its own energy and all molecules in here share these 384 energy units.

S: So if you raise the energy units, then they would go faster, then that would raise the temperature.

M: That's right. So, when you put heat in.

S: You're adding more energy.

M: You're adding more energy to the container and we'll do it from the bottom, so you're going to see that the dots are going to increase. Then what's going to happen?

S: Why is the temperature undefined?

S: Because it's only some molecules in the bottom that have more energy.

S: It's not dispersed.

S: So would it eventually move up?

M: Yes. So, it's undefined because if you open the window here and there, what would you see?

S: There would be faster moving molecules at the bottom.

M: So what about the temperatures at the bottom and the top?

S: The temperature at the bottom would be higher.

M: Yes, and that's why it's not defined because for the whole container there is not a single temperature. So that's really like putting this on a hotplate. You put energy in it which means you put heat in it.

M: When we say the dots move, there are not real dots. So what is that's really physically happening?

S: The molecules are hitting each other and when they hit each other harder, they'll make the other one go faster.

M: So, when you have a hotplate, you're really putting this in contact with very fast molecules in the hotplate. Have you ever heard of thermal equilibrium? What is it that's equal?

S: The overall speed.

M: The temperature is the same which is like saying that the molecules are moving at the same speed and then the temperature is defined and you can see the temperature is higher. So, there are more energy dots and they are more crowded. So, each molecule has more energy to share. Now we want to zap 2 different size containers.

S: So, when we zap you add heat?

M: Yes.

S: And we know that when you add heat, you're also adding energy.

M: OK, so what's the relation about energy and heat?

S: Well, I'm still not clear on heat.

M: So both have the same temperature and one is bigger than the other. Suppose you wanted to raise the temperature by the same number of degrees in both containers. What are you going to do? OK, suppose you put the same dollops in both, what's going to happen to the temperatures of the two containers?

S: They'd both raise, the second one not as much as the first.

S: Or maybe, you'd get this temperature <u>before</u> you get this one, by the time it gets to equilibrium.

M: So, you put the same dollops of heat in both, we wait until they equilibrate, what are the temperatures going to be? The same?

S: But they had the same temperature before and they got the same amount of heat. So....the same.

S: But they're not the same size. So the little one should get hotter.

M: But you put the same amount of heat to both of them. [They do the zaps]. Now, which one has more energy units?

S: The larger one.

M: And which one is hotter?

S: The smaller one.

M: So, is that a problem?

S: Well the smaller one has a smaller space.

M: Which means fewer molecules, OK? Try to think about mass and not space. So this one has less mass and it has less energy units.

S: Does this mean that energy units is not really related to temperature?

M: Well, it's related but it's not the same, right? So how can you bring the temperature of that to be the same?

S: Adding more energy.

M: So add one [they do it]. So, although it's still a little confusing, it's clear that temperature and energy units are not the same thing. But there _is_ a relation between dots and temperature. So when 2 things have the same temperature, what is it that holds true about the energy dots?

S: They're faster?

M: Not the dots--what's faster is the molecules.

S: The same amount of dots?

M: No...

S: The same amount per region?

M: That's right! The temperature is related to the amount of dots per region--to how crowded the dots are. But the number of energy units is important too. But what are the total number of energy units?

S: The heat?

M: So now does temperature measure heat?

S: No, it measures the crowdedness.

S: How much heat there's in a certain region?

M: So, the heat is really temperature. The more crowded, the higher the temperature. Because, if it's more crowded, each molecule has more energy. So, the temperature is really the energy of motion of each molecule, of <u>one</u> molecule. So, the heat would be what?

S: The total.

S: The number of molecules.

M: No,...

S: Of energy.

M: Yes. So now if you have a few molecules that move fast.

S: So the heat is like a bigger version of temperature. The heat is like total and the temperature is like a segment.

M: A little one and a big one. So what is it that's the same on both sides?

S: Temperature.

M: And how about the dots?

S: They are the same concentration.

S: And there would be more heat on this side.

M: Very good. Now let's go back to your collisions. You said that as the molecules were colliding they were generating heat. Do you still believe that?

S: No.

M: So what is heat?

S: The amount of energy in a certain...

S: It's the overall...if you take like...the amount of energy units in a whole thing...not in a region.

M: So, is it generated by the collisions you think?

S: If there's more heat there are more collisions and if there are more collisions then there's more heat.

S: If there were more collisions this would mean that there are more molecules per region. So then the temperature would be higher, if there are more molecules per region.

M: We haven't addressed that because it's always the same number of molecules per region, because it's the same material. Suppose you had 2 different materials and one had more molecules per region and the other one had less molecules per region. That gets tricky, right? If there are the same number of energy units, then the temperatures are going to be different.

S: But if they had the same energy, and there were a lot of molecules here and a few here.

M: Per region?

S: Per region. But if this had a few but heat had a lot of energy and this had a lot but it had a little energy, it could balance out and have the same temperature.

M: And this actually happens when you have 2 different materials. What heat is really is the amount of kinetic energy transmitted from the hotter thing to the colder thing. It's not that it make the molecules move faster, the heat itself is that energy.

S: So, to measure the amount of heat what would you use?

S: So, like what we did with the alcohol and the water? If the water was warm, then it would rise depending on the energy units that would go into the alcohol.

M: You put the alcohol flask into the water, and the energy units go from the water to the alcohol until the molecules of the alcohol have the same energy as the molecules of the water and then the level will stop. But how does the level rise? Is the mass of alcohol changing?

S: No, but the molecules are moving quicker--will that make the levels rise?

M: Right, they move faster, so they need more room.

S: So how do you measure heat?

M: What is called a calorimeter. It's a fixed amount of water and to measure the heat given by something hot, you give heat into the water and you see how much its temperature changes. But the temperature change is not the measure of the heat. It's a derived way of measuring the heat. Now let's go back to my question about the two pieces of steel. They were on hotplate for same amount of time.

S: The heat would be the same but the temperature wouldn't?

M: At the beginning they look like this--same crowdedness, same temperature. And then you put the same amount of dots in the little one and the big one. And this gets more crowded, so the temperature is higher. Now what happens when you put them in the cold water bath?

S: The bath will reuse the same because they have the same amount of energy.

M: Now the energy will move back from the steel into the water and once they gained the same amount of dots, they increase by the same temperature and in fact the water bath is a calorimeter. So what did you think of this?

S: It was good. I think it made us understand.

M: I think in an hour we did a lot! You must be tired. Any comments?

S: What you said before with the windows.

S: A little number in the bottom showing the speed of the molecule.

APPENDIX D

Pilot Study. Interview 3. The Braintree High School students: ninth grade

The Braintree High School Group : ninth grade

PRELIMINARY QUESTIONS. PROBLEMS. PROBING. CONCEPTUALIZATION

E[1]: What is the difference between Heat and Temperature? What is Heat and what is Temperature?
B: Temperature measures Heat.
B: ...and Heat is the absence of coldness.
G: I can't describe Heat but I know what Temperature is.
B: Temperature is the amount of Heat.
E: What is the difference between Heat and coldness?
G: Coldness is lack of Heat.
E: Is it lack of Heat or is it a thing in its own right?
G: I think they are opposite.
E: Problem: 200 calories in 100g of water. Temperature rises by 2. If you put the same amount of Heat in 200 g of water. What is the Temperature rise?
G: 1.
E: Problem with the hot plate and 2 pieces of steel (one twice as tall as the other)(see interview #1). Then put them in water. What are the Temperatures of the two pieces of steel? What are the Temperatures of the water?
G: The thermometer in the taller one will rise higher.
E: Why?
G: It's more, the heat touches the metal and heats the air around the thermometer.
E: Does everyone agree? Why more heat in the taller one?
G: Because it is taller and it gets hot because it has more metal.
G,B,B: The smaller is hotter.
B: The smaller will heat up quicker. The bigger one has more mass.
E: [In water bath.]
B: The Heat is going to get out from the metal to the water.
B: The smaller one will make the water hotter.
G: The taller one.
E: Flask with alcohol into water bath.
B: It is going to rise, because when something heats up the molecules they are going to expand.
E: What does it mean? Do molecules grow?
B: There is pressure inside...
G: When they are cold they don't push each other so much. Heat will make them separate.
E: Why? How does Heat do that?
B: Chemical change?
E: Have you ever heard of models?
G: Diagram to express what we're trying to say.
E: Why is a diagram more helpful than reality?

---

[1] B stands for one of the two boys and G for one of the two girls. E stands for experimenter. If some answers seem contradictory, it is because they were made by different students.

PRELIMINARY QUESTIONS, PROBLEMS, PROBING, CONCEPTUALIZATION

E[1]: What is the difference between Heat and Temperature? What is Heat and what is Temperature?

B: Temperature measures Heat.

B: ...and Heat is the absence of coldness.

G: I can't describe Heat but I know what Temperature is.

B: Temperature is the amount of Heat.

E: What is the difference between Heat and coldness?

G: Coldness is lack of Heat.

E: Is it lack of Heat or is it a thing in its own right?

G: I think they are opposite.

E: Problem: 200 calories in 100g of water. Temperature rises by 2. If you put the same amount of Heat in 200 g of water. What is the Temperature rise?

G: 1.

E: Problem with the hot plate and 2 pieces of steel (one twice as tall as the other)(see interview #1). Then put them in water. What are the Temperatures of the two pieces of steel? What are the Temperatures of the water?

G: The thermometer in the taller one will rise higher.

E: Why?

G: It's more, the heat touches the metal and heats the air around the thermometer.

E: Does everyone agree? Why more heat in the taller one?

G: Because it is taller and it gets hot because it has more metal.

G,B,B: The smaller is hotter.

B: The smaller will heat up quicker. The bigger one has more mass.

E: [In water bath.]

B: The Heat is going to get out from the metal to the water.

B: The smaller one will make the water hotter.

G: The taller one.

E: Flask with alcohol into water bath.

B: It is going to rise, because when something heats up the molecules they are going to expand.

E: What does it mean? Do molecules grow?

B: There is pressure inside...

G: When they are cold they don't push each other so much. Heat will make them separate.

E: Why? How does Heat do that?

B: Chemical change?

E: Have you ever heard of models?

G: Diagram to express what we're trying to say.

E: Why is a diagram more helpful than reality?

---

[1] B stands for one of the two boys and G for one of the two girls. E stands for experimenter. If some answers seem contradictory, it is because they were made by different students.

G: You can try things on it.

E: Mostly it's simplified. Only some aspects of reality are represented, while lots of other aspects are eliminated.

CONTAINER PROGRAM

Work with "same" substance. Choose two containers. Choose mass units: how much liquid. For example two equal mass containers. You can choose Temperature or choose total energy.Heat is a form of energy. You must know that molecules have energy. Molecules are moving fast or slow. If a lot of energy they move fast if not. slowly. Let's set the energy first. Choose 200 units of energy. These dots are energy dots not molecules, they represent amount of energy. Choose 200 units here and 300 units there

B: Why do they move?

E: It means energy can be exchanged between molecules. If a fast molecule collides with a slow one, what will happen?

G: The fast will slow down and the slow will speed up.

E: energy dots are moving... it's not that the energy travels by itself. It's molecules are hitting each other and transmitting energy. That's why the dots are moving. Is one container hotter than the other? You don't seem convinced.

G: The molecules are more expanded.

E: No. You have fallen into the trap. These are energy dots not molecules. You don't see the molecules. In fact because they have the same mass, these containers have the same number of molecules. What about the Temperature?

G: The hotter is on the right.

E: Next,you can VIEW the molecules. Moving at certain speed has to do with how much energy. 200 units are shared by all the molecules. Open the window in the other container. What will the molecules do there?

B: They are going to move faster.

E: Right. More,fewer,same number of molecules?
[Some say same, some say more].

E: In fact,they are going to be the same.

B: Oh,because the one on the right has more Heat not more molecules.

E: Right. The number of molecules is related to the mass and the mass is the same. So, the Temperature is higher, molecules are moving faster and there's more energy. Let's try 2 containers with different masses; Let's set the energy. The same in both containers this time. Does one container have more molecules than the other?

B: No.

G: No. they have the same mass in both.

E: Same mass? Are you sure?

B: Oh no, one is bigger than the other.

E: Right, this has 3 mass units and that 2 mass units. They have the same energy. What do you think the Temperatures are going to be? What about the speed of molecules?

B: The one that has less molecules will have more... Heat or Temperature.

E: What about the speed?

B: Molecules will move faster.

E: Why does this one have a higher Temperature? What does it mean in physical terms? This one has the same energy and fewer molecules. So, each molecule has more energy for itself. That's captured visually by the fact that the dots are closer together. Temperature is not related directly to the number of energy dots but to how crowded they are. Let's VIEW the molecules. You were telling me that Temperature measures Heat. You also told me that these energy units are Heat. So what do we have here? Energy units are the same so we have the same Heat, but the Temperatures are not the same.

G: There's the same number of energy units but the Heat is how fast they (the molecules) move.

E: What about Temperature?

G: No, sorry, I mean Temperature! Temperature is higher, because energy units move faster.

E: Energy units don't move.

G: Yes, the molecules.

E: How about Heat? Same or more in one?

G: This sounds stupid, but the Heat is the same amount but one has higher Temperature.

E: It's not stupid at all. That's exactly right. So T doesn't measure Heat.

B: It measures the amount of energy.

E: T measures amount of E? How do you compare energy with Heat? They are the same right? So,it's more like the Heat *is* the amount of energy. We'll run one more of these. Set the conditions.You want to do that? Choose 2 different size containers, 2 different Temperatures. We are going to see what the dots look like. One has 2 mass units, the other 4 mass units. One has T:50, the other T:60. What do you think the energy dots will look like? Will one have more? Will they be equally crowded?

G: The first container will be a little more crowded.

E: Why is that?

G: Because it's smaller...the molecules will move faster.

E: The big container which has higher T will have faster moving molecules. How will the energy dots look? Which one will have more energy dots?

G: The one on the left.

E: Because it's smaller?

G: It will be more crowded. We only put in 10 more degrees in the other one,that's twice as big. So, it's not going to be as crowded.

Other G: I think the small one will probably be more crowded.

E: Why?

G: Because it's smaller and it's at 50 and that's not a big difference and the other one is twice the size.

B: The bigger one will have more energy dots.

E: OK. Why do you say that?

B: Because it's at 60 and the other one is at 50.

E: So you think the Temperature is related to the number of dots?

Other B: The small one.

E: Will have more energy dots?

B: More crowded.

E: Even if they were more crowded,they are in a smaller space, so does this make it more dots necessarily? [Computer shows]

B and G: The bigger one has moe dots.

E: This one has 1440 and this one has 600 only. But what you have to differentiate is how many dots there are and how crowded they are. In this case,which one has more crowded dots?

G: The one to the right.

E: So, the one to the right has more dots and they are also more crowded. Now, the Temperature on the Right is higher because we set it to be higher. What does it relate to? The fact that there are more dots or that they are more crowded? What could we do to decide which it is? We'll erase and choose other numbers.

G: Let's make the difference further apart so it's clearly visible.

E: I think we could set the number of dots.

G: The energy ?

E: Yes, that's the energy. Two containers, one is twice as big as the other. How could we choose the number of energy units in each to answer the question we're trying to decide? Do you understand what I'm trying to decide? Here are two hypotheses: Temperature is proportional to the number of energy dots or Temperature is proportional to crowdedness. I'm trying to see which of the 2 factors is related to Temperature. I put twice as many dots in the bigger container as in the smaller one. Which one is going to have more crowded dots, do you think?

Students: The one to the right.
The one to the left.
The left.

E: Why?

B: The one on the left has 100 dots and the other one 200 dots.

G: Is it one half of the other?

E: Yes.

G: Then they'll be the same.

E: Aha! Are they going to have the same Temperature?

G: The one on the right...Because it has more dots. Let me think...

B: The one on the left will be hotter. 200 dots. The one on the right is 200? Then they'll be the same Temperature.

E: Why?

G: Because this one is 1/2 of that one and they have the same amount of energy.

E: No, the amount of energy is the number of dots, so we have a greater amount of energy here than here.

G: But in a greater space.

E: Yes,so what is the same? It's not the total amount of energy.

G: The Temperature is the same.

E: I believe you but I'm curious about how you knew that.
The speed will be the same because the Temperature is the same. How about Heat?

G: The amount of Heat is the number of energy units.

E: That's right. So we have the same Temperature but different amounts of Heat. Let's go back to your deduction. The Temperatures are the same and the speeds are the same. How do you know that? You haven't looked at the speed yet, right?

G: The one on the left moves twice as fast.

E: Why? I thought the Temperature was the same as the speed of the molecules. Let's VIEW it first.... They are moving in the same speed because Temperature is measuring the speed of the molecules. Try to tell me why you thought they would be faster.

G: I thought the Temperature would be the same, If one is 200 units and the other 100 units then that would move twice as fast.

E: You thought that, if you had twice as many molecules and they were twice as slow, then the Temperature would be the same. You still think that Temperature is a measure of Heat. But if you give up that idea and accept that Temperature is a measure of the speed of the molecules and Heat is the number of energy units, then it would be clearer. Now what makes these two containers have the same Temperature. We have twice as many dots in a container twice the size. There is something that's the same about the energy dots in each container.

G: They look the same.

E: What makes them look the same?

G: They are the same amount apart from each other.

E: Right, exactly.

G: Is that all you were trying to get me to say?!!!

E: Yes.

G: That was stupid.

E: They are equally crowded and that's related to the Temperature. What this means is that if you divide this into little regions, each region is going to contain the same number of dots. Each region contains the same number of molecules. So, if you have the same number of energy dots with the same number of molecules sharing them, each molecule is going to have on the average the same energy, and that's why Temperatures are the same; because Temperature measures the average energy of one molecule. Does that make sense? That also means that in order to have the same Temperature in two containers of different sizes, you need more energy in the bigger container, obviously, and therefore you need more Heat.

Now we are going to ZAP energy into the containers. We want two different size containers at the same Temperature. So, it's the same as before: We are going to have more dots on the right than on the left. Now we are going to ZAP energy - the equivalent of putting them on hot plates. ZAP one container at a time and put one zap at a time. Each zap is 100 energy units. Where are they going to start?

G: ....

E: At the bottom. You then see the dots spreading up. It's saying "in the process of equilibration". What does it mean equilibration?

G: It's equal.

E: Yes, something is becoming equal, what is it?

G: The dots... (??)

E: Yes, the spacing between the dots. You start with very crowded energy dots here and less crowded there. Then some of these move up and they become equally crowded. What does this mean in terms of Temperature?

G: It gets hotter?

E: When we put the energy dots in the bottom at first, if you have a thermometer here and one here, what would they read?

B: The Temperature.

E: Yes, but what would the Temperature be at the bottom and the top?

B: The bottom would be hotter.

E: Which makes sense, because the energy dots are more crowded, so each molecule has more energy. Then what does it mean that the energy dots are moving up? You have the fast moving molecules at the bottom hitting the slow ones at the top and giving them some of their energy.

B: That needs some time.

E: Exactly, that was my next question. Before you zap the container on the right, you see that the Temperature of the container on the left went from 8.33 to 13.56. What do you think this Temperature is going to be compared to the one on the left?

B: Higher?

E: Why?

B: More energy units.

E: So you think that just because there are more energy units, the Temperature is going to be higher. (to another child) You said less, why? Before we zapped they were at the same Temperature and then we gave the same number of energy dots in each side, so the same amount of heat.

G: .....the Temperature will be the same....

E: ...(?) Put the same energy in both and this is spread between more molecules in one case than in the other and so the Temperature is going to be lower.

Choose one unit mass container and a two unit mass container and try to raise them to the same Temperature. Let's try to raise them to 50°. What do we have to do in terms of zapping? OK which one has more molecules?

G: You want to put more energy.

E: Twice the energy units on the right than on the left?

G: Yes.

E: So you've pretty much understood it by now.

Go back to steel question. Two pieces of steel on the hot plate for the same amount of time. Is one going to be hotter than the other? How would you represent this with the model?

G: Like giving Heat.

E: So, what are you going to zap to mimic? If they stay on the hotplate for the same amount of time, does one receive more Heat than the other or the same amount of Heat?

G: ..same amount..

E: Yes, they will receive the same amount of Heat and now the smaller one is going to get hotter. So you zap both of them the same way. So, let's put one zap on both containers. So, the smaller one is hotter. Now if you put them in two containers of cold water, will one be hotter than the other?

G: ....(?) the hotter has faster molecules ......(?)

E: Yes but the other has more molecules, in fact we put the same amount of Heat in both and they are going to put out the same amount of Heat.

APPENDIX E

Interview 4. Adult subject: Andrea

INTERVIEW 4: ANDREA (24 year-old)

PRELIMINARY QUESTIONS

L: Do you know what heat is?

A: In general?

L: Yes.

A: I don't know....[long pause]...you mean like flame..or something like that?

L: OK...or what has heat in it?

A: Stoves...

L: What is cold?

A: The opposite of heat.

L: What is temperature?

A: Temperature is something that records heat and cold.

L: Is there a difference? If yes, what difference?

A: Heat is recorded by temperature.

PROBLEMS

L: (a) Take 100g of steel. Add heat. Its temperature rises by 10 degrees. Take 200g of steel; add same amount of heat. By how many degrees will its temperature rise?

A: 20 degrees.

L: (b) Take 2 containers (1 small, 1 big) with hot water. Does one have more heat in it?

A: No, because if you pour it from the pan into the 2 containers they have the same amount of heat.

L: (c) Imagine 2 steel block...[see interview #1]

A: The tall one is going to be half as hot as the other one.

L: Why?

A: Because it takes twice as much time to heat the taller one than it does the small one.

L: What happens if you put each piece of steel in a cold water bath?

A: The temperature of the small one (the bath that had the small piece of steel) is going to be twice as hot because the smaller block has more heat than the taller block.

L: So what will be the difference in temperature?

A: Probably twice as much (for the small one).

PROBING CONCEPTUALIZATION

L: Imagine a flask of alcohol in a warm water bath. The flask has a normal neck...what will happen to the alcohol level?

A: It will heat up, but not as much because alcohol takes a while to heat.

L: Will anything happen to the level of the alcohol?

A: It will rise.

L: All right. Can you tell me why?

A: There is some sort of chemical in it that will make it rise. I don't know exactly why...

L: If you had a microscope that would allow you to look inside the alcohol, a strong one...what would you see? What does the heat consist of?

A: Chemicals and water.

L: Have you heard of molecules?

A: Yes.

L: Do you think alcohol will have molecules in it?

A: Probably.

L: And actually that's the case. Everything has molecules in it. Everything. My skin, this table, the screen, wood, everything. Nobody can see them but they exist. Do you have any ideas about what happens to the molecules when they heat up?

A: They expand, that's why the alcohol rises.

L: So, what do you mean by expand, do they grow bigger?

A: Not bigger, big but they expand to a point where...just enough, so that...

L: Do molecules stand still, or move?

A: I don't know.

L: Molecules move and when you heat them up, they start moving faster. [Demonstrate with hands.] So by moving, molecules bounce into other molecules around them and they get further away and that's how the alcohol expands. Molecules that move faster also have a higher temperature. That's something that you should know. So, what do you think makes them move faster?

A: The heat.

L: Which is a form of what? Do you know that?

A: ....

L: OK, it is energy. Heat is energy.

L: So, a molecule that moves very little has...

A: Has less energy.

L: One that moves very fast has a lot of energy in it and also moving faster means a higher temperature too. OK?

A: Yes.

L: So if we go back to the alcohol/water example [Sketch molecules and arrows to explain what happens after the collision.], molecules of the hot water will hit molecules of the colder alcohol and after the collision they redistribute their energies. So this one will have...

A: More energy.

L: And higher speed, and the other less. And then this alcohol will probably hit another alcohol molecule, another of the same substance and it will give it energy, and after some time all molecules (in the alcohol container) will have an average energy and speed. Do you understand?

A: Yes, everything.

L: What do you understand about energy? What is it? Do you think you can see energy?

A: No, you don't see energy.

L: You can see...

A: I guess the boiling of the water which expands the alcohol, but you can't actually see the heat.

L: So energy, heat, is like a power that makes things move or acts on things.

COLLISION MODEL

L: Let's move to the model and see on a finer scale how 2 molecules behave. Set the speed. They move, one very slowly, the other fast. We see their trajectories. One made a very big jump meaning that it moves very fast.

A: OK.

L: Now, they collided. What do you think the green trajectory will look like now?

A: Faster.

L: And that's the case, and the red...

A: Is going slower.

L: You see they also change trajectories as well.
And their energies are represented with these numbers on the left. So, if we do it again the molecules start again with these speeds. The green one is gonna be really fast. Obviously...The other slow. They bounce...

A: Now it is the opposite.

L: Not exactly the opposite because they don't just exchange their energy exactly. The one that goes very fast slows down and the slow one goes faster. No, we see them again and again.

A: Until eventually they are just about the same.

L: Yes, exactly.

L: Also if we add the two numbers, ________ are their energies that make them move at a certain speed, they will always be the same. Because there isn't energy lost in the environment. At this point we are trying to modify a little bit this model and try to represent the amount of energy (heat) in each molecule so that you can see a representation of a molecule and be able to tell whether it has a lot of energy in it or not. A way to do that is to put a certain number of dots in it. Dots representing energy. So how would you represent this molecule over here?

A: With several dots.

L: And this...

A: With a smaller number.

L: OK and the only way that the number of dots in a molecule can change is by what?

A: The energy...actually...

L: How could one take some of these dots away from this molecule?

A: When they collide.

L: With something else that...

A: Has energy too.

L: But...

A: Less, less energy.

CONTAINERS MODEL

L: Good. Now let's move to the other model. We will deal with containers and not just molecules. So if a molecule has a certain amount of energy in it, we could represent with a certain number of dots. A whole container which has a lot of molecules in it will have...

A: A lot of energy in it.

L: Thus a lot of energy dots. So, choose 1 container. We can choose how big it will be, e.g., 2 mass units. And we can set its temperature or its total energy. We'll set the temperature.

A: Let's put it 70 degrees.

L: And it has energy dots. These are not molecules, but energy dots. Molecules are in there but we cannot see them. It has 840 energy units. Thus, if we said that every molecule in this container had 2 energy units, how many molecules would it have? It will have 420 molecules. Do you understand?

A: Yes, 420.

L: Of course this is a supposition. Containers of things have millions of molecules.

L: So, if you looked with the strong microscope would you be able to see the energy dots?

A: No.

L: I want to make sure that you don't mistake them for molecules. Now. You see these dots jump around? Why?

A: Because they bounce off the molecules, they're colliding.

L: Exactly. Because molecules don't stand still, they collide and exchange. You might ask whether molecules ever stand still. They do when they are in absolute zero, very very low temperature. In that case they don't have any energy in them.

A: What exactly is zero? I mean, as far as a glass of water is standing on the table...

L: In zero degrees molecules still have energy and they move around. Absolute zero is...

L: Suppose that this container is now at a higher temperature. How will it be represented?

A: A lot faster. What do you mean? The energy.

L: Yes.

A: Faster because it will be at a higher temperature.

L: How will they be represented on the screen. Will it look any different?

A: They will probably be...expanded...the container.

L: Yes, but let's say that the expansion is not so big to show on the screen. How about these dots? Is anything going to happen to these dots? Maybe the number of them.

A: It's going to get larger.

L: Let's try it. With a higher temperature. Let's say 120 degrees. Two containers: (a) 2 mass units, 70 degrees (b) 2 mass units, 120 degrees.

A: It has a lot more energy dots.

L: We could have made it twice as hot and then the energy units would be...

A: Twice as many.

L: Also you said that the speed...

A: Will change.

L: So the speed of this is going to be...

A: A lot faster.

L: Let's see them. View. Obvious...

A: Yes.

L: Do you think that the number of molecules will change in the 120 degree container?

A: It has twice as much energy.

L: Well not exactly twice.

A: Yes, all right. So it will have almost twice as much molecules.

L: You think you'll have more molecules?

A: Yes, we should.

L: So is mass going to increase?

A: ....

L: OK. Let's say this container is a piece of steel and you heat it up until it becomes 70 degrees. At this moment it has a certain amount of energy in it. And then you put it for longer on the hot plate, and it goes up to 120 degrees. Do you think the molecules, when it is at 120 degrees, will increase in number?

A: No, it is the same.

L: OK, because these dots <u>are not</u> molecules, these are energy.

A: Right, right.

L: And actually it is a representation. Somehow we had to show on the screen the amount of heat, of energy in this container. And this is one way to do it. By putting dots in it, the more dots you have, the more energy. Molecules in there. What is different per molecule?

A: The units.

L: OK. I could have made 140 degrees. So if in this one we had 2 energy dots per molecule...If the temperature was twice as much, how many energy units per molecule would we have here?

A: Twice as much.

L: Thus, 2 in here and...

A: 4 in there.

L: Great. So what the difference is that the number of energy dots, or amount of energy (same thing) per molecule is going to change. It will increase here and also the other thing we saw is the speed.

A: Here they are going to move much faster as in here.

L: Now. Let's talk about something else. 1 container (3 mass units), choose energy. Let's say this is a piece of steel. How in real life can we increase the energy in a container. (Of course the energy which is related to heat, thermal energy.)

A: By heating it.

L: For example.

A: On top of a flame...

L: What do you think is happening in a molecule in our container and in a molecule in the flame (or a hot plate)?

A: The hot plate is going to be a lot hotter. It will have a faster speed.

L: And if you could represent the energy in it with energy dots, the hot plate...

A: Will have a lot of energy dots.

L: OK. We are going to add to it a certain amount of heat from the bottom by zapping it. Zapping energy, energy dots, e.g., 2 zaps, each zap being 100 dots, therefore 200 dots, thus from 800 to 1000 energy units. Also we have more energy concentrated down here and if we looked at the molecules down here.

A: They will move a lot faster because they have a lot more energy.

L: OK. Why is temperature undefined?

A: Because it is heated by the bottom. We cannot really determine the heat in between until it is all spread.

L: So, this molecule here (bottom) that has a lot of energy and is at a high speed bounces with this one. This one will get more energy, then it will bounce with the other one..and after some time what do you think will happen? If we waited for a long time...

A: It will all expand. I mean from the bottom up it will be at the same temperature. It becomes the same temperature throughout the whole container.

L: Do you know how this is called? This is called <u>thermal equilibrium</u>. Meaning all molecules will have the same speed and in terms of energy dots...

A: It's going to be a lot faster.

L: Yes the speed. How about the energy dots per molecule?

A: Twice as fast.

L: As fast as what?

A: As it was before we zapped it twice, right?

L: Yes.

A: Which made it a lot hotter.

L: Yes, but we did not add twice as much energy as it had. It was 800 and it could have been twice as much energy if we added another 800. We just added 200. So, not twice as much in terms of energy. It's going to be a little higher in energy. OK. So if we view the molecules down here, this is going to be the speed

[Program got blocked, we lost the picture]

Do it again...view molecules.

Do you think at equilibrium the molecules collide?

A: Yes.

L: Why?

A: Because there is heat in them.

L: And when there is heat which in energy in them, they move and when they move they collide.

Two container option.

L: Equal sizes, 2 different temperatures: 40 degrees and 80 degrees. What do the dots look like?

A: On the 40 degrees it will be less than in the 80 degrees, 80 degrees has a lot more because of the temperature. So there is more energy per molecule. Twice as much as the 40 degrees.

L: Because there is more energy here (the 80 degrees) per...

A: Molecules.

L: And that's the case because 180 is half of 960. Do you think these 2 containers will have different numbers of molecules?

A: No.

L: Good, just checking. What is different is the amount of energy and in this case we have twice as much. So if we had a molecule over here and a molecule over there this one will have...

A: Less energy.

L: Half the number of energy dots as this one. Now we'll chose different energies, same masses: 100 energy units and 400 energy units. How do you think their temperatures will be related?

A: 4 times as much.

L: Show me. Very good.

L: View molecules in 2 containers.

Conduction

L: Put 2 containers into contact.

L: What do you think is going to happen?

A: One is gonna get...The small one is gonna get twice as fast and the other one twice as slow.

L: So what is happening with the energy, energy dots, the molecules...

A: They collide and the small one is going to get 4 times as fast and the other 4 times as slow.

L: Thus, on the left we're going to see a lot of energy dots and on the right very few?

A: No, sorry. It's gonna be the same. Not exactly the same.

L: What is going to happen over all?

A: Over all the speed is going to... [pause]

L: You can actually see what is happening. How will the temperatures compare?

A: Just about the same.

L: So they will be at...

A: The same speed.

L: Yes. One speed and also...

A: One temperature.

L: And also the units per molecule.

A: Are going to be the same.

L: How did we call that before?

A: Equilibrium.

L: Now [case #1] 3 mass units, temperature = 30 in one container and 3 mass units, temperature = 70 in the other. One has more...

A: Energy.

L: But in terms of molecules...

A: They are equal.

L: The only difference is the number of energy dots per ...

A: Molecule.

L: We put them in contact, what is going to happen?

A: They (energy dots) are going to move from the higher temperature into the lower temperature. And they will become "equilibrium"--

L: So do you know what the temperature will be after...

A: 50 degrees.

L: Very good.

L: [Case #1] 1 mass unit, temperature = 30 in one container and 1 mass unit, temperature = 70 in the other. Now we have fewer energy units because we have fewer molecules contact. What will happen?

A: Same temperature.

L: Consider both cases. Were there more energy dots exchanged in one case than in the other?

A: It should be the same because it's the same temperature. No the units, the mass units were different. I think in the other containers it should have been more...

L: Why?

A: Because the containers were bigger.

L: So, they had...

A: More energy.

L: Yes they had more total energy, because there were more what?

A: More molecules.

L: Yes and every molecule had...

A: Twice as much

L: No. It had the same number of energy dots per molecule. But more molecules in this one (container starting at 70 degrees) gave their energies to more molecules to that one (container staring at 30 degrees). Do you understand that. Let's move to UNEQUAL CONTAINERS. 1 mass unit, 200 energy units in one container and 3 mass units, 200 energy units in the other. What will the temperatures be like?

A: One is going to be hotter than the other.

L: Which one?

A: The one on the left is going to be a lot hotter than the one on the right, 3 times as hot.

L: Very good. If you told me temperature is the recording of the heat. Now that we put the same amount of heat in the 2 containers, we see, however, 2 different temperatures. What is going on?

A: (smiles). So...there is a difference...

L: If we didn't know what the numbers were on the top. How could we tell by just looking at the containers whether one has a higher temperature?

A: Because they jump faster.

L: Without considering the jumping around. Just from screen...

A: One is faster than the other.

L: That's fine and we could do the view option to see it. [We did it and verified that was the case.] But how could we tell otherwise, that one is at a higher temperature?

A: Because of the container.

L: Yes, what is difference.

A: The size. One heats faster than the other.

L: Try another one [?] Is one at a higher temperature?

A: The one on the left.

L: How did you guess it? You are correct.

A: They move faster, they are jumping.

L: Yes, but is there any difference in the way they look?

A: Because I know that the smaller the container the faster it heats up.

L: Yes, but right now we haven't seen the process of heating up. We just see a certain amount of heat in them. Do you see any difference in the way the dots look?

A: They are tight, they are closer.

L: Exactly, that's what I was waiting for. They are more crowded!

L: Do they have a different number of molecules in them?

A: No.

L: NO!!!

A: Oops, sorry. The bigger one has more molecules.

L: Yes, because it is the same stuff. It is just that for this one (the bigger) we cut a bigger piece. And we put the same amount of energy. So each molecule in here (small container) will have more energy dots in it than each molecule over there (big container), because they'll have to divide this amount of energy into less number of molecules than over there (big container). So, each molecule will have more energy in it (small container), thus it will move faster and it will have a higher temperature. Do you understand the crowdedness concept?

A: Yes.

L: Do another example. Put the same temperature into 2 different sized containers (1 twice as big as the other), e.g., 180 degrees. Which one is going to have more energy dots?

A: This one has twice as much.

L: Yes. Very good. And, as we said, they have the same temperature? How can you tell again from the picture?

A: They have the same crowdedness.

L: Thus, there are 2 different ways of thinking about temperature..

A: a) by the molecules...by how fast they move and b) by crowdedness.

L: And the way to think about heat is...

A: By the speed.

L: No, No, No. That, we said, is the temperature. Look at the 2 containers on the screen. Does one have more heat?

A: Yes.

L: How can you tell?

A: By the sizes.

L: Yes, and of course the total number of energy units.

L: You look exhausted. A little more to go. If we put 2 containers together (of same temperature) what will happen?

A: They will equal out, equilibrium.

L: But is there really anything going to happen? Let's see. Do you see anything happening?

A: The speed of the molecules...no...

L: See anything moving?

A: No.

L: Why is nothing happening?

A: Because it is at the same temperature!

L: Yes, because each molecule over here (left) has the same..

A: Units in it.

L: Thus the same speed. Thus, if this one bounces with one over there they'll exchange the same energy so,it will make no difference overall.

END OF FIRST SESSION

Andrea B

L: Repeat from last session: 2 containers, 2 different sizes: 2 and 4, same amount of energy in them: 500 energy units [hide the caption]. Do you think one has a higher temperature?

A: Yes, the small one.

L: Why?

A: Because it's a smaller container.

L: Yes...What is happening with the molecules?

A: Oh, they are bouncing with each other.

L: I mean in terms of energy per molecule.

A: It has twice as much as the other one. Twice less than the other. Sorry. The smaller container has twice less than the large container. No it's 4 times. No, it's two times...

L: This is half of this (on the left). So, each molecule over here will be what?

A: Twice as much as the other one.

L: Right. Twice as much ENERGY. So, let's say if this one has (smaller) 2 energy dots per molecule. This one (larger) will have...

A: Yes, twice as much.

L: ??

A: If this one has 2, this one is twice as big.

L: But, it has twice the amount of molecules. Be careful now, I'm talking about the energy in each molecule. The 2 containers have the same <u>total energy</u> because we put 500 dots here and 500 there.

A: Oh...

L: However, you said that one will have a higher temperature. Which one?

A: This one [the (small) one].

L: And I'm asking you in terms of energy per molecule, energy dots per molecule. How will the molecules in the 2 containers compare?

A: They are the same. Because we put 500 dots in each, same number.

L: Yes. However, what does the big container have more?

A: More molecules.

L: OK. So all these molecules will share/divide the energy in each container. The 2 containers have the same amount of energy. However, the big one has twice as many molecules. So, do you still think that this one...

A: OK, molecules. OK, no. This one has twice as much molecules as this one.

L: So. In terms of energy (energy dots) per molecule...are they going to be different?

A: The smaller container will have twice as many molecules.

L: Molecules? Try to separate the molecules from the energy dots. What you see is not the molecules. The same number of dots are in here as in here.

A: OK. And that's energy.

L: That's right. However, this container has twice as many molecules as the one on the left. So, in terms of energy dots per molecule...

A: It has twice as much.

L: Which are?

A: The left [smaller] one.

L: So do you understand now?

A: Yes.

L: Because the same amount of energy will be shared/divided by fewer molecules [in the small container]. Thus each molecule will have more energy in it. Here (the big container) energy, the same energy, will be shared by more molecules, thus each molecule will have less energy. So, by having more energy molecules will move faster, thus be at a higher temperature. Understand that?

A: Yes.

L: So, remember when, at the very beginning, I asked you about what temperature was, and you said that it recorded heat? Do you see now that this cannot be the case, since, although we put the same amount of heat in each of these containers, the temperatures are different?

A: Yes, because the size of the containers makes a difference.

L: All right. So, I'll give you the following problem. 2 different sized containers, one twice as big as the other. If you had to put energy dots in them, how could you make them so that they came out to be at the same temperature? E.g., put in the small one 40 energy dots.

A: Then we need to put 80 in the big one.

L: Very good.

L: Now: one container has 1 unit mass, and the other 3 units mass. Both have energy = 600 dots. [Before showing the screen] Which has a higher temperature?

A: The smaller one.

L: And how about energy per molecule?

A: The one with 3 mass units is gonna take more energy to heat up.

L: The energy is in there already.

A: OK, small are more energy per molecule. Because of smaller space.

L: And how will the molecule behave?

A: Lot faster speed.

L: Thus, higher temperature

A: Also more crowded container.

--Show on Screen--
--View molecules in 2 containers--

Conduction

[Containers into contact]

L: Are any dots going to move? Movement of energy?

A: Yes, until they equal out in temperature.

L: Where are they going to leave from and where to?

A: From mass 1 to mass 3

L: Why?

A: Because there is more heat in one (small).

L: NO. Same heat, different temperatures.

A: Oh, yes. Right...

L: Remember the collision model. When 2 molecules collide, the molecule with more energy gives some to the molecule with less energy. Until finally they equal out. Left container molecules have more energy than the ones on the right.

A: OK, now I get it.

L: Do you think the process will stop when the number of dots in the 2 containers will be the same?

A: No, molecules never stop moving.

L: I don't mean the molecular movement. I mean the energy movement. [Repeat question.]

A: Yes. (Same number of energy dots in both.)

L: Are you sure?

A: They started out being equal.

L: But then we saw energy moving. Don't you remember? The denser one gave energy dots to the other. So what is going to happen at the end? You said same temperatures? What does this mean?

A: .....

L: That per molecules, they will have the same energy (same energy dots). However, what about the containers? Are they going to have the same number of energy dots?

A: No. Because this one (big) is 3 times as big as the other.

L: OK. Also, the stage they are in right now (same temperature) is called thermal equilibrium. And we see that on screen by the same density [of dots] in the containers, same crowdedness. However, tell me again which container has more heat.

A: Same.

L: HEAT!!

A: Oh, the one 3 times bigger.

ZAPPING

L: Choose 2 containers, masses 1 and 4 units, same temperature: 80 degrees.

L: How (from screen) can one tell they have the same temperature?

A: Crowdedness.

L: ZAP. Same energy (2 zaps). Why is temperature undefined?

A: Because hotter at the bottom, colder on top.

L: OK.

L: Which are increased more in temperature?

A: The small one.

L: Because you added the same energy and it has to be shared in a smaller mass. Now choose sizes 2 and 4, same number of dots (40), ZAP same number of zaps. Where did the larger temperature change take place?

A: In container size 2.

L: OK. Other problem. 2 containers, masses 2 and 4, same temperature = 60 degrees. How many zaps to increase both temperatures by 10 degrees?

A: ....

L: If I increase this (small container) by 10 degrees (make it 70 degrees), how many zaps do I have to give to the other one to make it 70 degrees also?

A: Twice as much.

TASKS

Task #1

L: Same mass units. Which has higher temperature?

A: On the right, more crowded.

L: OK.

Task #2

L: Same sizes/mass. Fill the container on the right so that its temperature is 80 degrees.

A: E.g., 200, less energy dots.

L: Close. OK.

A: [Tries 2 more times until temperature is close to 80 degrees.]

Task #3

L: Container on left has 1 mass unit. Fill the container on right (3 mass units) so that its temperature is 7. (On the left we have 10 degrees, 60 energy units.)

A: So I want the temperature to be less...

[Andrea makes a mistake]

A: I have to put more energy because...

L: Because we have 3 times the space. You'll have to increase the energy units.

[She wants to put exactly 180 energy units. She does not understand why that makes the container on right 10 degrees exactly. Finally she gets it right, and adds less than 180 energy units.

Task #4 skipped.

Task #5

Left container: 3 mass units, temperature = 40, energy units 720. Right container: same mass, temperature = 80, energy units 1440. 2 zaps in left container. The container on left now has 920 energy units and temperature = 51.11. How many zaps does container on right need to get to a temperature close to the container on the left?

A: So you want to go down in temperature?

L: I agree there is a problem here. Need to subtract energy. Escape it [!]

Task #6

Container on left: 3 mass units, temperature = 80 degrees, energy = 1440 energy units. Container on the right: 2 mass units, temperature = 40 degrees. How many energy units?

A: So, the one on the right has half the temperature, thus half the energy units also.

L: No, because the right container has smaller mass.

A: OK.

[Each container gets 5 zaps. The temperature of the container on the left goes up to 191.11 degrees. Predict the temperature of the container on the right.]

L: On left we gave 5 zaps and it went up 111.11 degrees. On the right we gave exactly the same number of zaps. However,...

A: It's less energy...

L: No, it's the same amount of energy (5 zaps). It's less mass. If the left went from 80 degrees to 191.11, what, more or less, will the temperature on the right be? I don't want exact numbers. Is it going to be more than 40 degrees + 111.11 degrees = 151.11 degrees or less, or what?

A: Just about 135.

L: So you say that it is going to go up less than 100 degrees. Why less, since less mass? Added energy is going to be shared by less mass.

A: So...

L: [Repeat the problem and explain.]

A: Go up more than 111.11, maybe 122.22.

L: Let's try it. Temperature = 200 degrees.

A: It went up more.

Try another problem from Task #6. Container on left: 2 mass units, temperature = 70 degrees, energy units = 840. Gets 3 zaps. Temperature goes up to 570 degrees. Container on the right: 4 mass units, temperature = 40 degrees, energy units = 960. Gets 3 zaps. Predict its temperature.

A: This is the opposite of the previous problem because the right container is bigger now. Increase will be less than 500 degrees.

L: How much less (more or less)? See this one is twice as big.

[Andrea gets confused. Thinks that the temperature on right will be more than 500 degrees.]

L: Let's see the solution. It's 220 degrees.

A: Why?

L: Because we added same number of zaps into a bigger container, twice as big in fact. So energy got shared by more molecules.

L: Try one more problem from Task #6.

Now containers happen to have same size.

[Andrea does it OK.]

Task #7: same size containers. Conduction.

[Andrea does it right.]

[Another problem from Task #7, Andrea correct again.]

Task #8

Container on the left: 4 mass units, temperature = 70 degrees, 1680 energy units. Container on the right: 2 mass units, temperature = 50 degrees, 600 energy units conduction. Equilibrate at temperature = 63.3 degrees. How many energy dots were exchanged?

A: Temperature on right is 63 333.

L: OK. How about the energy units?

A: Half of the ones on the left.

L: OK.

SPECIFIC HEAT

L: A molecule with a certain amount of energy in it moves at a certain speed, and the more energy, the faster it moves. However, the energy of a molecule is not only related to its speed. If a molecule has more than 1 atom, there is energy due to associated with vibration of atoms. It is called

Internal Energy. So, if you give some energy to a molecule of a substance, e.g., water, some will be used to make it move faster and some to vibrate more. However different molecules have different amount of vibrations. So if a molecule vibrates a lot, and we give it some energy, only a little will be left to make it speed up. Example with a molecule vibrating a lot and a molecule vibrating a little. Give them both 100 energy dots. The first molecule uses 80 dots to vibrate and 20 dots to speed up. The other molecule uses 40 dots to vibrate and 60 dots to speed up. Thus their speeds will be different. However, how fast one molecule moves has to do with temperature. So, the second molecule will be at a higher temperature. Example with alcohol and water (water molecules vibrate a lot), which gets hotter?

A: Alcohol, because it moves a lot.

APPENDIX F

Interview 5. Four adult subjects

INTERVIEW: SANDRA & JORI (ages 20)

PRELIMINARY QUESTIONS

L: Do you know what heat is?

W: It's hot...it's heat. It's hot energy coming from something.

L: What's cold?

W: The absence of heat.

L: Do you know what temperature is?

W: It's the measure of heat.

L: Is there a difference between heat and temperature? What is it?

W: Temperature is harder to measure than heat. Heat is always hot. Temperature isn't always hot.

PROBLEMS

L: [A few problems]. 100g steel and 200g. Give same heat to both. If, in the big piece the temperature is raised by 10 degrees, what will the temperature rise be in the other one?

W1: Seems like it would be 1/2 the amount because there's more substance to heat.

L: Do you agree?

W2: Maybe only 1 degree higher. It has to be more--higher temperature. It's going to take more heat to heat this than to heat that.

L&
W2: But you put the same amount of heat.

W2: But you want to raise it 10 degrees?

L: No, I just put them on the same hot plate for the same time and this one was raised by 10 degrees. What is that going to be?

W2: Oh, OK. I would say only 1/2.

L: So you agree. Alright. Do you know what a model is?

W: It's just a visual example.

L: Anyway, I'll give you another question. 2 containers; 1 is twice as big as the other. Does it make sense to say that one has more heat than the other?

W1: No, they both have the same amount of heat.

W2: No! they're both the same temperature but one has more quantity. If you stuck your finger they'd both burn but the bigger pot might burn more 'cause there's more water in it.

W: I think it has to do with how far the molecules [inaudible] than it has to do with the heat. I think the heat is going to be the same.

L: So you think it's going to be the same and you think this is going to have more? Other question: 2 steel blocks, 1 twice as big as the other. They are placed on identical hot plates for identical time, not enough to get as hot as the plate. How will the final temperatures of the steel blocks compare?

W2: The same.

W1: I think that the heat will start at the bottom and will slowly move up so the bottom will be at the same temperature. I think the temperature will be the same.

L: Then you take these blocks and you drop them in identical cold water baths. What are the temperatures going to be?

W2: It seems it will be the same if these two had the same amount.

L: What do you think?

W1: I don't think they'd be the same but I don't know why. I think the smaller one will be higher.

PROBING CONCEPTUALIZATION

L: Now we have a flask with alcohol. Dip it in a container of hot water. What will happen to the alcohol?

W1: They'll both become the same temperature.

L: To the level?

W1: Yeah, it'll probably expand.

L: Do you agree Sandra?

W2: Yeah.

L: Do you know why?

W2: The molecules will expand.

L: Do you think the molecules themselves will become bigger?

W1&
W2: No, the space between them..they move more.
The hotter it is, the faster they move and they take up more space that way.

L: Exactly. What makes them move faster when you heat them up?

W: The energy from the heat.

L: What *is* heat?

W: Heat is the energy.

L: Heat *is* energy, right? So heat does not *have* energy; it *is* energy. How do you describe energy?

W: Like a power.

L: Yeah! How would you make a model of what's happening?

W: The thing is that heat is energy, but there has to be a source--say, this water is heated by the sun.

L: What's the source in this case?

W: The hot water.

L: What's the difference between the molecules of the water and the alcohol?

W: They move more quickly.

L: So we'll make the arrow of the speed very long. So this molecule will hit this one and they will redistribute their energies. This one is going to move faster and this will move slower. After some time they'll end up what?

W: Being the same.

COLLISION PROGRAM

L: Yes. Now we see how 2 colliding molecules behave. The one that has a lot of energy will move fast. Choose one very slow and one fast. We'll see their trajectories. Then they'll collide. What do you think we'll see afterwards?

W: They'll go in different directions.

L: Yes, they're not going to go like this. If we look at the speed of the red molecule. It's going to be?

W: It's slower.

L: And the green one?

W: Faster.

L: [Shows energy circles--total energy is the same] We represent energy by dots in molecules. The only way that we can change the energy in a molecule is how?

W: I guess raising the heat.

L: Let's say we want to make this one faster.

W: Add more dots.

L: How do you add more dots? Make it move faster?

W: If it collides with something.

L: Right--very good. You cannot just remove or add heat. It has to collide with something.

CONTAINER PROGRAM

L: Now we have container of things--collections of molecules in each, having a certain energy. We're not going to see the molecules in the containers--these are energy--represented by a number of dots. Choose mass: how big it'll be, e.g., 2 mass units. Choose total energy: e.g., 33 units. If we look with a microscope would we be able to see the energy dots?

W: No.

L: Right, it is just a representation. Why do you think they are jumping?

W: Banging into each other?

L: But what's colliding. The energies themselves?

W: No, the molecules.

L: Yes the molecules are there but their outlines are invisible.

W: So each energy unit does not exist within one molecule.

L: This container is at 33.33 degrees. If it were at 66.66 degrees, how many energy units would be applied? Let's do it. Which one would have more energy dots?

W: The one with the higher temperature.

L: How much more?

W: It seems there will be twice as many energy dots.

L: Is one going to have a different number of molecules?

W: No. You're just changing the energy that molecules have.

W: That's the whole point of taking a stone and heating it and then putting it in your bed. Then the temperature goes away and you heat it again to get more energy.

L: One difference is that each molecule here will have less energy than each molecule over there and what else is going to be different?

W: The temperature and the speed.

L: And we can actually see that (VIEW). If we jump to a window over here, what will happen?

W: They'll be faster.

L: Let's see. Exactly!

[CHOOSE NEW CONTAINERS AND SET TEMPERATURE]

L: ...it automatically gives us energy units. How in real life do we increase the energy of a container? How do we increase temperature?

W: We put it in hot water or...we turn it on.

L: Or put it on a flame or a hot plate. So in terms of this model, how would you represent it? How would you model the heating?

W: This is showing us the temperature and also the energy at that temperature. I'm not sure how it differs from what you're asking us.

L: But what if you put a hot plate underneath?

W: The molecules in the hot plate are moving faster--they have more energy units.

W: So it depends how long you're going to leave it on the hot plate if you want the temperature of this to become as high as of tl .

L: In this model we ZAP it with energy. Now it's adding energy.

W: That's a very slow way.

L: We could do it faster. Why is the temperature undefined now?

W: Because.........mmmmmmm

W: Because the reaction hasn't finished. It isn't homogenous.

L: The heat hasn't spread all over. These are moving very fast while these are not. What will happen if we leave it for a long time?

W: They will even out.

L: Exactly. If we VIEW the molecules at the bottom, they move very fast. Now it's all spread out and this is the final temperature. Initially there are more energy units in the molecules in the bottom.

W: So, energy units <u>can</u> go in and out of molecules when they bump into each other.

L: However, energy units are just a representa of energy. When everything is at the same speed and at ne energy, we are at thermal equilibrium. One last question. When at thermal equilibrium, do you think molecules collide?

W&W: Yes. They go at the same speed and when they collide they just go opposite directions but still have the same speed.

REVIEW

L: Remember last time. Each molecule has a certain amount of energy and as a consequence, is moving at a certain speed; the faster the speed the higher the temperature. Also we ZAP with energy and we waited for some time to reach equilibrium--the point where each molecule has the same speed and the same amount of energy. How exactly did the transfer happen?

W: Just by bumping.

L: Last time we only dealt with 1 container. Now let's choose 2 equal containers. Choose 2 different temperatures.

W: 79 degrees C in one and 29 degrees C.

L: Can you tell me how the energy dots will look in these containers? I don't want exact numbers.

W: There'll be more [in mine].

W: And fewer in mine.

L: Do you think that these 2 containers have a different number of molecules in them?

W: Not necessarily.

W: Same size, so they have the same number of molecules.

L: What's different is the number of energy units per molecule. How do the speeds of the molecules compare?

W: These would be going faster.

L: OK, so let's see that [VIEW].
Now choose 2 containers, same size and put different energies in them; 99 and 300. What are their temperatures going to be?

W: Mine is going to be hotter.

L: Right. We can also [VIEW]. Obviously, they'll be quicker in this one.

L: Now we'll put them in [CONTACT] with each other. What do you think will happen?

W: The temperature will change.

L: Is there anything moving?

W: Yeah/No. I think they'll begin to mix the energy.

L: So you think energy will leave this container to go there?

W: Yes.

L: That's indeed the case. If we waited a long time what would happen?

W: They'd even out.

L: Yes, thermal equilibrium. What does it mean?

W: They'll have the same number of energy units on both sides and the same temperature.

L: Make 2 containers the same mass. Choose the temperatures: 30 degrees and 70 degrees. Put them in contact.

W: They'll try to approach thermal equilibrium.

L: Yes, after some time every molecule will have the same energy units. Do you know what the final temperature would be?

W&W: I'd say 50 degrees.

L: Very good! Remember this case and now make 2 containers, both smaller in size. The temperatures = 30 degrees and 70 degrees like before. Put in contact. What will happen?

W: Thermal equilibrium-- still at 50 degrees.

L: Were there more dots exchanged in this case or in the previous one?

W1: The same.

W2: No! It would be more dots [in the previous one] because there were more dots to start off with. In the previous case one had like 1000 dots in them.

L: I agree with Sandra (W2) because there were many more molecules in the previous case. So, more total energy was given in that case. This is now thermal equilibrium and we see dots moving. Why?

W: Energy always moves.

L: Right. Molecules still collide but they give energy and get the same amount back. We'll now move to unequal containers. We'll put the same number of energy dots in the two. How will the temperatures compare?

W1: They'll be the same temperature.

W2: They have the same amount of energy, only one has more molecules than the other. But we're talking about the temperature.

W1: I don't know.

L: OK. This one has a higher temperature. Because, let's take a molecule in this container and one in the other. Each molecule here will have more energy units and thus a higher speed and thus higher temperature. We said speed is related to temperature. At the beginning you said temperature is just a measure of heat, but that's not the case and you can see that here.

L: Now we take 2 unequal size containers and chose the same temperature this time: 50 degrees. Do you think one will have more heat in it? More energy?

W: Yes, because there's more energy dots.

L: So temperatures means a certain number of energy units per molecule.

W: Yes, because there's more energy dots.

L: So temperature means a certain number of energy units per molecule Here however we have more molecules. So more total energy units. Now choose 2 containers with same amount of energy. You see that this has a lower temperature. How could you tell it by just looking? There are 2 ways of looking at temperature. If we look at 2 molecules...

W: It depends on how many energy dots there are in a molecule and that makes it move faster.

L: So one way to tell about temperature is the speed of the molecule and another way is to look at the density of energy dots in the container. What is the total energy? Choose 2 containers: 30 degrees in both. The crowdedness of energy dots is the same. Has one more energy in it?

W: The one on the right, because of its size.

L: Yes. Now let's solve a little problem. 2 containers: 1 = twice the size of the other. Can you define the energies so you get the same temperature in both?

W: You have to put in twice as much.

L: Exactly. Very good. If we put these in contact, what'll happen?

W1: They'll try to reach thermal equilibrium.

W2: But the temperatures are equal.

L: Let's do it. Is anything happening?

W1: No.

L: Why?

W1: Oh, they're already equal.

L: Yes, each molecule has the same amount of energy. Now let's put same number of energy dots.

W: So, you've only changed the size here.

L: What else will be different?

W: The temperature--hotter also denser.

L: If we put them in contact?

W: The temperature changes.

L: Now, do you think when the process of equilibration ends the two containers will have the same amount of energy dots?

W1&
W2: Yes.

L: What else will they have the same?

W1: Heat.

W2: Temperature.

L: Same temperature, so each molecule will have the same number of energy dots here and here. But we have more molecules here.

W1: Right, so there will be more energy dots to fill the molecules. I'm so glad I didn't take physics. That's very confusing.

W2: It was easier when they were the same size.

L: Let us choose another pair of containers. 2 different sizes. Same temperature. ZAP same number of energy dots. What do you think the final temperatures will be? They started the same.

W1: This is going to have 1/3 more energy dots than this. More dots per molecule here.

W1: It's going to be denser here. If it's denser, it'll be hotter because there's more energy in a smaller space and that's the speed which is the heat.

L: No the speed is the temperature.

W1: So density is the heat.

L: No, density is the temperature.

W1: The speed and the density is the temperature?

L: Yes, the speed and the density is the temperature.

W1: So, the denser it is the faster they're moving, the hotter it is. It doesn't matter how many energy units are in the molecules.

L: It matters!

W1: Wait a minute!

L: So, they started with the same temperatures. This does not mean that they have the same heat. It means same amount of energy/molecules. So if this has more molecules it means more energy overall. We now add the same amount of energy into both of them.

W1: The temperatures were the same when we started?

L: Yes.

W1: Now that one has more molecules but this one has more energy units per molecule.

L: Do QUICK. The answer is that this one has a lower temperature.

W1: Because this one has more energy units/molecule?

L: Yes.

TASKS

Task #1: 2 containers, which one at higher temperature?

W2: The one on the right.

L: Why?

W2: More energy dots/molecule.

L: Yeah--I mean...

W1: It's denser.

L: <u>Task #2</u>: 2 mass units, 100 degrees and 1200 energy units on the left. How many energy units to make the other one 40 degrees?

W: 450 energy units?

L: Good. Very close, 37.5 degrees.

W: [illegible] That's a guesstimate, OK?

L: <u>Task #3</u>: Two same size containers. Temperature = 90 degrees.

W: So you put the same amount in.

L: That was an easy one!

<u>Task #6</u>: same size containers. Predict the temperature of the one on the right.

W1: It's gonna be hotter.

W2: But not that much more.

L: Note here they have the same size.

W: I guess the temperature will be 200.

<u>Task #7</u>

W: It'll be the same because they're equal.

<u>Task #8</u>

L: Can you predict temperature of one on right?

W: It should be...wait a minute...

W: It will be more.

L: We have 2 objects and we put them in contact and we leave them for a long time. This will be 90 degrees--what would the other one be?

W2: 80?

W1: It'll be less.

W1: Wait a minute. This will have more molecules, but the number of energy units in this one and this one will be the same because they're reaching equilibrium.

W: Oh, they're supposed to be equalized. The temperatures will be equalized.

L: Yes, and the ones that have more mass will have more energy. So how about energy units?

W: The one on the right will have half as many?