DOCUMENT RESUME

ED 303 367 SE 050 357

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TITLE	The Differentiation of Heat and Temperature: An Evaluation of the Effect of Microcomputer Models on Students' Misconceptions.
INSTITUTION	Educational Technology Center, Cambridge, MA.
SPONS AGENCY	Office of Educational Research and Improvement (ED), Washington, DC.
REPORT NO	ETC-TR-88-20
PUB DATE	Apr 88
CONTRACT	OERI-400-83-0041
NOTE	55p.; Draft article of a paper presented at the Annual Meeting of the American Educational Research Association (New Orleans, LA, April 5-9, 1988).
PUB TYPE	Reports - Research/Technical (143)
EDRS PRICE	MF01/PC03 Plus Postage.
DESCRIPTORS	*Computer Assisted Instruction; Grade 9; Grade 11; *Heat; Laboratory Experiments; Laboratory Procedures; *Misconceptions; Physics; *Science Instruction; Science Tests; Scientific Concepts; Secondary Education; *Secondary School Science; *Temperature
IDENTIFIERS	*Laboratory Interfacing

ABSTRACT

This paper describes the characterization of a student's framework of heat and temperature, and the development of a microcomputer-based laboratories (MBL) intervention program for grade 9 and grade 11 students. The report presents the results of classroom study, including interview questions and answers and pretest/posttest, from experimental and control groups. In the posttest, the students in the experimental group displayed a firmer grasp than the control group students of the various thermal concepts, laws, and principles, both at the theoretical and applied levels. Their knowledge formed a more integrated whole, and they showed fewer remaining misconceptions. Finally, they were more able to relate phenomena at the macro level to molecular events. (YP)

TR88-20

THE DIFFERENTIATION OF HEAT AND TEMPERATURE: AN EVALUATION OF THE EFFECT OF MICROCOMPUTER MODELS ON STUDENTS' MISCONCEPTIONS

July 1988

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Draft article of a
paper presented at AERA Meeting
New Orleans, Louisiana
April 1988

The research presented here was supported in part by the Office of Educational Research and Improvement (Contract # OERI 400-83-0041). Opinions expressed herein are not necessarily shared by OERI and do not represent Office policy.

ACKNOWLEDGEMENTS

The authors have many people to thank for their contributions to this research project. Judah L. Schwartz has played an important role in the development of the software; his rich and interesting understanding of physics, as well as his insights into modeling, were invaluable. Walter Engstrom at Braintree High School, Braintree, Mass., let the Heat and Temperature Project conduct the study with two of his classes. He and Stephen Cremer gracefully devoted a lot of time to the project, in spite of busy schedules. Their enthusiasm, optimism, and flexibility were great assets to the study. Stephen Cremer made numerous and invaluable contributions to the software and curriculum design. Special thanks are due to the Braintree High School students for their participation. Risa Evans of ETC helped with interviewing the students, and Lorraine Grosslight of ETC contributed to the teaching intervention. Reviews by Mary Maxwell Katz and Judah L. Schwartz were, as always, very helpful. Ellin Sarot contributed editorial assistance.

INTRODUCTION

The concepts of heat and temperature are the basis for thermodynamics and play an important role in other areas of physics (e.g., conservation of energy, theories of matter) as well as in chemistry (e.g., endothermic and exothermic reactions) and biology (e.g., metabolism). Unfortunately, these concepts are very difficult for students to master. For the past few years, the research of the Heat and Temperature Project at the Educational Technology Center has been focused on high school students' understanding of basic thermal physics, particularly the difference between heat and temperature. We have tried to determine the source(s) of students' difficulties and to design curricula to alleviate those difficulties.

We view learning as the interaction between the information about a domain of knowledge presented in class and in textbooks and the internal mental state of the student (i.e., the students' pre-existing knowledge about that domain). Driver and Erikson (1983) refer to such preconceptions as "alternative frameworks," because they are different from the theory to be learned. Alternative frameworks represent two major stumbling blocks for learners and, consequently, are often difficult to displace. First, students may be unwilling to give them up because of their familiarity and intuitive appeal, attributes generally lacking in textbook theories (Posner, Strike, Hewson and Gertzog, 1982), as seems the case, for example, in mechanics (McCloskey, 1983; Clement, 1983). Second, students may not even understand the textbook theories, because the concepts, rules, and explanatory schemata they use to interpret the textbook statements are inappropriate; the more students' mental models diverge from the theories to be learned, the poorer the learning. We argue here that learning basic thermal physics is particularly hard, because students need to undergo a complete conceptual reorganization.

If one assumes that holding an alternative framework is a major obstacle to learning about a domain, then one must understand that framework thoroughly in order to determine the ways the students' concepts differ from and prevent the assimilation of the textbook concepts. One also needs to develop a curriculum that takes the alternative framework into account — that not only challenges students' misconceptions empirically but also makes the textbook concepts easy to abstract and represent mentally (Driver and Erikson, 1983).

Our group has had three interrelated goals: to characterize the initial state (i.e., the ideas and concepts students develop on their own and bring to the classroom); to develop a microcomputer-based curriculum optimally adapted to these preconceptions that will lead to reconceptualization; and to monitor the resultant 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 students' conceptions and modify the curriculum accordingly. A fourth goal is to develop methods suitable to assess the effects of our teaching interventions. This paper presents our characterization of the students' framework and two different curricula developed to teach the textbook theory, one based on Microcomputer-Based Laboratories (MBL) and the other on computer models.

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 of them 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 is clearly undifferentiated with respect to the physicist's heat and temperature; it 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 students' heat is transmitted from hot to cold objects and can be generated by chemical reactions. Like temperature, the students' 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 students' 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). Everyday experiences may also reinforce misconceptions: the dials on stoves and ovens are marked in degrees; since stoves and ovens are 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.

MBL INTERVENTIONS

This section summarizes our first attempts at teaching basic thermal physics to high school students. The teaching interventions based on MBL were conducted with ninth graders.

Rationale

To help students differentiate between heat and temperature, it is important to demonstrate to them that these are different physical entities whose relation is not that one is the measure of the other. Science teachers, aware of students' need for differentiation, usually start by telling or showing them that the effect of a given amount of heat on temperature depends on the amount of substance being heated. They also teach about specific heat: typical laboratory activities demonstrate that, for a given heat input, temperature rise is a function both of the mass and of the nature of the substance heated and that at the same initial temperature equal masses of different substances release different amounts of heat while cooling. Phase change and latent heat demonstrations also emphasize the difference between heat and temperature: during melting or freezing, temperature stays constant, although heat is gained or lost.

But such demonstrations are likely to be effective for students who already have some sense of the distinction between heat and temperature, who know there is a difference between those concepts, even if they are not clear about distinguishing properties. For most students, however, the difficulty is not a matter of not being clear about the distinction;

most firmly believe there is no distinction between heat and temperature and attempt to fit the demonstrations into their own framework. In their effort to interpret a demonstration of phase change according to their undifferentiated concept, they distort empirical information and draw such conclusions as "0° C is as cold as ice can get," or conclude from a demonstration of specific heat that "alcohol heats up faster than water because it is less dense." This Catch-22 of instruction in thermal physics — that to understand activities that demonstrate that heat is different from temperature one needs from the beginning to differentiate between heat and temperature — is probably why traditional teaching meets with little success, in spite of using demonstration topics that ought to be convincing.

The same is true of heat and temperature measurements. As traditionally taught, 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*, particularly its extensivity, 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.

We decided to use Microcomputer-Based Laboratories (MBL) because they give students more direct access to a sense of the extensivity of heat and demonstrate visually that heat and temperature are not always correlated. In our studies students use heat pulse generators — "heat dollopers" — to heat 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 software and hardware 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, in turn, would enrich their concepts of heat and temperature and consolidate the differentiation. In summary, it was hoped that the MBL lessons would trigger the reorganization of their beliefs about thermal phenomena.

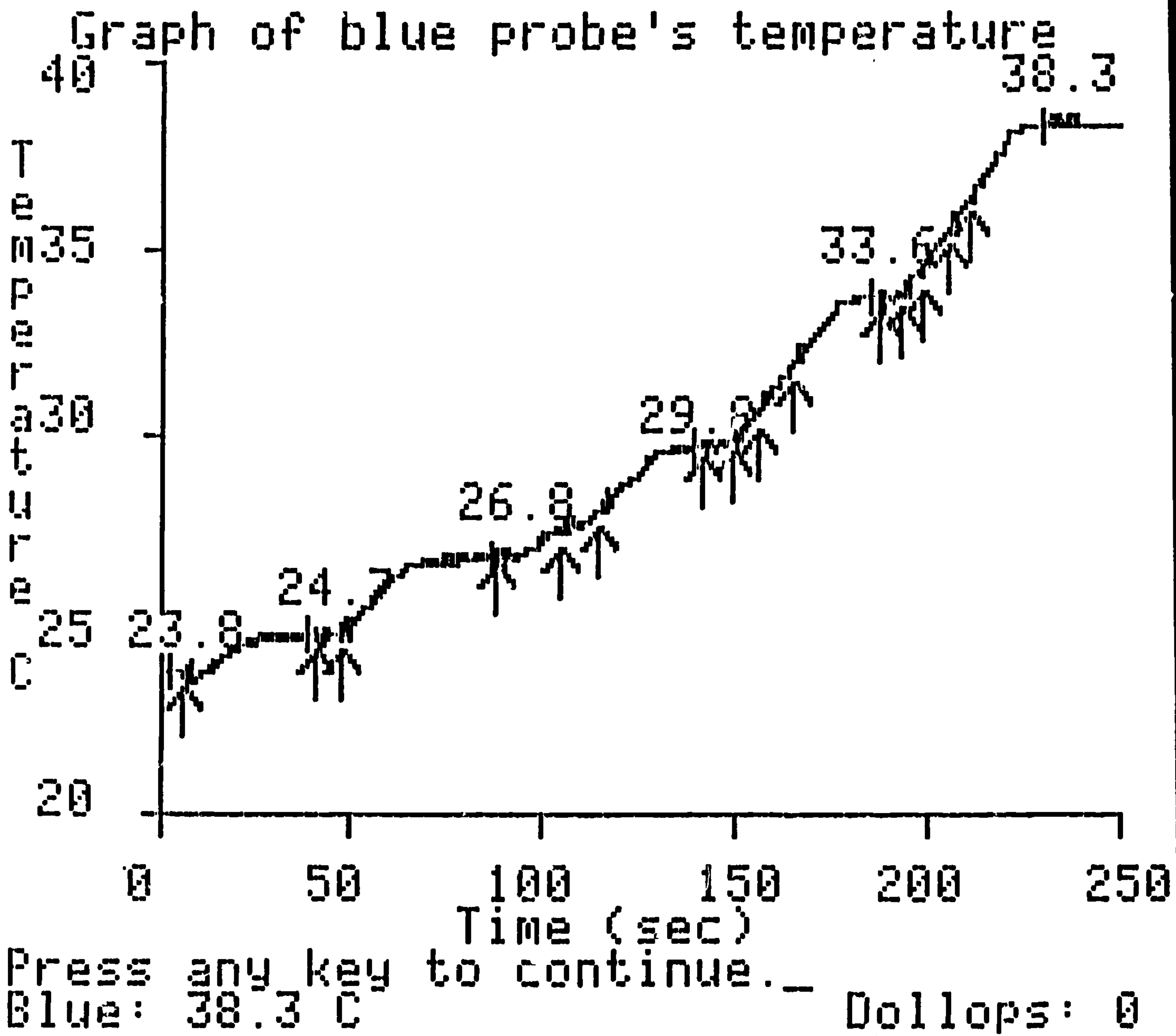
Procedure

Two classroom studies were conducted in which ninth-grade students were divided into a computer group who received the MBL curriculum and a control group exposed to traditional laboratory teaching. The content of the lessons was the same for both (quantitative relation of mass, heat, and temperature, specific heat, cooling curves, and latent heat). The teaching intervention was immediately preceded and followed by two evaluative tests, one consisting of a series of quantitative problems similar to those generally given in science classes and closely related to the content of the teaching interventions and the other consisting of open-ended qualitative questions probling the students' concepts.

Results

The results (presented in detail in ETC Technical Report TR85-17, *Designing a microcomputer-based laboratory to induce the differentiation between heat and temperature in 9th graders* and ETC Technical Report TR87-5, *The differentiation of heat and temperature: An evaluation of the effect of microcomputer teaching on students' misconceptions*) indicated that our MBL interventions were relatively successful at the quantitative problem-solving level, most likely because they gave students a working concept of unit of heat (the dollop) which helped them deal with quantitative laws. But at the conceptual level we found no positive MBL effect compared with traditional teaching. The phenomena the students explored in the laboratory and the quantitative laws they were to infer from the data rarely led (in either the MBL or the control group) to the reconceptualization we were aiming for, i.e., the differentiation of heat and temperature and the acquisition of the concept of amount of heat in the extensive sense. The laws either were not learned, or were learned only as problem-solving procedures ("When units of heat and units of mass are mentioned in a problem, divide the former by the latter"), or, when internalized at all, were often vague and incomplete and therefore wrong.

We believe students distort such physical laws not out of carelessness or information processing limitations (although these probably play a role), but because they retain only the parts or aspects of those laws that make sense within their own framework. For example, students had to learn that "if the same amount of heat is given to two 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 the intensity of heat received by the two masses (for them, it is the only measure of heat). If the same heat is given, clearly the temperature has to be the same! Others interpreted "same amount of heat is given "as" the same heat is applied (to the two masses)" and used a "diffusion" shema to make sense of the law while retaining the notion that heat is intensive. 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 betweeen the different masses, but only qualitatively; it is not based on an extensive concept *amount of heat*, which



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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.

would allow students to conceptualize temperature as (roughly) heat/mass[1], and solve problems quantiatively. Similarly, the law "It takes more heat to raise the temperature of a bigger mass of substance by a certain number of degrees" was ignored or interpreted qualitatively as "heat must be applied for a longer time to fill the bigger mass," or it led to total confusion ("a larger mass of water is hotter than a smaller mass of the same hot water"). Some students ended up with a concept of heat that has 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 them, for example, to answer correctly the question "Is there more heat available in a big container of warm water or in a small container of hot water?" because the "heats" in the two containers, being of different degrees, are not directly comparable. Thus, many students learned that mass had something to do with heat, but only within the contrainsts of their pre-existing framework whose basic tenet (temperature measures heat) remained unaffected.

A similar case can be made about specific heat. Students who learned anything about specific heat 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"). To understand the textbook interpretation of the demonstrations they would have had to give up the notion that temperature measures heat; unwilling to do so, they concluded that, if alcohol, for example, gets hotter than water when exposed to the same heat, it is because it absorbs more of the heat. Their mechanical model for heating makes it easy for the students to accept that different substances react differently to heat: denser substances "resist" heat more than lighter ones. In order to acquire the expert concept *amount of heat*, novices must do much more than learn that heat is extensive. They have to revise their concept of heat entirely, and especially give up the core notion of heat as hotness. Our teaching interventions did not accomplish that goal.

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

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[1] 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 of the center of mass and energy in the internal modes of molecular motion, but it captures the extensive/intensive distinction between heat and temperature. It is, in fact, the idea developed in our second model, HEAT & TEMPERATURE.

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 and, thus, generate more heat. This last example, aside from demonstrating the influence of pre-existing conceptions on the assimilation of knowledge, shows the potential role of molecular models as unifying frameworks.

Conclusions

These findings show that, without a conceptual reoganization (which our MBL intervention did not trigger), students cannot assimilate the textbook theory because the theory is based on concepts and explanatory schemata that differ from those they already have. 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. Simply challenging students' beliefs with experimental evidence and encouraging them to infer regularities in their data did not seem to lead to conceptual change. Whatever clarifications MBL brought at the phenomenological level were insufficient at the conceptual level.

In the following section we argue that a different type of intervention is needed, one in which the textbook concepts are made explicit, and we present the computer models we have developed for this purpose.

COMPUTER MODELS OF THERMAL PHENOMENA

In retrospect, it is not surprising that little reconceptualization was triggered by our MBL intervention. We were asking students to make a theoretical shift that took 150 years in the history of science (Wiser and Carey, 1983). In that students are *taught* the new theory and do not have to *create* it, they resemble, not the creators of a new paradigm, but the scientists working within the old paradigm, who, on being presented with the new one, are asked to reject their own position (Stenhouse, 1986). Unlike those scientists, however, the students are at a great disadvantage in that they are not aware that the theory presented to them is an alternative to the one they hold. They do not know that familiar terms (e.g., heat, temperature) about which they have certain beliefs carry different meanings in the teacher's theory. Nor do they know that they should reconstruct the teacher's meanings from the definitions given and from the laws they are asked to derive from empirical data, rather than interpret those definitions and laws according to their own concepts. The goal of our present and future work is to facilitate reconceptualization at two levels: at the metaconceptual level, students should be made aware of the mental process involved in rejecting one paradigm for another, while, at the conceptual level, the content of the textbook theory (the new paradigm) should be made meaningful.

Introducing students to the nature, limitations, and revisability of scientific theories, models, and concepts and encouraging them to generate, test and revise hypotheses is a neglected but important part of science teaching (Carey, 1986) which has been shown to contribute to reconceptualization (Smith, Snir, and Grosslight, 1987). It is likely that making them aware of their own conceptions, of the constructivist nature of understanding, and of the potential differences between the meanings they assign to scientifc terms and those intended by teachers, and encouraging them to ask the kind of questions that would help them grasp novel meanings — in brief, teaching them that learning science, physics in particular requires undergoing theory changes — would contribute to better learning (Driver and Oldham, 1986). We will explore these issues as they relate to thermal physics in the near future.

This past year, however, we focused on content, rather than metaconceptual, issues on the assumption that the most important factor in fostering reconceptualization is to present the textbook theory in such a way that it will be understandable *in spite of the misconceptions* students held. We sought to minimize the distortions resulting from mis-assimilation into the students' framework by explicating the concepts at two levels: a macro level, which corresponds to the empirical and phenomenological level where variables are apprehended and measured, and a molecular level, where those variables, and the laws relating to them, find their meaning. Because our computer models depict concepts rather than phenomena we call them "conceptual" models.

Our six computer-based models, described below, relate temperature and heat to the amount of mechanical energy in one molecule as well as in a whole object[2]. HEAT & TEMPERATURE, the main model, illustrates visually the difference between heat and temperature and the quantitative relation of heat, mass, and temperature. In the model, the amount of heat energy in an object is represented on the screen by a discrete number of "energy dots" in a rectangle, each dot representing one unit of heat and the size of the rectangle representing the mass of the object. Consequently temperature is correlated with the density of the energ dots (for a given substance) (see "SIMPLIFIED PHYSICS" below, and Fig. 2). In another program, ENERGY IN MOLECULES, molecules, represented by open circles containing the energy dots, can be made to appear within the rectangle, to show that temperature is also correlated with the number of energy dots per molecules (see footnote 2). Another model, which involves repeated collisions between two molecules, "defines" the energy dots as units of mechanical energy by showing that the number of dots in each molecule is proportional to its kinetic energy and that the total number of dots is conserved during collision[3] (Fig. 3). The distinction between the translational energy of a molecule (kinetic energy of its center of mass motion) and the energy of its internal modes of motion (associated with the rotation and vibration of its atoms) is introduced at a later stage, in a program designed to explicate the concept of specific heat.

Using models to teach thermal physics is not new, of course; most existing curricula include a molecular model of thermal phenomena, but do not exploit it systematically to

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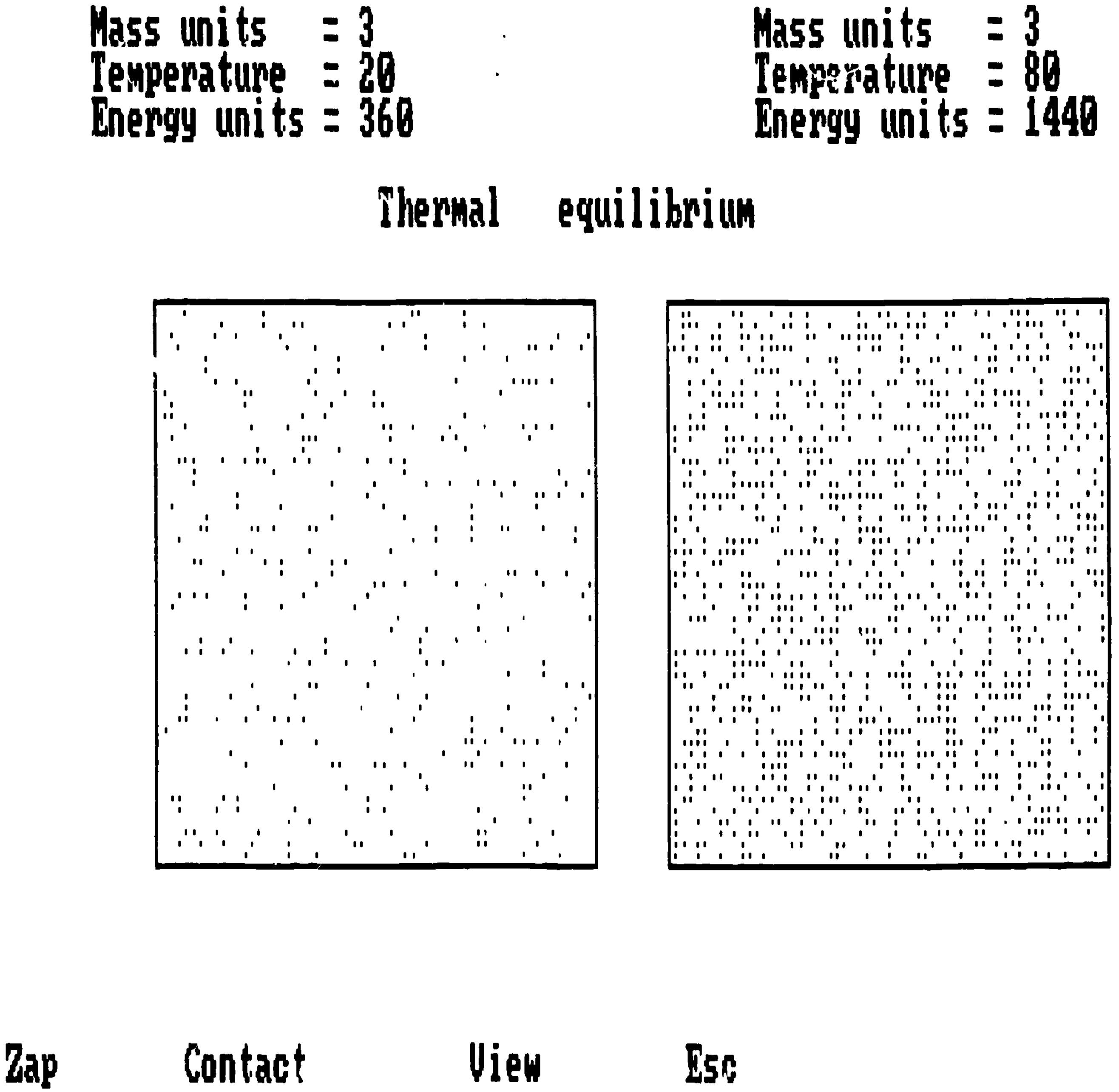
[2] In our models all the molecules in an object at equilibrium have the same speed (i.e., we ignore velocity distribution) and we refer to the amount of heat *inside* an object. See below, "SIMPLIFIED PHYSICS."

[3] See footnote 1. In our initial models we do not differentiate between kinetic energy of the center of mass and total (disorganized) energy per molecule. See below, "SIMPLIFIED PHYSICS."

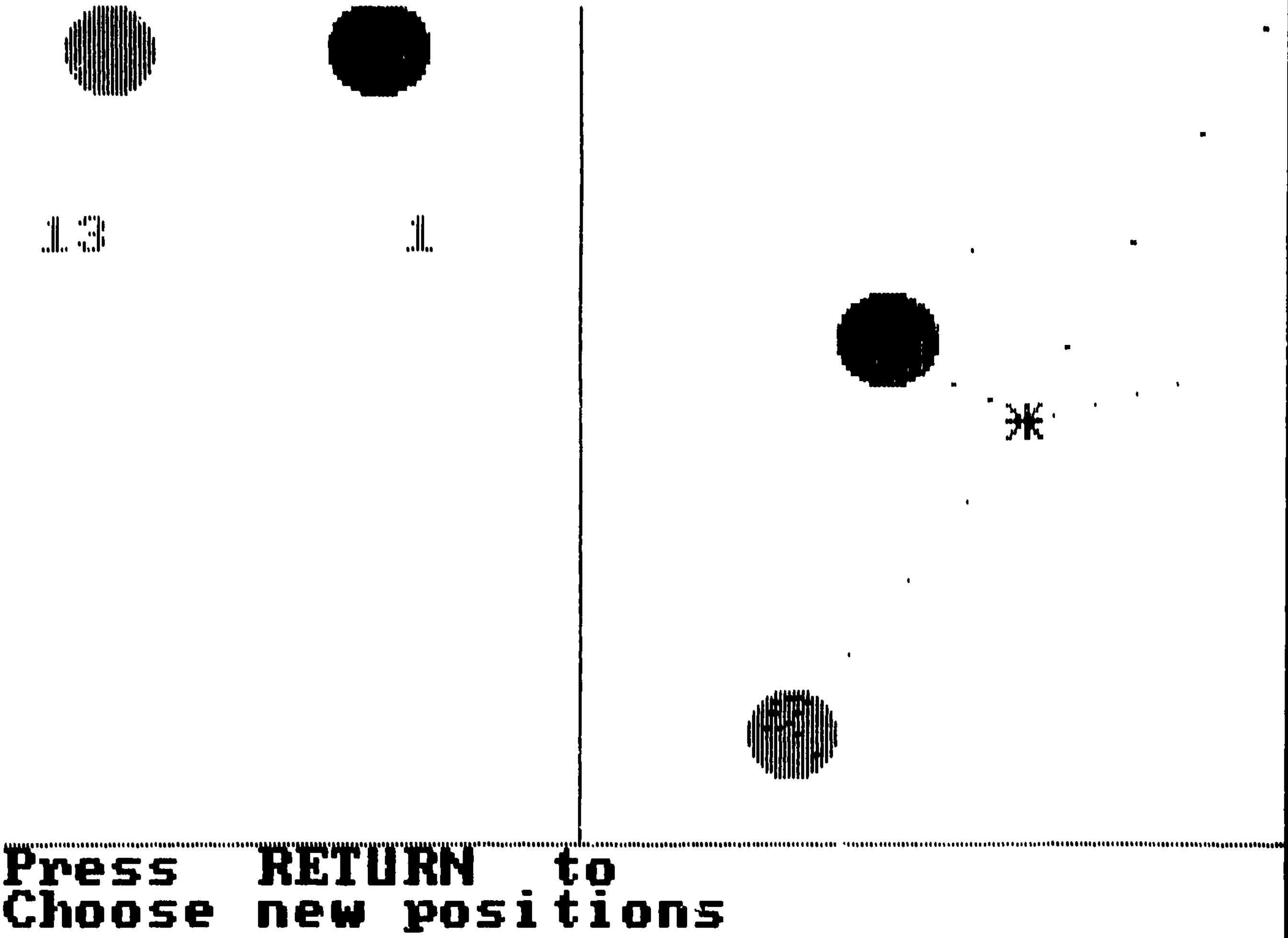


Mass units = 3
Temperature = 20
Energy units = 360

Mass units = 3
Temperature = 80
Energy units = 1440

Thermal equilibrium

Figure 2. Screen from the HEAT & TEMPERATURE 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).



Press RETURN to
Choose new positions

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

dispel misconceptions or to give students a structured framework into which they can integrate new information. The core notion of that molecular model is that molecular velocity increases with temperature, which accounts very well for thermal dilation and conduction and which, indeed, students find compelling and easy to assimilate, but it 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.

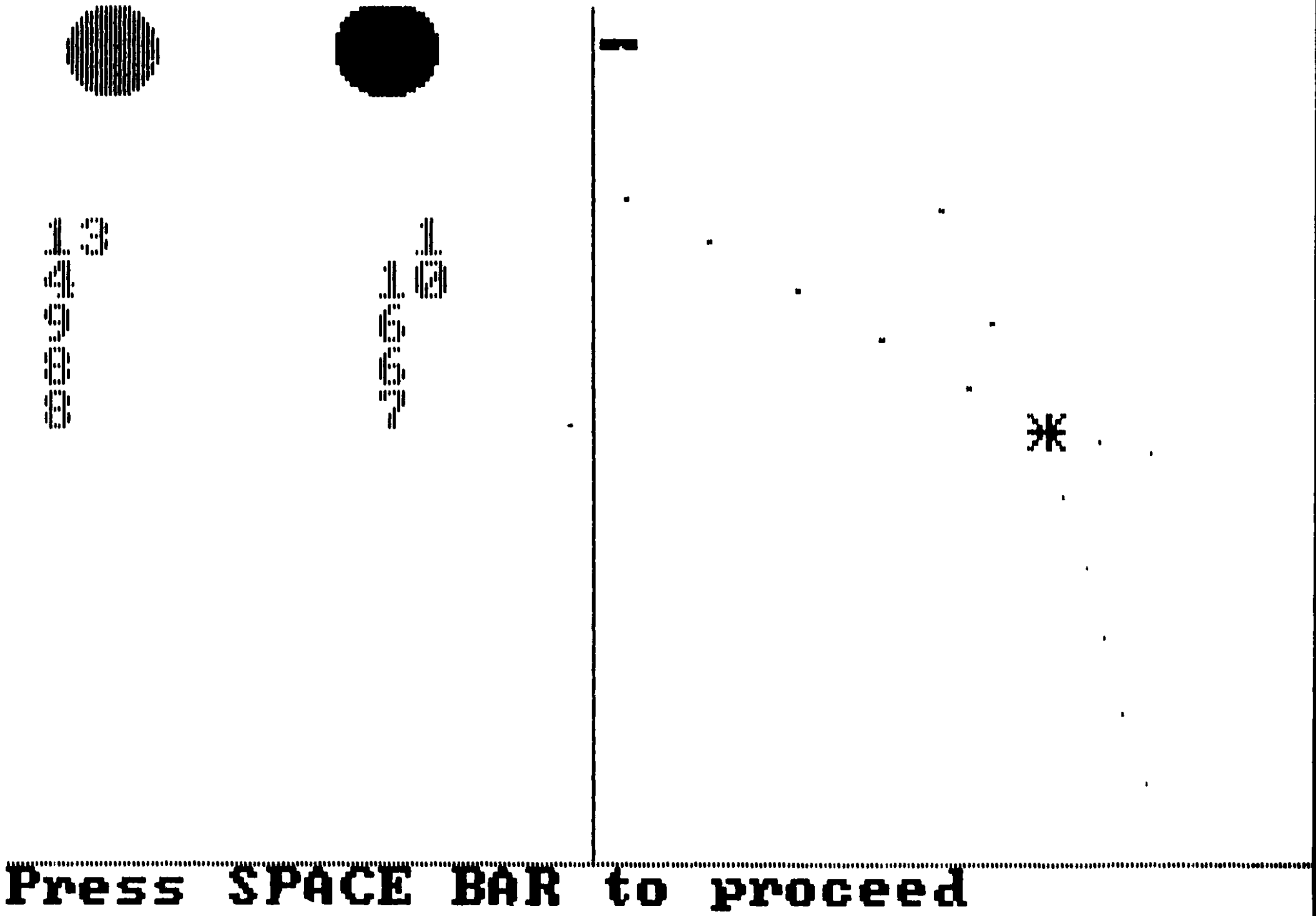
In contrast, our conceptual models are tailored to present both explicitly and transparently the particular aspects of the concepts that the students' misconceptions make hard to grasp in a traditional curriculum: the extensivity of heat (represented by the total number of energy dots) and the intensivity of temperature (represented by dot density) are evident in the visual displays, and the quantitative relation of heat, mass, and temperature is embodied in the visual representations (total number of dots = rectangle size*dot density). The models also show that heat is mechanical energy and that specific heat is a property of substances whose nature is such that (everything else being constant) higher specific heat implies smaller temperature rise. We return to this issue, of the effectiveness of our models in overcoming misconceptions, after the following detailed review of them and a discussion of the reasoning behind some theoretical simplifications the models embody.

THE CONCEPTUAL MODELS

The COLLISION and HEAT & TEMPERATURE programs present a macro level model and a micro (or molecular) level model of the nature of heat and temperature and of their relation. The ENERGY IN MOLECULES, KINETIC & INNER ENERGIES, SPECIFIC GRAM, and SPECIFIC HEAT programs present a macro level model and a micro (molecular) model of specific heat.

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. 4). 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



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13              1
4              10
9               6
8               6
8               7
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Press SPACE BAR to proceed

Figure 4. 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.

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).

HEAT & TEMPERATURE program

In HEAT & TEMPERATURE, the main model, objects are represented on the screen as rectangles. The students are told that the rectangles can represent chunks of solids (aluminum, steel) or containers filled with liquids or gases, and the information presented is general enough to apply to all cases. The amount of heat energy is represented by a certain number of dots and the temperature (when a single substance is considered; see footnotes 1 and 2) by their density. In the normal mode, the molecules are not represented in the rectangle.

The initial choice is "Try your own" or "Tasks." With "Try your own," the user sets the parameters (mass, temperature, or heat), to explore their interelation as well as their relation to 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 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 degrees and 100 degrees; these degrees are proportionally related to degrees Kelvin (at 0 degrees there is no thermal energy in the container, a point explicated only with more sophisticated users) but are 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. 2),,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). Above each container on the screen appear its mass (number of mass units), temperature, and energy (number of energy units). Thus, 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).*

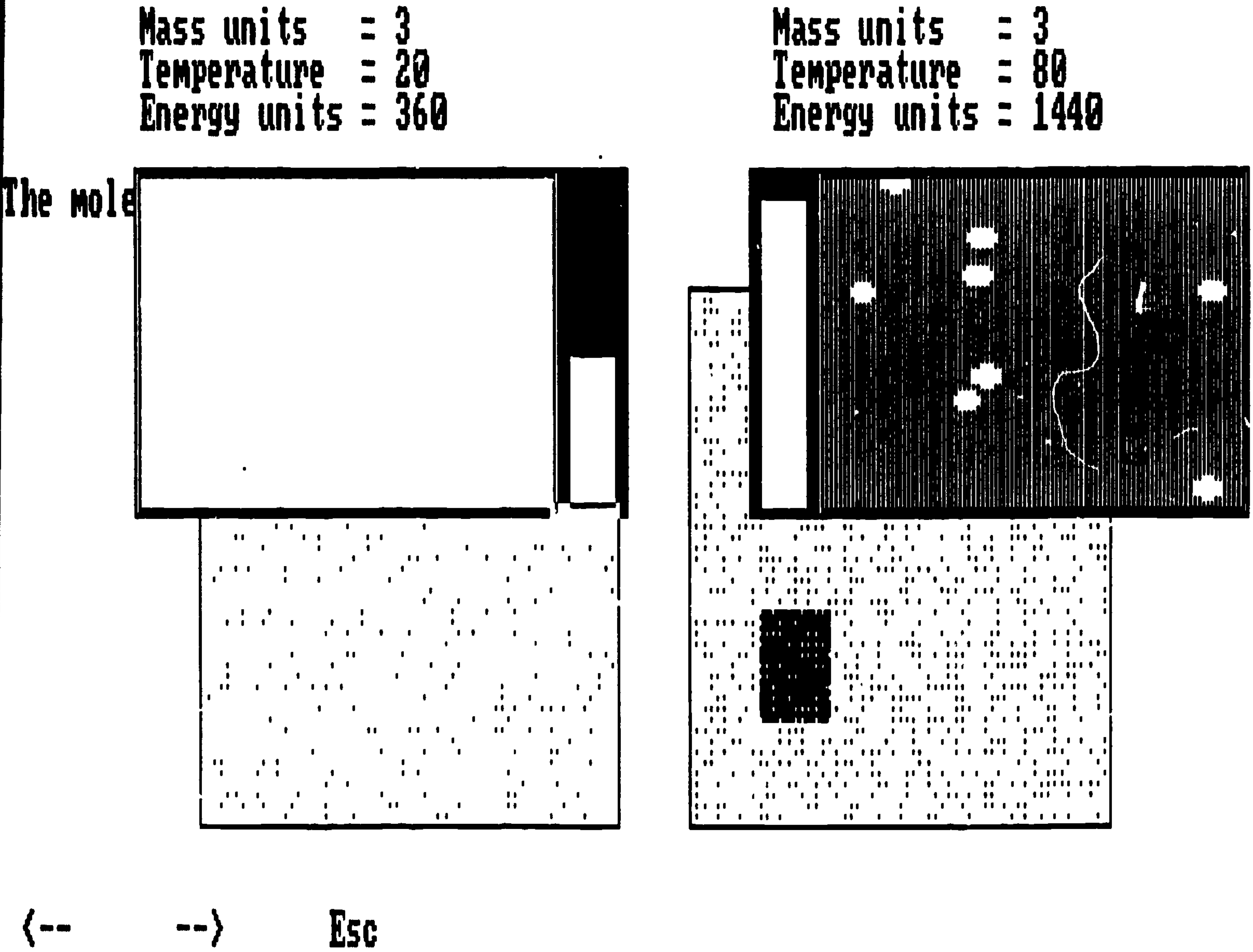
The user can interact with the display in several ways. The first option, VIEW (Fig. 5), allows the user to watch molecules in motion and thus to verify that higher temperature means faster moving molecules (see footnote 2). With left and right arrow keys, the user can choose a container to VIEW. A white 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 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 in the caption. During the equilibration process the temperature is labeled "Undefined" 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. 7). 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.

ENERGY IN MOLECULES program

The ENERGY IN MOLECULES program uses a small number of molecules to make explicit the quantitative relation of heat, mass, and temperature by showing how that relation works at the molecular level. Two pieces of the same material are presented, one made of twelve molecules, the other of six, the first piece thus with twice the mass of the second. As in the other programs, at the start the objects are at 0 degrees, so that the user can easily see the distribution of energy dots. As in HEAT & TEMPERATURE, the user can add heat to the objects by using the ZAP option to add dots (energy) to the molecules. With the VIEW option, the user can see the effect of the heat on the molecules' motion.

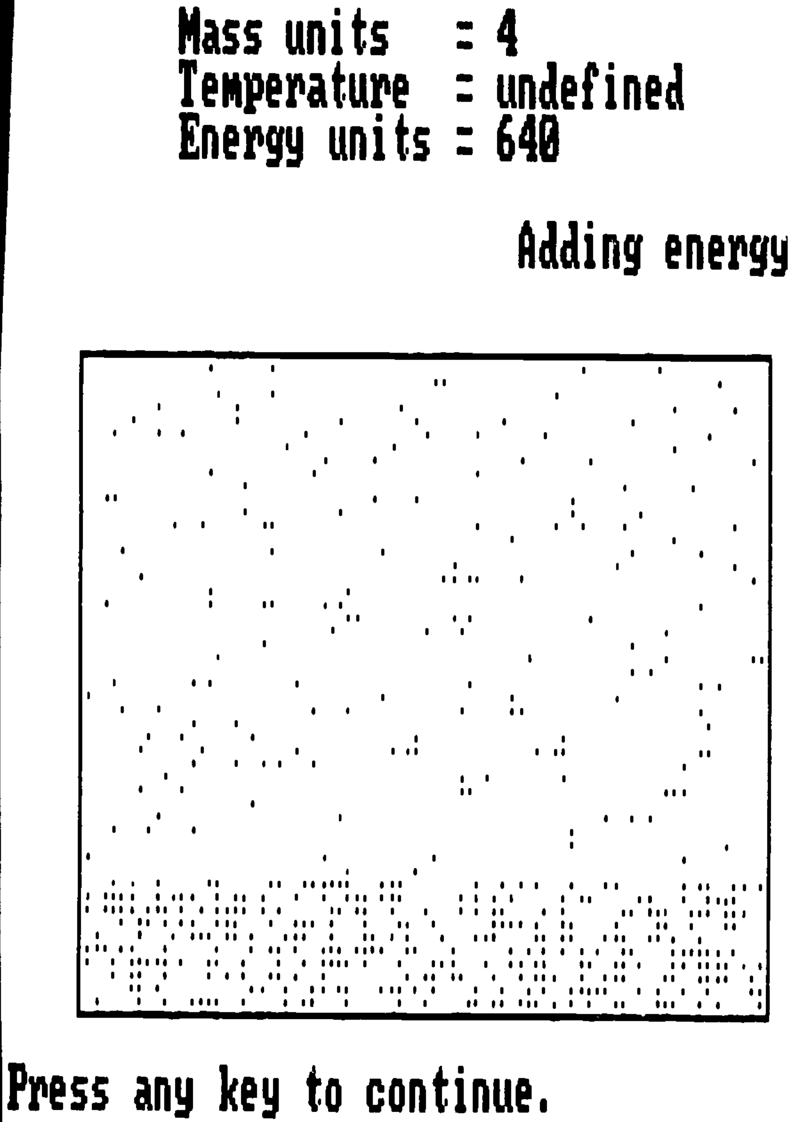


```
Mass units   = 3
Temperature  = 20
Energy units = 360
```

```
Mass units   = 3
Temperature  = 80
Energy units = 1440
```

The mole

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

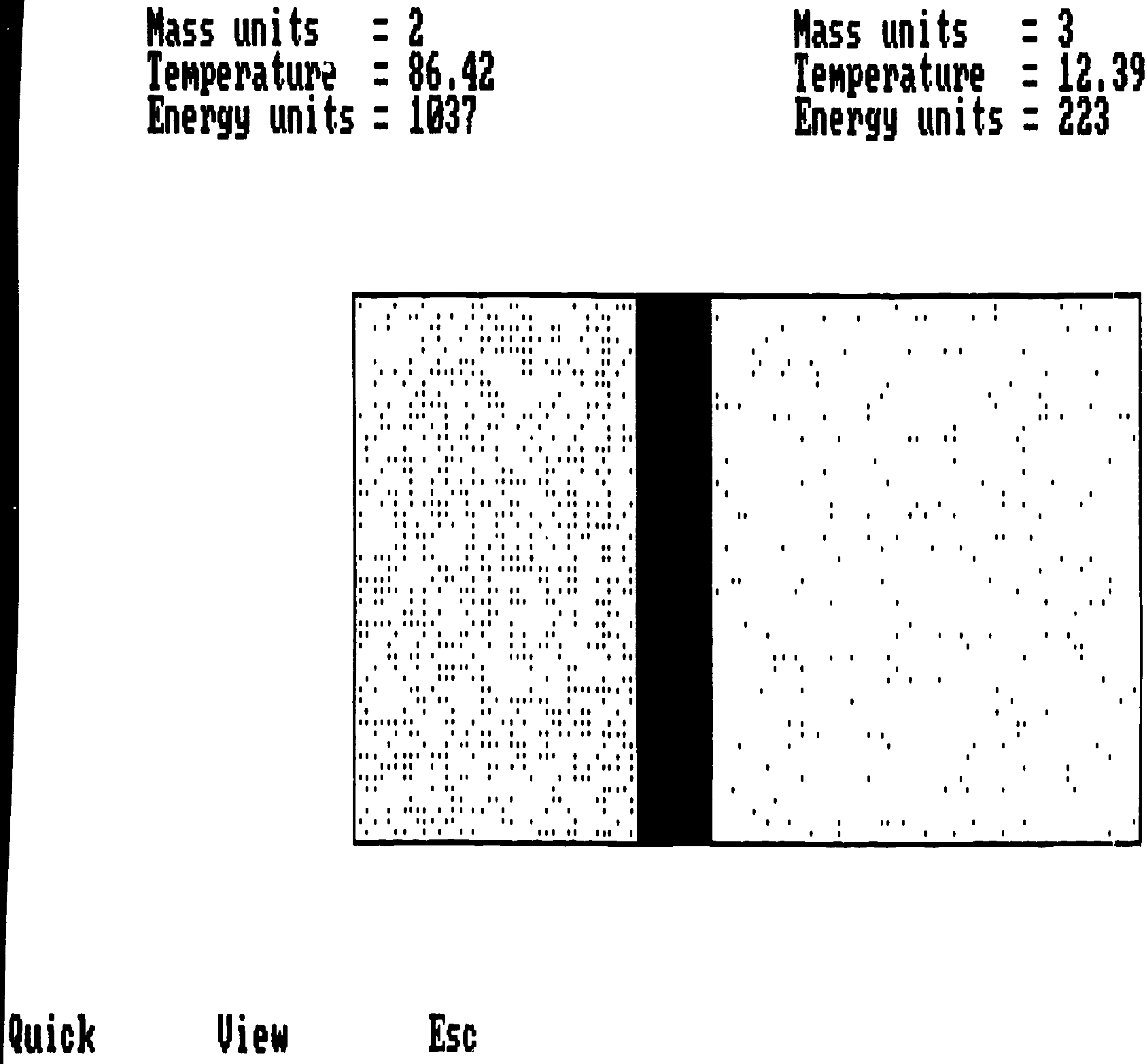


```
Mass units    = 4
Temperature   = undefined
Energy units  = 640

                Adding energy

Press any key to continue.
```

Figure 6. Screen from the HEAT & TEMPERATURE program, ZAP option. Inital stage: energy dots are added at the bottom.



```
Mass units   = 2                    Mass units   = 3
Temperature  = 86.42                Temperature  = 12.39
Energy units = 1037                 Energy units = 223
```

Figure 7. Screen from the HEAT & TEMPERATURE program, CONTACT option. The black bar symbolizes thermal contact between the two containers.

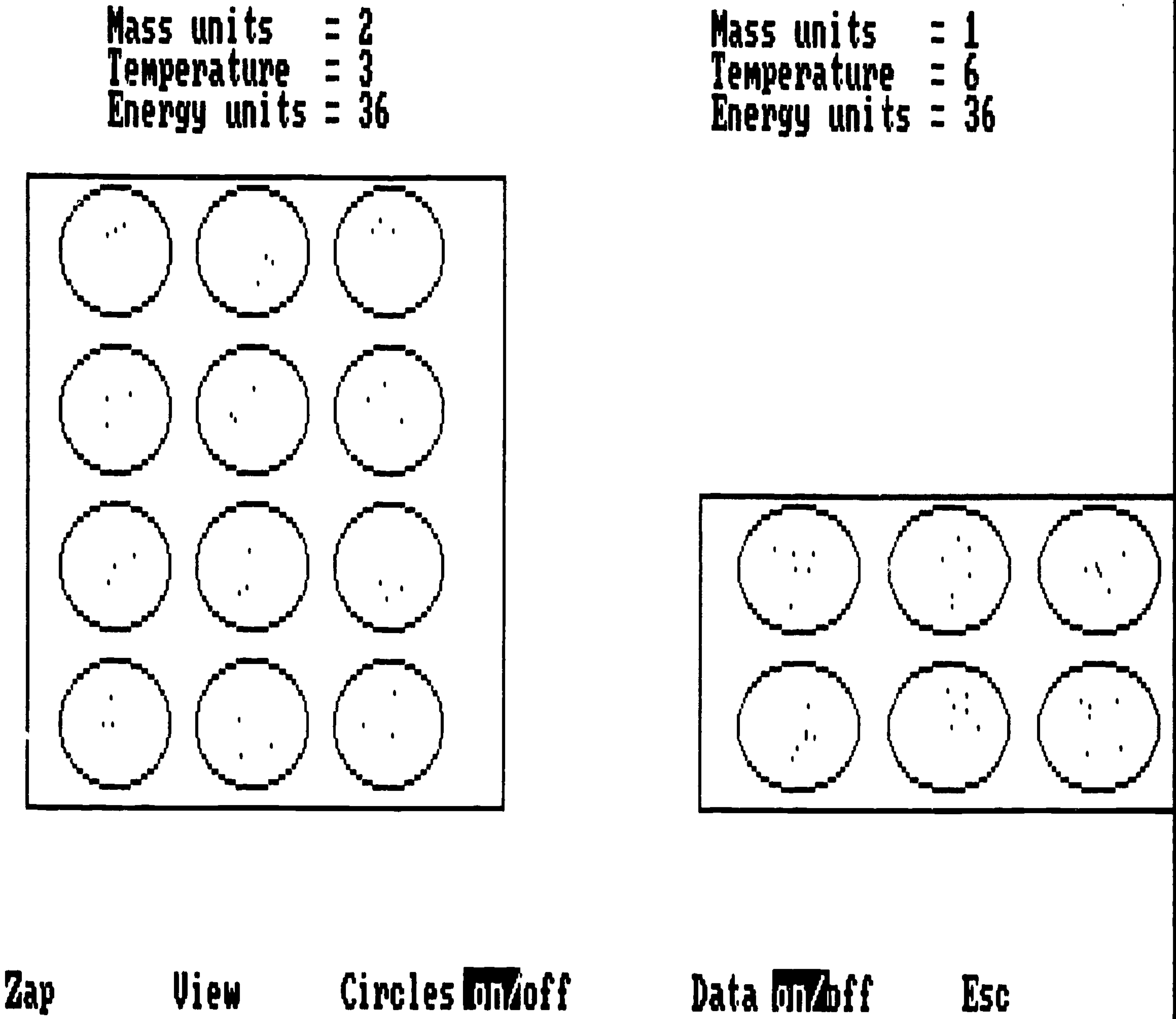
Two new options are added, DATA and CIRCLES ON/OFF. The DATA option is an on/off (toggle) function. The capacity to display or hide information (at the top of the screen) allows the user to make predictions and check them. The CIRCLES ON/OFF option (here the term "circles" refers to the screen representation of molecules) allows the user to display or hide the circles. When the molecules (circles) are "hidden," only the energy dots remain on the screen, i.e., only the energy of the molecules is represented. When both circles and energy dots are on the screen, both the molecules and their energy are represented. Using both circles and energy dots to represent molecules allows the relation between temperature change and added heat energy per molecule to be seen (Fig. 8).

The program emphasizes that the addition of one unit of heat to each molecule of the object (one energy dot per molecule) makes the temperature go up one degree, whatever the mass of the object. The program also emphasizes that adding the same amount of heat to different masses of substance will cause a higher rise in temperature in the smaller mass (since the energy dots are divided among fewer molecules, each molecule ends up with more dots and the increase in temperature of the object is, therefore, higher). Removing the circles from the screen allows the user to think in terms of amount of heat (total number of energy dots) and temperature (dot density), exactly as in the HEAT & TEMPERATURE program.

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 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 one gram of water and one gram of alcohol each receives one 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 out of. A diatomic 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,



```
Mass units   = 2                    Mass units   = 1
Temperature  = 3                    Temperature  = 6
Energy units = 36                   Energy units = 36
```

Figure 8. Screen from the ENERGY IN MOLECULES program. The container on the left has half the number of molecules as the container on the right. The dots represent the energy in each molecule.

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 9. 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. The size of the steps (the distance between two successive dots) is proportional to their speed. On the screen the molecules have a barbell shape, the length of the bar being proportional to their inner energy (symbolic of the fact that atoms vibrate farther from each other when inner energy increases). 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, continuing as long as the user wishes.

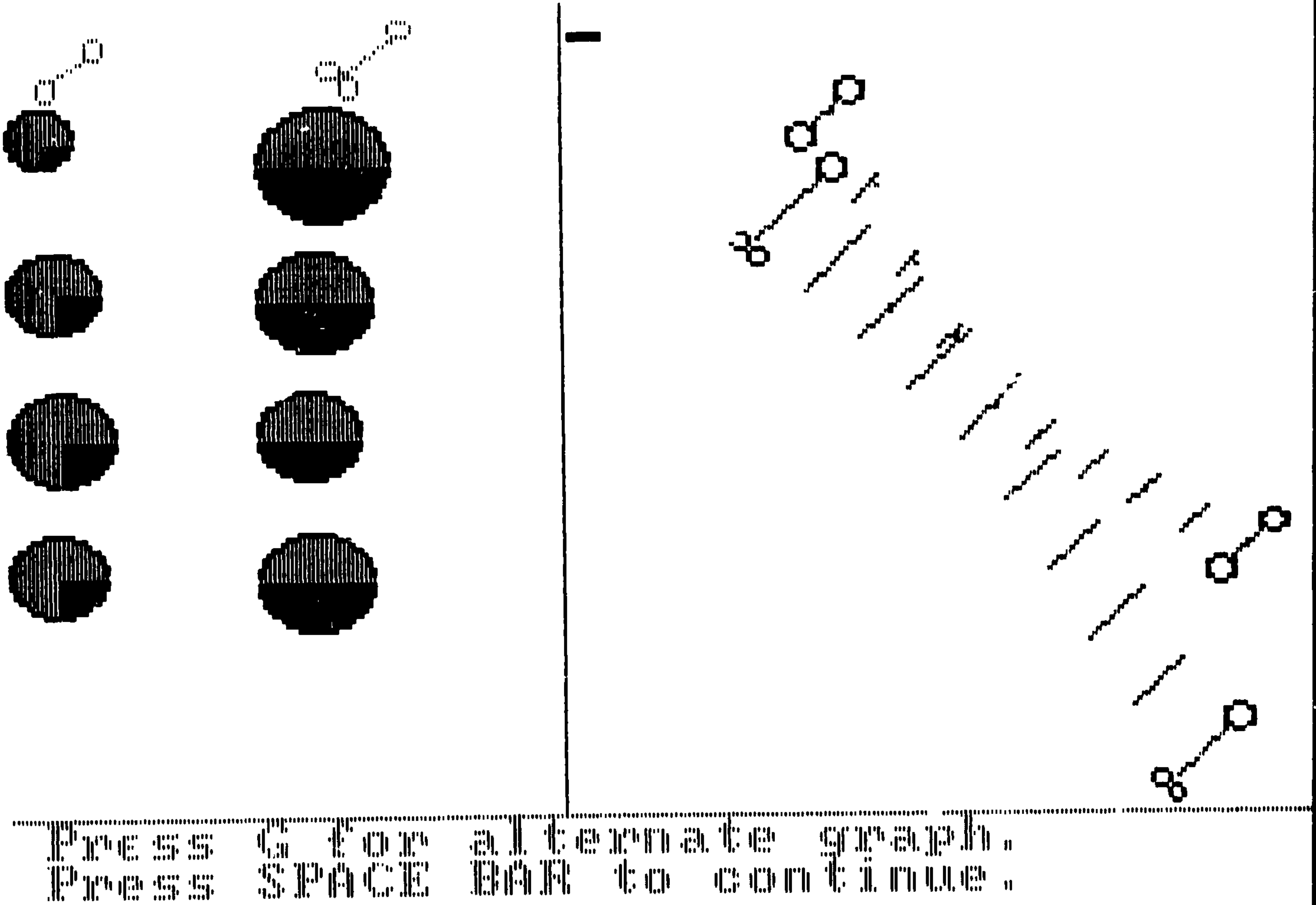
As that occurs on the right side of the screen, on the left the energies are represented by both circles and dots; the total energy for each molecule is the area of an "energy circle." After each collision, the circle expands or shrinks, depending on whether the molecule received or lost energy. If the 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 would be different).

SPECIFIC GRA 1 program

Specific heat as a function of molecular mass

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



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

Figure 9. 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.

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 motion (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 one gram of substance A, which is made of light molecules, and one gram 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 one gram of substance A will be less than in one gram 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 energy of the center of mass motion (contributing to temperature rise) differs; even if each molecule in both substances had received the same amount of energy, each would have different center of mass kinetic energy and the temperature increases in the two substances would be different[4].

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 model: SPECIFIC GRAM. The KINETIC & INNER ENERGIES program would be used to explain the second factor.

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[4] 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.

The 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 one gram of different substances. The user can choose from among four substances[5] that differ either in number of molecules per gram or ratio of inner to kinetic energy in a molecule, or both. Substance A has 6 molecules per gram and [illegible] 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 (Figs. 10 and 11). As before, kinetic energy is represented by green dots and inner energy by red. In this program, one green dot per molecule corresponds to one degree. The user selects two substances, and two rectangles of equal size appear on the screen representing one gram 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 one degree 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 Figure 11 and Figure 12, which represents an increase of one degree 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 or V and then G to see only the green ones 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.

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 HEAT & TEMPERATURE 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. 13).

SPECIFIC HEAT program

This program is the macro level version of SPECIFIC GRAM. As in HEAT & TEMPERATURE, the user chooses the masses and either the temperatures or the energy contents of two containers, which here represent different substances chosen from 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. 14). The number of dots depends on the temperature and on the specific

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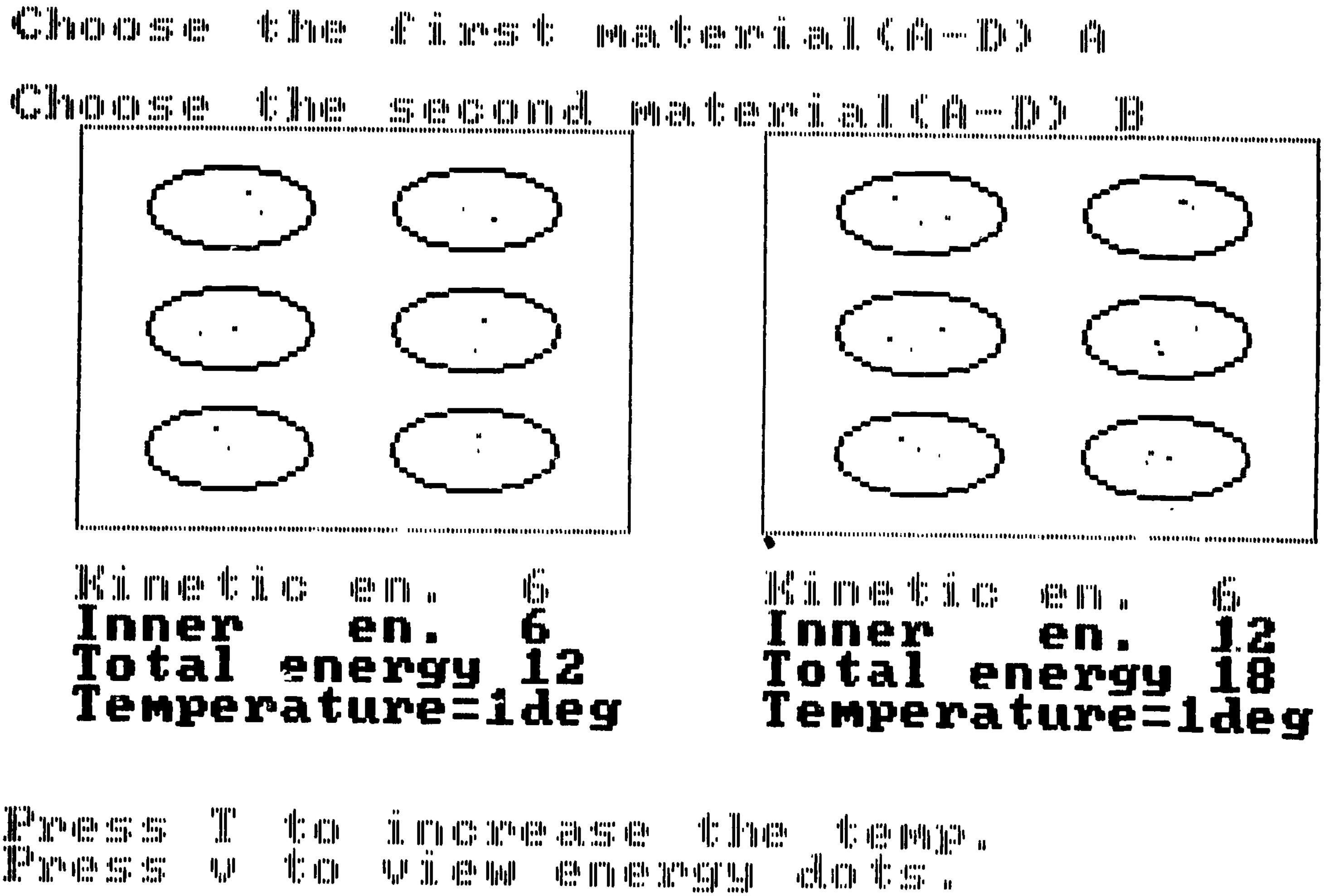
[5] Students are warned that these substances are entirely fictional; one gram of any real substance actually contains millions of molecules. We chose to represent only a few molecules to make concepts easier to grasp.

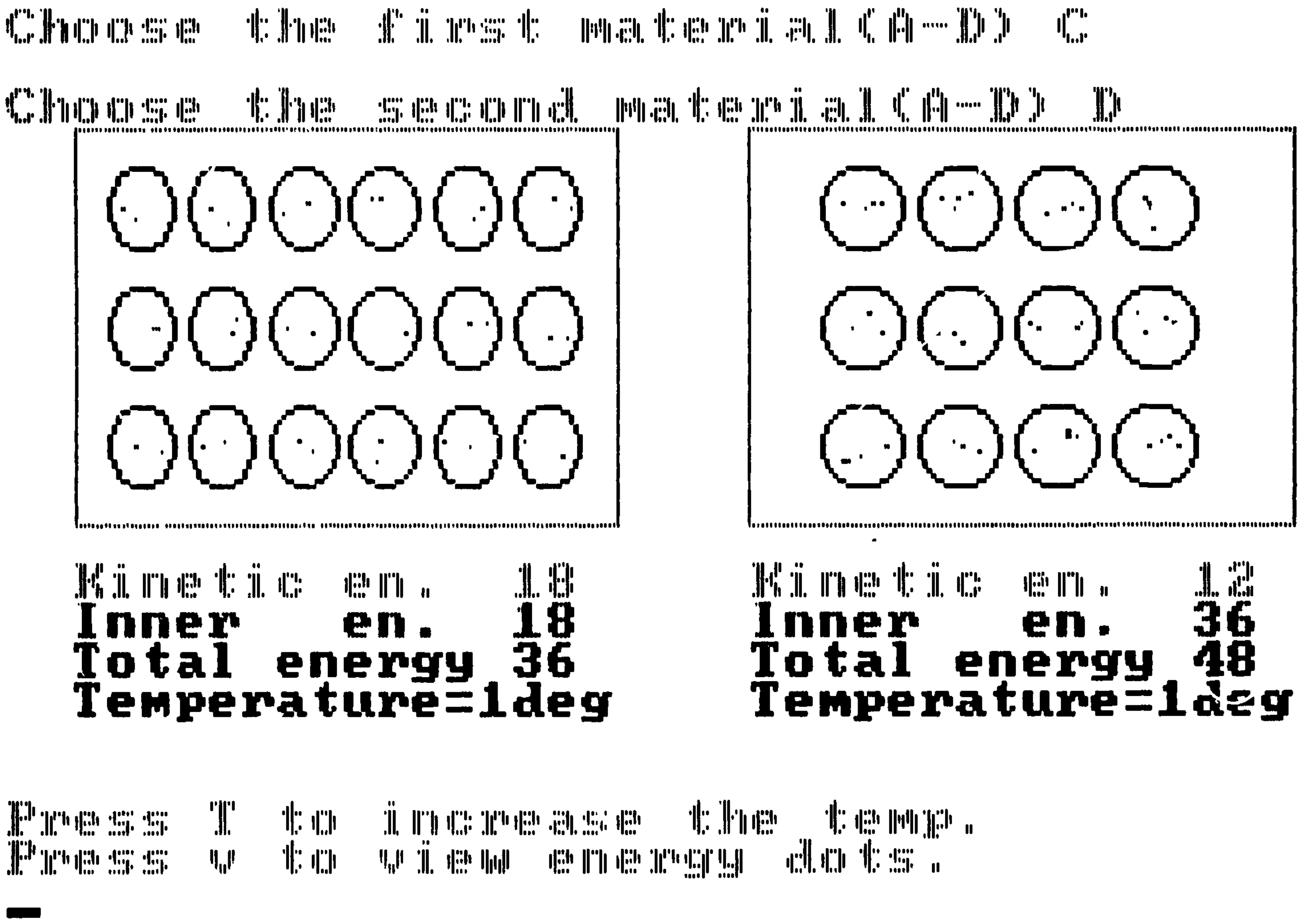


```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.   6                Kinetic en.    6
Inner   en.   6                Inner    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 10. 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 the inner energy. The small dots (green on the screen) represent the kinetic energy.

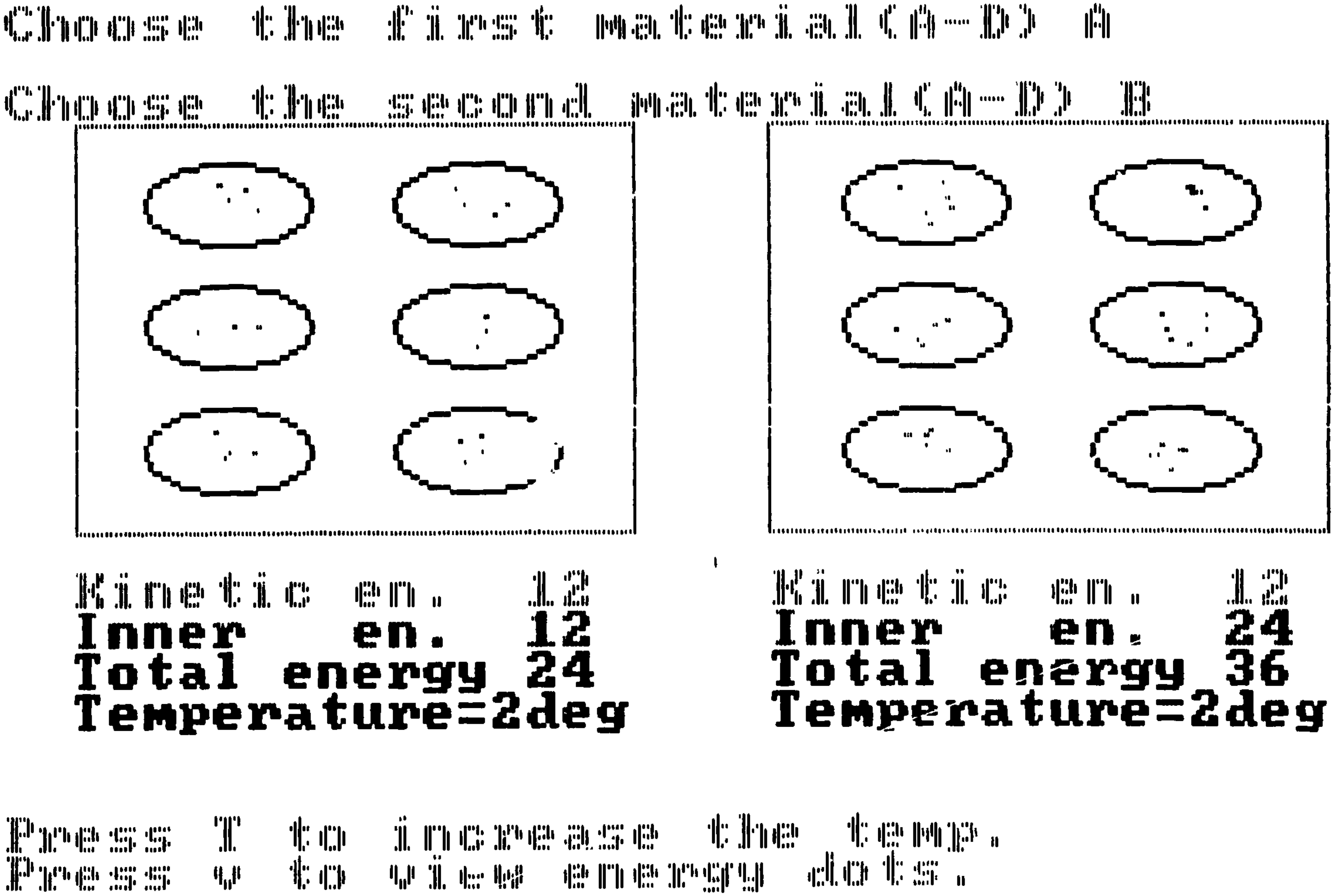


```
Choose the first material(A-D) C
Choose the second material(A-D) D

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


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

Figure 11. 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 the inner energy. The small dots (green on the screen) represent the kinetic energy.

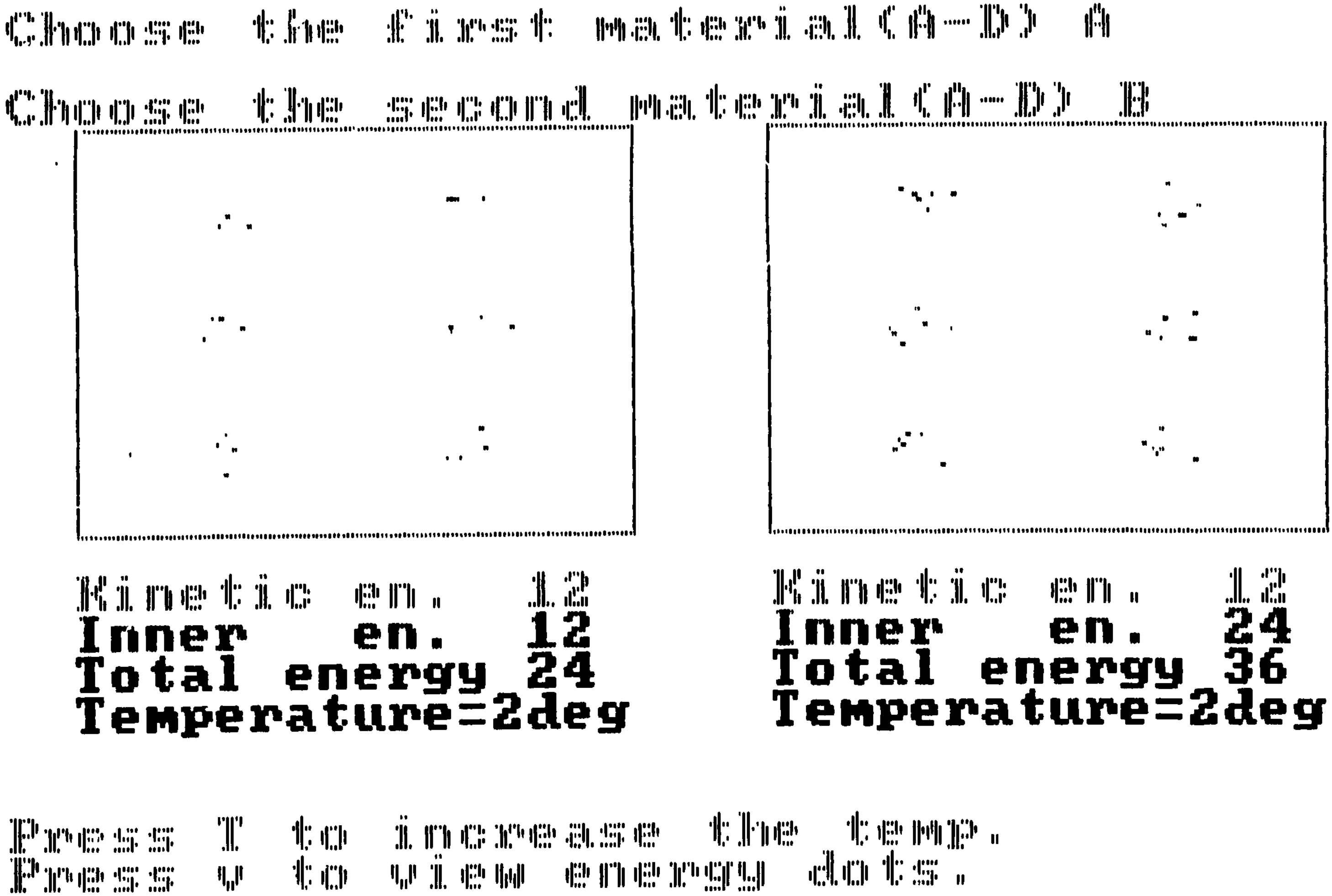


```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.    12          Kinetic en.    12
Inner   en.    12          Inner   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 12. Screen from the SPECIFIC GRAM program. The temperature of both substances has been increased by 1 degree. (Compare with Fig. 10.)

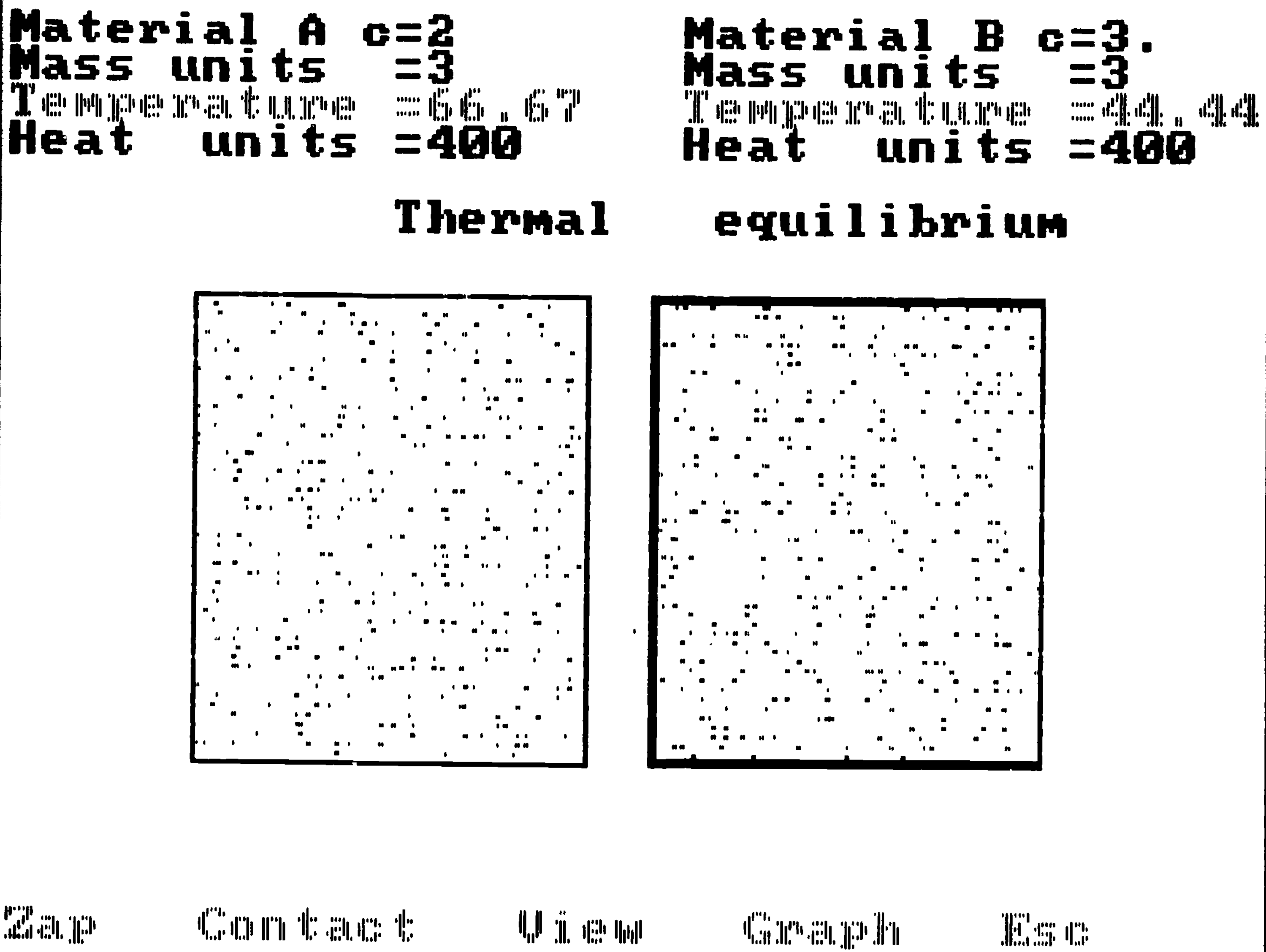


```
Choose the first material(A-D) A
Choose the second material(A-D) B

Kinetic en.   12          Kinetic en.   12
Inner    en.  12          Inner    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 13. 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. 12.)



Material A c=2
Mass units =3
Temperature =66.67
Heat units =400

Material B c=3.
Mass units =3
Temperature =44.44
Heat units =400

Thermal equilibrium

Figure 14. Screen from the SPECIFIC HEAT program. The dark dots (red on the screen) represent the inner energy and the light dots (green on the screen) represent kinetic energy.

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 HEAT & TEMPERATURE, 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 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. 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., three), the user can compare the data from before and after ZAPping (Fig. 15).

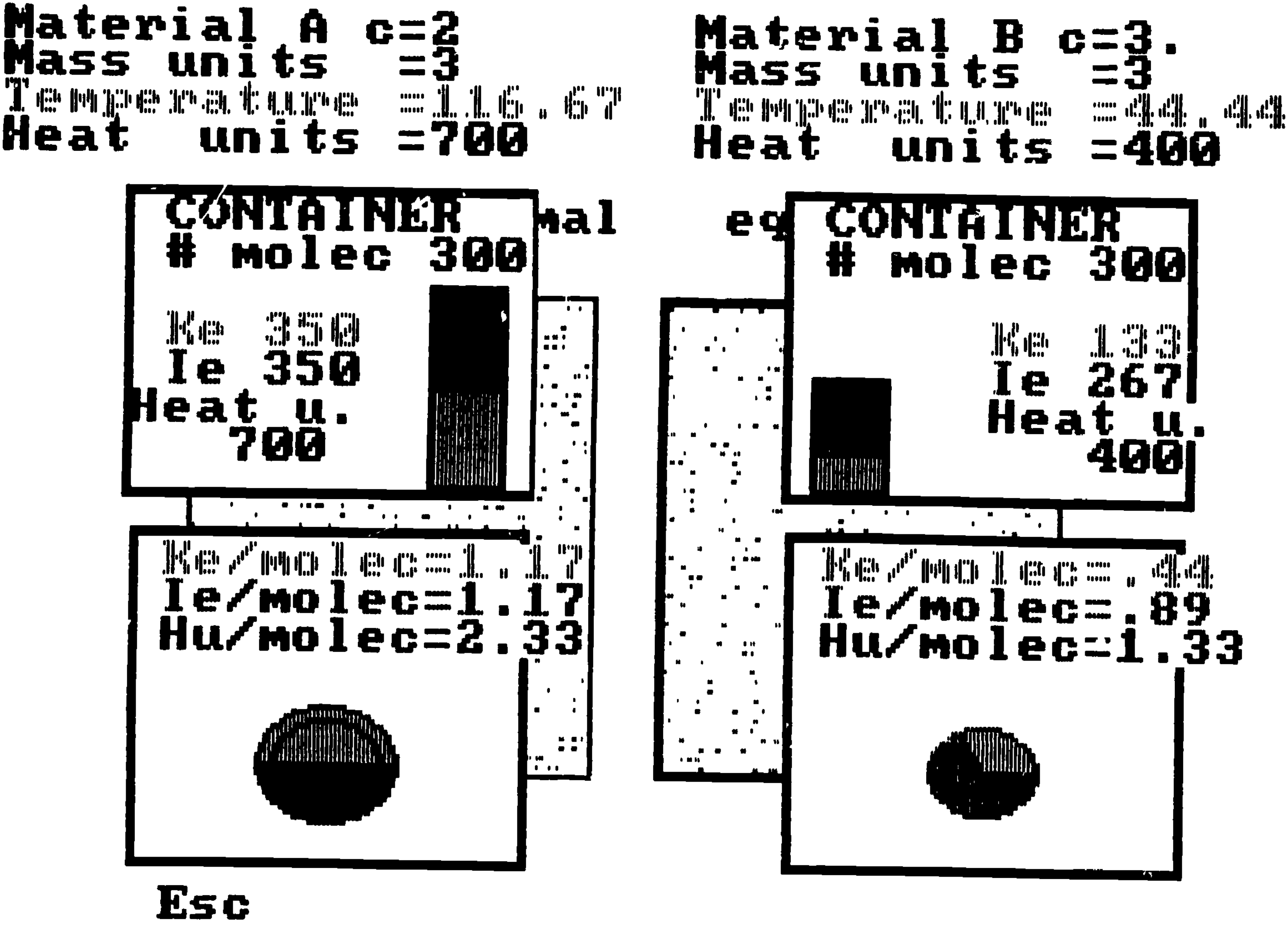
The SPECIFIC HEAT program combines HEAT & TEMPERATURE, KINETIC & INNER ENERGIES, and SPECIFIC GRAM; it embodies the quantitative relation of mass, heat, specific heat, and temperature; and it relates macroscopic events (total energy input, temperature rise) to molecular events.

"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:

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, to equate heat and internal energy.

Similarly, temperature is, of course, not simply the density of heat (heat per molecule), but this idea captures an important difference between heat and temperature (extensivity versus intensivity), which can be elaborated on later, once students are



```
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 15. Screen from the SPECIFIC HEAT program, GRAP and HISTORY options.

comfortable with the extensivity of heat. However, 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 in fact proportional to temperature.

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 what is actually 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 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.

One can find further "simplifications" in that we ignore the distribution of molecular velocities and pretend that all the molecules in a body at thermal equilibrium have the same speed.

Every teacher knows it is difficult to make things clear without lying. We agree, but chose to "lie." Not lying while keeping matters simple implies sometimes vague, sometimes confusing statements (e.g., "Temperature is the average kinetic energy of the molecules," without explaining average over what); such statements truly can impair learning. One cannot be vague with a computer model: either the molecules have the same speed, or they do not. We chose not to represent in the model aspects of the theory not necessary for the main distinctions we wanted students to learn.

Because our models are presented as abstractions, as simplified representations of reality, and because part of our teaching will be devoted to understanding the nature of models and, in particular, to their revisability, we believe our simplifications will not hurt students, even if to some experts they look heretical.

CLASSROOM STUDY

After establishing in a pilot study (see ETC Technical Report TR88–7, *Can models foster conceptual change? The case of heat and temperature*) that our computer models made sense to subjects untrained in physics and helped them to differentiate between heat and temperature, we conducted a classroom study among eleventh graders to evaluate the effectiveness of our models compared with a traditional curriculum. Our model-based curriculum included one short discussion about models (metaconceptual teaching), but otherwise focused on explicating the textbook concepts of heat, temperature, and specific heat and on teaching students how to use the models to represent laboratory experiments and solve quantitative problems. We predicted that reconceptualization would be more widespread, and deeper, among Model than among the Control students, and that the Model students might also be better at problem solving.

PEDAGOGICAL ASSETS OF CONCEPTUAL MODELS

Our goal in designing the software was to create models that explicate the concepts and their relations, that show heat and temperature differ, and *why* substances differ, not simply that they *do*, in specific heat. We wanted to give students an explanatory framework that could help them relate and integrate piece of information often treated as separate topics in the traditional curriculum, as well as help them solve problems about these topics.

In our models, the spatial properties of visual representations of heat and temperature are *analogues* of the distinguishing properties of the concepts — the representation of heat is extensive and the representation of temperature is intensive — and the quantitative relation of heat, mass, and temperature is represented by the spatial relation between their visual representations; thus, the difference and the relation between heat and temperature are explicit visually. Further, by allowing users to set heat content and temperature independently, our models provide a more flexible environment for understanding the distinction between heat and temperature than real laboratory experiments can, in which heat transfer is not so easy to control as temperature and cannot be dissociated from it.

By allowing students to move from the representation of phenomena at the macro level (e.g., heat input, temperature change) to their interpretation at the molecular level (e.g., change in energy per molecule) within a single display, and by using a single format (energy dot), the models give students a sense of the nature of the variables and provide an explanatory mechanism for the laws and principles they need to learn. In doing so, the models give these principles a necessity not available at the phenomenological level.

The programs can be used easily to model laboratory experiments and to solve problems, because the parameters directly correspond to the variables manipulated in experiments and mentioned in problems; some options represent laboratory activities (e.g., ZAPing mimics a hot plate effect and CONTACT can be used to represent mixing two quantities of substance), thereby helping to establish and maintain the link between phenomenological variables and their representations.

We were encouraged by both the finding from previous research that students who learned to differentiate between heat and temperature already had a molecular model for thermal phenomena (see ETC Technical Report TR87-5, *The differentiation of heat and temperature: An evaluation of the effect of microcomputer teaching on students' misconceptions*) and by the success with computer models of the ETC Weight and Density research project (Smith, Snir, and Grosslight, 1987). Like that group, we are dealing with the differentiation of an intensive and an extensive variable, although in their case the variable that gives the students trouble is intensive (density) while in ours it is extensive (heat).

There is, of course, no guarantee that, even if the textbook theory is made meaningful, students will give up their own conceptualization, which is why the metaconceptual issues discussed above (see COMPUTER MODELS OF THERMAL PHENOMENA) must ultimately be integrated into the curriculum (Perkins and Simmons, 1986). Moreover, learning the new theory at the content level may itself benefit from metaconceptual teaching. As stated earlier, we intend to make metaconceptual issues an important and integral part of future classroom interventions, but, with the exception of a short lesson about models, addressed only the content issue in the study reported here.

METHODOLOGY

Our models were recently tested in a classroom study conducted in two eleventh grade classes in a school in a middle-class area near Boston, Massachusetts. The students in both classes were science Honors students of equivalent ability. One class was randomly chosen to receive the curriculum based on the computer models (the Model group; 16 students), the other class serving as a control (the Control group; 13 students). The Control group was taught the teaching intervention by the students' regular physics teacher, and the Model group was taught it by another teacher familiar with our models. In both groups the intervention lasted three weeks.

In this study we decided against having the same teacher administer both kinds of interventions, because of possible bias for or against the model-based curriculum. In one of our MBL studies when the same teachers taught both the MBL and control interventions, they admitted to a bias against the MBL curriculum which may have affected the outcome of the study. Although the alternative (different teachers) can have serious methodological drawbacks, we believe that, in this study, the two teachers were of equal ability, were accustomed to teaching the same level students, and taught each curriculum to the best of their ability.

The content of the curriculum was the same for both groups: nature of heat and temperature, conduction, thermal expansion, quantitative relation of heat, mass, and temperature, phase change, specific and latent heat, absolute zero, mixtures, the relation between work and heat. The students used the same textbook (*Conceptual Physics* by P.G. Hewitt) and performed the same laboratory experiments (with Microcomputer-Based Laboratories software) but received different worsheets. In the Control group the teaching intervention consisted of a series of lectures focusing on the concepts, followed by lab experiments and paper-and-pencil exercises. In the Model group the lectures were kept to a minimum; the students spent most of their time in pairs, performing lab experiments on a given topic and then learning the computer model related to that topic. Their worksheets contained detailed instructions for using the software, theoretical information related to each model, descriptions and interpretations of the models, and exercises to be performed while interacting with the computer models. The teacher was available to answer questions.

The students were tested before and after the teaching intervention. They were interviewed individually, for about half an hour, and took one written test consisting of quantitative problems. The interview was of a conceptual nature, presenting the students with a series of open-ended, nonquantitative problems. The quantitative test, which will be discussed elsewhere, shows a nonsignificant advantage of the Model group over the Control group in their progress from preetest to posttest. In this paper we present an initial analysis of the interviews. The results of our initial analysis are subject to revision after inter-judge agreement has been assessed (and, for that reason, no quotations from them can be permitted). So far, interviews of only 11 of the students in each group have been analyzed.

The Interview

The interview questions probed students' ideas about the relation between heat and temperature, their nature and their measurement, thermal equilibrium, specific heat, and the mechanism of thermal conduction. The questions listed below formed the backbone of the interview; students' answers were closely followed by the interviewer, who asked for clarifications, pointed out potential inconsistencies, and encouraged them to express their conceptualization as explicitly as possible.

The main questions the students were asked were:

Is there a *difference between heat and temperature?* If so, what is it?

Thermal dilation question: Suppose a flask of alcohol is placed in a hot water bath; what will happen to the alcohol level? What makes the level rise? Will the level stop rising? Why, or why not?

Conduction question: If you had an instrument that allowed you to watch heat transfer, what would you see?

More water question: If I pour more of the same hot water around the flask, will the level rise higher? Why, or why not?

Snow question: Suppose I have two big boxes of snow. I pour one cup of hot water into one box and two cups of hot water into the other. Will more snow melt in one of the boxes? [In neither case will all the snow melt.] Why, or why not?

Challenge: [Posed only to the students who said more water would not make the alcohol rise higher and that two cups of hot water would melt more snow.] In the case of alcohol, you told me that more hot water would not make any difference; here, you tell me that more hot water would melt more snow. Is there a conflict between your two answers?

Beaker questions: (a) If I fill a small beaker and a big beaker with hot water from the same kettle, does it make sense to say that there will be more heat in one of them? If so, which one, and why? (b) *(Posttest only)* Consider a small beaker filled with hot water and a big beaker filled with warm water. Does one contain more heat? How do you know?

Steel questions: (a) Imagine holding two pieces of steel on the same hot plate for a brief time. They have the same cross section but one is twice as high as the other; neither has time to reach the temperature of the hot plate. Will one be hotter than the other? Why, or why not? (b) You place both pieces in identical cold water baths. Will one make the water hotter than the other?

Alcohol and water questions: (a) Imagine two flasks with equal masses of water and alcohol. Both are placed in the same hot water bath. What will their temperatures be after a few seconds? Will they contain the same amount of heat? (b) In the long run, will they reach the same temperature? Will they contain the same amount of heat?

Thermometer question: How does a thermometer work?

Pizza question: Have you noticed that when you try to eat a pizza right out of the oven, you burn yourself on the sauce but not on the crust? Do you know why?

The answers to each main question, including responses to further probing by the interviewer, were subjected to multiple categorizations, to yield information about each student's differentiation between heat and temperature, or the lack thereof, their understanding of thermal equilibrium, knowledge about specific heat, and use of molecular arguments. For example, information about differentiation could be found mainly in answers to the *More Water, Snow, Challenge, Beaker, Steel,* and *Pizza* questions; information about equilibrium mainly in answers to the *Thermal dilation, Conduction, Challenge, Alcohol and water, Thermometer,* and *Pizza* questions; and so on. For each question students were categorized according to degree of understanding of each topic (see above, Differentiation, Equilibrium, etc.). A pattern analysis across questions of each student's conceptualization of each topic is in progress and will be reported elsewhere at a later date.

RESULTS

Differentiation of Heat and Temperature

(1) *Explicit definitions of heat and temperature.* More students in the Model group learned that there was a difference between heat and temperature (73% versus 44%) and were able to state contrasting definitions (64% versus 27%) and then elaborate on them (64% versus 0%). See Table 1.

(2) *More water question.* To the pretest question, "Would pouring more of the same hot water around the flask make the level of alcohol go higher?" students answered either "No, it is the same heat." or "No, it is the same temperature." In the posttest, the majority of the Model students (64%; 7 out of 11) refined their answer, spontaneously contrasting amount of heat and temperature: "No, there is more heat, but it is still the same temperature." Only 20% (2 out of 10) of the Control students did so. See Table 2.

(3) *Snow question.* In the pretest, only two students showed that they thought of heat as an extensive variable, by stating that two cups of hot water would melt more snow because it had more heat. The others said either that one cup of hot water would melt the same amount of snow as two cups because they had the "same heat," or that two cups would melt more because it covered a larger area of snow. Of those students, 89% (8 out of 9) in the Model group but only 27% (3 out of 11) in the Control group stated in the posttest that two cups would melt more snow because it had more heat. See Table 3.

The above results indicate a much better grasp of the difference between heat and temperature and greater willingness and ability to articulate those differences explicitly

TABLE 1. Percentage of Students Who Know There is a Difference Between Heat and Temperature, Can State Definitions, and Can Elaborate on Those Definitions.

	Model (N = 11)	Control (N = 11)
1. Know there is a difference	73%	44%
2. State definitions	64%	27%
3. Elaborate	64%	0%

TABLE 2. Number of Students Showing Evidence for or Against Differentiation in the More Water Question.

Model Group

Pretest

		Evidence against differentiation	No evidence for or against differentiation	Evidence for differentiation	Total
Post Test	Evidence against differentiation	0	0	0	0
	No evidence for or against differentiation	0	4	0	4
	Evidence for differentiation	1	6	0	7
	Total	1	10	0	11

Control Group

Pretest

		Evidence against differentiation	No evidence for or against differentiation	Evidence for differentiation	Total
Post Test	Evidence against differentiation	1	2	0	3
	No evidence for or against differentiation	2	3	0	5
	Evidence for differentiation	0	2	0	2
	Total	3	7	0	10

TABLE 3. **Number of Students Giving or Not Giving Evidence for Differentiation in the Snow Question.**

Model Group

Pretest

		No evidence for differentiation	Evidence for differentiation	Total
Post Test	No evidence for differentiation	1	0	1
	Evidence for differentiation	8	2	10
	Total	9	2	11

Control Group

Pretest

		No evidence for differentiation	Evidence for differentiation	Total
Post Test	No evidence for differentiation	8	0	8
	Evidence for differentiation	3	0	3
	Total	11	0	11

among the Model students than the Control students. What follows shows that their superiority is maintained at the level of qualitative problem-solving.

(4) *Beaker questions*. In the analysis presented here, students were classified according to whether they showed complete intensive/extensive differentiation or not. Several degrees of lack of differentiation in answering the first *Beaker* question ("If I fill this small beaker with hot water and that big beaker with the same hot water, does it make sense to say that one has more heat than the other?") are not reflected in this analysis: heat as purely intensive ("Both beakers have the same heat because they have the same temperature"); lack of differentiation between the extensivity of heat and the intensivity of temperature ("The big one has more heat and it is hotter" or "The small one has more heat because it is hotter, because the heat is more concentrated"); heat has degree and amount ("The big one has more of the same temperature heat," "The big one has more of the same degree heat"); and "dynamic" differentiation ("The big one has more heat because it took longer to heat it"). For a detailed argument about the last two categories and why they do not show true differentiation, see Wiser, 1986.

In the posttest, a second *Beaker* question was added: "Consider a small beaker full of hot water and a big beaker full of tepid water. Does one contain more heat than the other? Why?" Subjects who differentiated betweeen heat and temperature gave the following kind of answer: "They could have the same amount of heat, it depends on their temperature and mass." To fit into the category of complete differentiation in the posttest, students had to give such an answer and had to show complete differentiation in the first *Beaker* question. Of those who showed no differentiation or incomplete differentiation in the pretest according to this criterion, 100% of the Model students versus 29% of the Control students showed complete differentiation in the posttest. See Table 4.

(5) *Steel questions*. To be classified as differentiating between heat and temperature, students had to give correct answers [6] to both steel questions and had to justify their answers

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[6] 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

TABLE 4. Number of Students Showing or Not Showing Complete Extensive/Intensive Differentiation on the Beaker Question.

Model Group

		Pretest		
		No differentiation or incomplete differentiation	Complete differentiation	Total
Post Test	No differentiation or incomplete differentiation	0	0	0
	Complete differentiation	9	2	11
	Total	9	2	11

Control Group

		Pretest		
		No differentiation or incomplete differentiation	Complete differentiation	Total
Post Test	No differentiation or incomplete differentiation	5	0	5
	Complete differentiation	2	4	6
	Total	7	4	11

on the basis of the amount of heat received and released by the two steel pieces, in the extensive sense of amount of heat. Of those who showed no differentiation in the pretest, 43% of the Model students and 0% of the Control students showed compete differentiation in the posttest. If the criterion for differentiation is relaxed, so that only a correct and correctly justified answer to only one of the two questions is required, the numbers become 100% versus 33%. See Tables 5 and 6.

Equilibrium

Many questions involved thermal equilibrium ("Will the level of alcohol stop?" "How does a thermometer work?" "If we leave the water and the alcohol flasks in the water bath for a long time, will they reach the same temperature?" and so on). In relation to the cluster of questions, rather than any one particular question, slightly more Model students than Control students (88% versus 71%) moved from never basing their answers on equilibrium, or invoking only an equilibrium of heat ("The level rises until their heat is the same" or "until the alcohol has the same amount of heat as the water"), to mentioning thermal equilibrium at least once. Thermal equilibrium was often defined or explicated in the course of the post-interview: "When the temperature equalizes, the heat stops flowing"; "Equilibrium is established when the molecules in both objects have the same speed"; "Equilibrium means that the molecules in both objects have the same [average] kinetic energy, so they have nothing to give to each other." In both groups from pre- to posttest, the velocity and heat-flow arguments increased in equal proportion, but the kinetic energy arguments appear in the posttest mostly in the Model group (55% versus 9%).

Integrating Equilibrium with Heat Extensitivity

Challenge question. In the pretest, students could not resolve an apparent conflict between the *More water* question and the *Snow* question. Most of them correctly predicted that more water would not make the alcohol level higher but that more water would melt more snow. They were asked, "How is it that more water has more effect in one case but not the other?" Only one student could answer the question. The solution involves heat extensivity and equilibrium; it requires students to see that more hot water will transmit more heat to an object only as long as there is a difference in temperature between the water and the object. Of the Model students 53%, versus 25% of the Control group, moved from being unable in the pretest to resolve the conflict to being able in the posttest to give a well-articulated solution. See Table 7.

The ability to integrate extensivity with equilibrium is also necessary to reach an "advanced" solution to the second *Steel* question ("If we drop both pieces into identical baths of cold water, will one make the water hotter?"; see footnote 6). In the pretest no student gave an advanced answer. In the posttest, four students gave an advanced answer, all of them in the Model group.

To summarize these preliminary results, it appears so far that the Model group reached a deeper understanding of the extensivity of heat, of the concept amount of heat,

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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.

TABLE 5. Number of Students Showing or Not Showing Extensive/Intensive Differentiation on the Steel Question.

Model Group

		Pretest		
		No differentiation or differentiation on first question only	Complete differentiation	Total
Post Test	No differentiation or differentiation on first question only	4	0	4
	Complete differentiation	2	1	3
	Complete differentiation: "sophisticated" answer	1	3	4
	Total	7	4	11

Control Group

		Pretest		
		No differentiation or differentiation on first question only	Complete differentiation	Total
Post Test	No differentiation or differentiation on first question only	4	4	8
	Complete differentiation	0	3	3
	Complete differentiation: "sophisticated" answer	0	0	0
	Total	4	7	11

TABLE 6. Number of Students Showing or Not Showing Extensive/Intensive Differentiation on the Steel Question-Alternate Scoring.

Model Group

		Pretest		
		No differentiation	Complete differentiation	Total
Post Test	No differentiation	0	0	0
	Differentiation on first question only	4	0	4
	Complete differentiation	2	1	3
	Complete differentiation: "sophisticated" answer	1	3	4
	Total	7	4	11

Control Group

		Pretest		
		No differentiation	Complete differentiation	Total
Post Test	No differentiation	3	0	3
	Differentiation on first question only	1	4	5
	Complete differentiation	0	3	3
	Complete differentiation: "sophisticated" answer	0	0	0
	Total	4	7	11

TABLE 7. Number of Students Who Solve or Don't Solve the Snow Conflict.

		Model Group		
		Pretest		
		Do not solve snow conflict	Solve snow conflict	Total
Post Test	Do not solve snow conflict	1	0	1
	Partially solve snow conflict	3	0	3
	Solve snow conflict	5	1	6
	Total	9	1	10

		Control Group		
		Pretest		
		Do not solve snow conflict	Solve snow conflict	Total
Post Test	Do not solve snow conflict	6	0	6
	Partially solve snow conflict	0	0	0
	Solve snow conflict	2	0	2
	Total	8	0	8

and of thermal equilibrium. Moreover, they were able to integrate these concepts into predictions about novel situations (i.e., those not discussed in class).

Specific Heat

Three questions probed the understanding of specific heat: both *Alcohol and Water* questions and the *Pizza* question. In the posttest, the performance of the Model students was much better than that of the Control students, both in the solutions and the justifications they offered.

Alcohol and Water questions. In the pretest, a large majority of students did not answer these correctly. Most of them knew that the temperature of the alcohol would not rise at the same rate as that of the water, but gave the wrong reasons. They argued that one was denser than the other, that it was harder for heat to go through a denser material, or that one had a higher boiling point than the other (the relation between boiling point and heating rate was never explained to our satisfaction), or simply that they were made of different materials and thus "reacted" to heat differently[7]. They thought that if one material was hotter than the other, it was because it had absorbed more heat. Similarly, those who knew that, in the long run, the alcohol and the water would reach the temperature of the bath thought that the two substances would absorb the same heat to get there. Thus, in the pretest their answers revealed no evidence of differentiation between heat and temperature on the basis of specific heat.

In the posttest, 70% (7 out of 10) of the students in the Model group who had given nondifferentiated answers in the pretest showed differentiation on the basis of specific heat in the posttest. They said that, after a few seconds, both flasks absorb the same amount of heat [8] but would not reach the same temperature, because the two substances had different specific heats, but, in the long run, both would reach the same temperature but absorb different amounts of heat. Two more students showed a differentiation between amount of heat absorbed and temperature change and an understanding of specific heat, although their answer to the second question was wrong (they said that, even in the long run, the temperatures would always differ), bringing to 90% (9 out of 10) the proportion of Model students who moved from pretest to posttest from no differentiation to differentiation between heat and temperature on the basis of specific heat. In contrast, only 25% (2 out of 8) of the Control students similarly moved from no differentiation to this level of differentiation.

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[7] They meant reacted in the chemical sense.

[8] This answer is wrong for several reasons. The amount of heat absorbed depends on thermal conductivity and on the temperature inside the flask, both of which differ for the water and alcohol. However, our curriculum did not address those issues. Given the limited information available to the students, this answer can be considered correct and certainly shows differentiation.

The students' justifications follow the same pattern. In the posttest, many in both groups (9 in the Model group, 7 in the Control group) invoked specific heat and defined it correctly (none did in the pretest), but only the Model students were able to explain where differences in specific heat came from. Of the Model students, 64% (7 out of 11) explained that only part of the heat received by an object contributes to the kinetic energy of its molecules, and thus to the temperature increase of the object, the rest of the heat being used to increase the energy in the internal degrees of freedom of the molecules (rotational and vibrational energy). They were also able to explain that differences in specific heats are due to difference in the ratio of kinetic energy to rotational/vibrational energy of the molecules and that this ratio, in turn, depends on molecular structure. In contrast, only one Control student could explain specific heat; the others offered arguments similar to those in the pretest: density, chemical composition, boiling points.

The results of the *Pizza* question are similar. Of the Model students 40% (4 out of 10) who said in the pretest that the sauce burnt because it was hotter, and that it was hotter because it absorbed heat more easily or did not lose it as fast, explained in the posttest that the crust and the sauce were both at the temperature of the oven but that the sauce burnt because it stored and released more heat. In contrast, only 11% of the Control students (1 out of 9) did so. Six more Model students and 3 more Control students, not thinking of thermal equilibrium, said that the sauce and the crust had both absorbed the same amount of heat, but that the sauce burnt because it was hotter, because of its lower specific heat. Thus, of students who showed no differentiation in the pretest, 100% of the Model students but only 44% of the Control students showed it in the posttest.

Quite clearly, the Model group assimilated the concept of specific heat much better than the Control group at the level of qualitative problem-solving, and especially at the explanatory level.

Molecular Arguments

In the posttest, the Model students used many more explanations based on molecules than the Control students. For example, the Model students were more likely to justify their answer to the *Steel* question at the molecular level (the small piece is hotter because the same amount of heat is distributed among fewer molecules) or to account for equilibrium on a molecular basis. To quantify this observation, each student was classified as either using or not using a molecular argument in answer to the questions listed in the Interview section above. The Model students averaged 4 more molecular arguments in the posttest than in the pretest, versus 1.5 for the Control students.

Of particular interest are students' account of *conduction*. In the pretest only one student gave a mechanical account of conduction, explaining that heat is the motion energy of the molecules and is transmitted when the fast-moving molecules in a hot object collide with and give energy to the slow-moving molecules in a cold object. Most of the other students thought of heat as a kind of (unknown) energy emitted by hot sources and spreading through objects in contact with them, thus making them hotter; some said that heat also made molecules move faster. Some students (27% in each group) had a "friction" schema:

the heat from the source makes molecules in the recipient move faster; the molecules rub against each other, thereby generating heat in the recipient and increasing its temperature.

Of the Model students who had not given a mechanical account of conduction in the pretest, 89% did so in the posttest, versus 22% of the Control students. Moreover, 2 Control students held on to their friction schema in the posttest, but none of the Model students did so.

These results, as well as those for thermal equilibrium and specific heat discussed previously, indicate that the Model students had a better grasp than the Control students on the molecular mechanisms underlying thermal phenomena.

The computer models appear to have helped the poorer as well as the better students. In the Model group, some of the best posttests came from students whose pretests showed very strong misconceptions and little knowledge of the textbook theory. In contrast, the pretest and posttest performances of the Control group appear more closely linked, i.e., the students who showed strong misconceptiosn in the pretest appeared to have learned little from the intervention, while those who showed a good grasp on the textbook theory in the posttest were those who aready knew something about it before the intervention.

CONCLUSIONS

The conclusions from this study are straightforward. The purpose of the computer models was to "show" students the extensivity of heat (amount of heat = number of dots), the intensivity of temperature (dot density), the quantitative relation of heat, mass, and temperature (total number of dots = size* dot density) and the mechanical nature of heat transfer at the micro level, as well as to help them understand the concept of specific heat at the molecular level and, thus, differentiate further between heat and temperature.

As the interviews show, the computer models were quite helpful. In the posttest, the Model students displayed a firmer grasp than the Control students on the various thermal concepts, laws, and principles, both at the theoretical and applied levels. Their knowledge formed a more integrated whole, and they showed fewer remaining misconceptions. Finally, they were more able to relate phenomena at the macro level to molecular events.

Understanding how the subjects came to give up their own beliefs (especially that temperature measures heat) and instead adopt the computer model was not the goal of this study, nor of the pilot study (see ETC Technical Report TR88–7, *Can models foster conceptual change? The case of heat and temperature*), and the data from these studies do not lend themselves to a systematic analysis of the process of reconceptualization. We can, however, draw a tentative sketch of the evolution of students' thinking, based on the classroom discussions on this study and the pilot study interviews.

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. The first was mapping temperature on dot density. This was relatively easy, because this notion fitted well within their own framework (denser dots means more dots per molecule, thus more energy per molecule, which they already knew means faster-moving molecules and, therefore, hotter substance). The second thread was the realization that amount of heat is represented by the total number of energy dots, a realization that came more slowly because the students had to adopt a new concept (heat extensivity) which violated their initial belief. In the beginning, the students mapped the energy dots onto their undifferentiated concept of heat: the COLLISION program showed them that dots represented energy transmitted from a hotter body to a colder one but did not attempt to establish the differentiation between heat and temperature, they interpreted COLLISIONS as "the dots have something to do with heat." Later, ZAPping evoked dolloping, reinforcing the notion that heating was represented by adding more dots. The students 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 (because dot density and total number of dots are different). Once this mapping was complete, the students adopted the model as a representation of heat and temperature: they had undergone conceptual change. The differentiation was faciliated by the micro (molecular) level representation; at this level the students saw the molecules in the object, each with a certain number of dots, and recognized that raising the temperature involved giving *every* molecule a certain number of extra dots, the total number of being proportional to the number of molecules. Relating the total number of dots to the total number of molecules fostered in the students a sense of extensivitiy for heat, because the number of molecules is so obviously extensive. The students' 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.

REFERENCES

Carey, S. (1986). Cognitive science and science education. *American Psychologist*, 41, 1123-1130.

Clement, J. (1983). A conceptual model described by Galileo and used intuitively by physics students. In D. Genter and A. L. Stevens (Eds.), *Mental models*. Hillsdale, N.J.: Lawrence Erlbaum.

deKleer, J. and Brown, J. S. (1985). A qualitative physics based on confluences. In D. G. Bobrow (Ed.), *Qualitative reasoning about physical systems*. Cambridge: MIT Press, pp. 7–83.

Driver, R. and Erikson, G. (1983). Theories-in-action: Some theoretical and empirical issues in the study of students' conceptual frameworks in science. *Studies in Science Education*, 10, 37-60.

Driver, R. and Oldham, V. (1986). A constructivist approach to curriculum development in science. *Studies in Science Education*, 13, 105-122.

Hewitt, P. G. (1987). *Conceptual Physics: A High School Physics Program*. Menlo Park, Calif.: Addison-Wesley.

McCloskey, M. (1983). Naive theories of motions. In D. Genter and A. L. Stevens (Eds.), *Mental models*. Hillsdale, N.J.: Lawrence Erlbaum.

Perkins, R. N. and Simmons, R. (1987). Patterns of misunderstanding. An integrative model of misconception in science, math, and programming. Paper presented at the Second Seminar on Misconception and Education Strategies in Science and Mathematics, Cornell University, 26–29 July 1987.

Posner, G. J., Strike, K. A., Hewson, P. W., and Gertzog, W. A. (1982). Accommodation of a scientific conception: Toward a theory of conceptual change. *Science Education*, 66, 221- 227.

Smith, C., Snir, J., and Grosslight, L. (1987). Teaching for conceptual change using a computer-based approach: The case of weight/density differentiation. Educational Technology Center Technical Report TR87–11. Cambridge: Harvard Graduate School of Education.

Stenhouse, D. (1986). Conceptual change in science education: Paradigms and language games. *Science Education*, 70, 413-425.

Wiser, M. (1985). Designing a microcomputer-based laboratory to induce the differentiation between heat and temperature in 9th graders. Educational Technology Center Technical Report TR85–17. Cambridge: Harvard Graduate School of Education.

Wiser, M. (1986). The differentiation of heat and temperature: An evaluation of the effect of microcomputer teaching on students' misconceptions. Educational Technology Center Technical Report TR87–5. Cambridge. Harvard Graduate School of Education.

Wiser, M. (1987). The differentiation of heat and temperature: History of science and novice-expert shift. In S. Strauss (Ed.), *Ontogeny, phylogeny, and historical development*. Norwood, N.J.: Ablex.

Wiser, M. (1988). Can models foster conceptual change? The case of heat and temperature. ETC Technical Report TR88-[illegible]. Cambridge: Harvard Graduate School of Education.

Wiser, M. and Carey, S. (1983). When heat and temperature were one. In D. Genter and A. L. Stevens (Eds.), *Mental models*. Hillsdale, N.J.: Lawrence Erlbaum.