Everything you’ve always wanted to know about what your students think they know but were afraid to ask.

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ABSTRACT

A review of the educational literature on naive concepts about principles of chemistry and physics and surveys of science museum visitors reveal that people of all ages have robust alternative notions about the nature of atoms, matter, and bonding that persist despite formal science education experiences. Some confusion arises from the profound differences in the way that scientists and the lay public use terms such as materials, metals, liquids, models, function, matter, and bonding. Many models that eloquently articulate arrangements of atoms and molecules to informed scientists are not widely understood by lay people and may promote naive notions among the public. Shifts from one type of atomic model to another and changes in size scales are particularly confusing to learners. People’s abilities to describe and understand the properties of materials are largely based on tangible experiences, and much of what students learn in school does not help them interpret their encounters with materials and phenomena in everyday life. Identification of these challenges will help educators better convey the principles of materials science and engineering to students, and will be particularly beneficial in the design of the Materials MicroWorld traveling museum exhibit.

INTRODUCTION

In December 1998, MRS Council approved the concept of the Materials MicroWorld, a traveling museum exhibit that will teach the general public, and younger children in particular, about materials. The need for public education is likely apparent to any practicing materials scientist who has tried to explain what he or she does — the average citizen does not even know what materials science is, much less understand the science behind materials and their properties. Part of the exhibit development process was to determine in greater detail what the target audience for the exhibit already knows about materials and what misconceptions it holds. Some research has been done (primarily with student populations) on the knowledge of basic principles of chemistry and physics related to materials. These studies are often overlooked by the materials science community because they are published in educational journals. One product of the MicroWorld project is a compilation of these sources, easing access to the information.

PROCEDURE

The public conceptions and misconceptions reported in this paper were identified via a review of the educational literature and through two front-end audience surveys commissioned by MRS and conducted among visitors to the Maryland Science Center in July, 1999. The literature search was performed using the education abstracts and ArticleFirst databases available through OCLC’s FirstSearch using the following keywords: misconceptions; materials science education; chemistry misconceptions; physics misconceptions; chemistry education; and physics education. The ERIC educational materials database was also searched for similar keywords, as were the contents of relevant journals, such as The Journal of Research in Science Teaching. References from the initial search hits provided additional sources. This report is an abbreviated
sample of the complete findings of the study.

The front-end audience surveys were conducted by the firm of Randi Korn & Associates (RKA). The results of this work were provided to MRS and are excerpted below. "In general, front-end evaluation is conducted to provide exhibit planners with information about their audience during planning stages of an exhibition. The objectives of the evaluation were to determine visitors’ ability to recognize and identify different types of atomic models, visitors’ ability to interpret changes in scale necessary to model structures of the microworld, how visitors describe materials, and how visitors talk about the properties of a material and their ability to draw a relationship between a material’s properties and its atomic structure. Two sets of interviews were conducted. In one interview, visitors were asked a combination of open-ended and close-ended questions about atomic models and images depicting scale changes. In the other, visitors were asked a series of open-ended questions about a group of materials (everyday objects)."[1] Open-ended questions were used to encourage and motivate visitors to express their opinions and feelings, recollect memories and associations, and share with the interviewer thoughtful responses to complex questions. Close-ended questions were used to discern specific knowledge and abilities of the visitors, in this case pertaining to atoms. "All interviews were tape-recorded and transcribed to facilitate analysis. The interviews were conducted in a quiet area on the fourth floor of the Maryland Science Center in Baltimore."[1] To select participants, the interviewer approached the first eligible visitor (children ages 10-14 and adults ages 18 or older) to cross over an imaginary line on the floor and asked him or her to answer a few questions. "Two separate interview guides were used to conduct the interviews. In interviews about atoms, visitors were asked some questions about atomic models, labeled images of models used by materials scientists, and made selections about scale changes from four sets of images. In the other interview, interviewees were asked to describe a variety of materials and their properties. After the visitor completed the interview, the interviewer awaited the next eligible visitor. A total of 30 interviews about atoms (15 children and 15 adults) were conducted over three days. A total of 30 interviews about materials and their properties (15 children, 15 adults) were conducted over two days."[1]

DISCUSSION

Not surprisingly, the results of the front-end surveys and the literature survey were consistent with each other. "Overall, interviewees expressed a familiarity with models and illustrations of atomic structure, often talking about them using the appropriate terminology. However, much of this knowledge was superficial, and some misconceptions became apparent. In particular, though interviewees recognized the models and illustrations generically to represent atoms, molecules, elements or chemicals, they often used this terminology interchangeably. Furthermore, they were unable to talk about the models more specifically or to differentiate between them when asked to do so."[1]

"In general, interviewees described a group of three models of atomic structure (two 3-dimensional models and one illustration) in very simple terms. When interviewees were initially asked to look at the models, most adults attempted to immediately identify rather than describe the models, while most children began with descriptions and then had to be prompted to identify the models. Nearly all adults, yet only a few children, identified the models as being representative of atomic or molecular structure, yet could elaborate no further. Moreover, most interviewees who did express recognition of the models lacked confidence in their responses. And some interviewees, particularly children, talked about atoms and molecules interchangeably.
with terminology associated with biology, such as genes and cells, when describing the models.[1] The confusion of atoms and human cells is often seen among students, and as such they perceive atoms as being "alive."[2] Many students are cognizant of the fact that atoms are constantly in motion within materials, but erroneously perceive this motion as "being alive" rather than being due to thermal energy.[3]

"When presented with a group of four illustrations of atomic structure and asked to identify them using a collection of labels, all interviewees had a difficult time matching the images with the labels. In fact, when asked, all interviewees stated that they were guessing. Interestingly, though interviewees found some of the images more familiar than others, this did not always preclude correct labeling. For example, nearly all of the adults and many of the children stated aloud that the third image (a molecule) was familiar, yet very few interviewees labeled it as a molecule. Instead, most interviewees labeled the image as an atom or nucleus.[1] This lack of ability to identify common models is compounded when taking into consideration other difficulties the general public has with understanding models. Dyche found that students will ascribe aspects of a model used to describe an abstract concept or an invisible object that are not related to the scientific content as actually being part of the content.[4] An atomic model using prongs to signify electrons given or accepted in bonding resulted in students believing that all atoms had prongs and indentations. Students learn the model, but not the concept it is supposed to be conveying. Taking the model literally, students will ascribe physical changes made to an object (such as flattening a ball of clay) as happening to the individual atoms (atoms flatten out). Shifts between models are very difficult for the learner. A particular materials related model that proves difficult is the electron cloud or electron shell model.[5] Students hold a wide range of beliefs, including a picture of a matrix in which electrons exist like water droplets in a cloud, and shells akin to sea shells, clam shells, or egg shells surrounding an atom.

With regards to size and scale, "interviewees know that the scale of the atomic world is small and understand what it means to change scale in terms of zooming in and out. Yet when confronted with comprehending the micro-scale world of atoms, their own perceptions of "small" no longer work. In particular, children, because of their heavy reliance on "the way things look" rather than interpreting size through labels, expressed this difficulty more so than adults. For example, when asked to guess the size of an atom compared to the width of one human hair, most interviewees guessed that hundreds or thousands of atoms would fit. For them, this guess did indicate an extremely small scale, something they could no longer see. Very few interviewees guessed correctly, which is a million, or even near correctly, suggesting a significant gap in potential visitor’s understanding of "very small" and the truly micro-scale size of materials science."[1] These findings are reinforced by other studies [6,7] which have found that students confuse atoms and molecules and cannot accurately estimate the size of molecules, generally believing molecules to be larger than they are in reality. In fact, many students believe that an optical microscope can be useful in seeing molecules.[6]

"Interestingly, though using different methods, nearly equal numbers of adults and children chose the more magnified image when shown multiple images. It seems that children "guessed correctly" some of the time, and more notably, adults sometimes misinterpreted the labeling. Overall, the zoom lines and scale bars were most often misinterpreted by adults and children; the "flea in the foreground," a visual label, followed by the x1000 notation were interpreted correctly most frequently. Though the "flea in the foreground" was the most successful label for all interviewees, it should be noted that many of the adults seemed at first stymied by the flea, it being an unconventional form of labeling."[1]
"Interviewees were not initially accustomed to talking about materials in the terms of materials science. However, once they were taken through the process of looking at and describing a variety of materials and prodded through continuous questioning, most visitors indicated that atomic structure was responsible for the differences among materials. When interviewees were first asked to define "materials" (after having been told that the interview was about materials science), most responded by listing things they considered to be materials. Adults most often associated "materials" with natural resources and things found in nature, such as wood, water, and minerals. Children most often associated "materials" with fabric, clothing, and man-made objects. Interestingly, many interviewees also defined "materials" in ways that seemed personally relevant to their lives. For instance, a number of adults associated materials with building supplies, and some children with school supplies. Very few interviewees initially talked about "materials" in terms of atomic structure."[1] These results are not surprising. Stavy found that students had difficulty explaining what "matter" is.[8] Students in grades 1,3,5, and 7 responded either by means of example, by means of function, by means of structure ("made of things"), by means of properties, or by referring to things such as reading materials. When asked to decide if something was matter, students did well with solids, but had problems with liquids, biological material, and gases. As they age, there is a shift in the classification toward a more scientific one, but there is not an accompanying change in the explanation or definition of the term matter. For many, matter is something they can see and grasp, preferably solid and inanimate. These findings parallel those of Birley, who found that children correctly classify materials that are overtly solids with little difficulty.[9] For things that are "intermediates" (cloth, paper, rubber foam, table tennis ball, ice) there is no easy way for the children to characterize the substances based on the properties they use to describe the materials. Children seem to have three distinct perceptions of solids — rigid, non-rigid, and powders.

"When interviewees were asked to describe a series of materials (iron bolt, ceramic mug, copper spring, rubber band, plastic case, and aluminum ring), most responded initially by identifying the object and/or material which the object was made of and also providing some description of observable physical characteristics, such as color and texture. They did not at first seem familiar with describing the objects in terms of their behavioral properties. After the interviewer gave a few suggestions for thinking about the way the material behaves in different conditions (e.g., think about what happens when it is heated, when it drops onto the floor, when it is in water), they were able to describe some behavioral properties. However, most interviewees did not use the correct terminology when describing the behavioral properties of the materials. This made it difficult to determine whether, for instance, they knew the difference between hardness and plasticity."[1] Again, this is consistent with what has been found by other researchers,[9] who have found that most children have a rather restricted concept of a metal, exemplified by a large heavy piece of steel; heavy, silvery in color, magnetic, and hard. The children depend on properties when describing materials, but often these properties differ from those that scientists consider important (e.g. malleable, ductile, and conductors of heat and electricity). Students rely upon intuitive knowledge and things they have learned before, such as recognizing an object as steel wool and recalling that steel is metal. This raises problems with categorization - if students don’t know that steel is metal, but know that a knife is made of steel, then they think a knife is not made of metal. Students have difficulty with the hierarchy of categories (e.g. copper, steel, and aluminum are all metals, not separate from metals).

"Interviewees found it easier to describe the behavioral properties of some materials more than others. Most adults and children talked most easily about the behavioral properties of
materials that were either familiar to them or those with properties that could be observed through simple manipulation. For instance, the plastic case is a familiar object. Through past experience with similar objects, interviewees were about to talk about its hardness and plasticity (though not using this terminology). Furthermore, by manipulating the copper string and rubber band, most adults and children were able to talk about, through observation, their behavioral properties. By pulling and stretching the two objects, interviewees could easily witness elasticity and plasticity. The exception to this was the ceramic mug, another familiar object. Rather than describe its behavioral properties, most adults focused on its uses and most children focused on the way it looked in terms of shape and color. On the contrary, few interviewees described the behavioral properties of objects that were less familiar and less easily manipulated, specifically the iron bolt and aluminum ring. Most interviewees focused their descriptions of these two objects on the observable physical characteristics, such as texture and appearance.\[1\]

"When initially asked what makes some materials behave differently from others, most interviewees responded by stating simply that it was because they were made of different materials or because of the way they were manufactured. However, after multiple rephrasing of the question, most adults responded by talking about the atomic or molecular structure of the materials, often describing the differences in the way atoms and molecules are bonded. Nearly half of children were able to describe the differences in materials in this same way, though usually not in as much detail.\[1\] The use of such terms does not guarantee understanding, however. Often students do not make a distinction between the properties of a substance and the properties of the individual atoms that make the substance up, describing an atom of copper as being malleable \[10\] or perceiving atoms in steel to be hard.\[4\] When describing what atoms of carbon might look like, students generally begin with "black" and involve other tactile properties associated with graphite or coal.\[11\] This extends to the perception of changes in materials. For example, when considering the boiling of water, many students believe that the molecules are different sizes in the liquid and the gas phase, expanding as the temperature increases.\[3,4\] They also believe that different molecules of water can vary in size, and that the mass of water molecules can differ among molecules in the same phase and in water molecules in different phases.\[3\] This suggests the more general difficulty people have with differentiating physical and chemical changes. For example, elementary school teachers in England were found to confuse chemical changes with physical changes, with many describing the boiling of water as a transformation in which water molecules are broken apart.\[12\]

People often hold misconceptions about the properties of materials themselves. When asked, even college students often claim that when you crumple up a sheet of aluminum foil, you make it heavier.\[13\] While they may be able to use sophisticated vocabulary to describe mass and density and weight, they don’t understand the differences and don’t know why objects float. In fact, some students believe that objects must contain air to float.\[14\] As a part of a general difficulty in understanding thermal properties of matter, many respondents with density involve understanding what happens to the density of a piece of material when its temperature is changed.\[14\] This is likely due to the fact that students have great difficulty differentiating between the concept of heat (vibrations in the atoms of a material) and temperature (the measure of how much heat is present).\[15\] Students also have problems predicting what happens to the temperature of an object kept in a furnace and predicting what a temperature change or heating means at the atomic/molecular scale, often predicting that atoms change in size when heated rather than vibrating with a greater amplitude. \[16\]

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CONCLUSIONS

It is clear that much of the general public and a large portion of students harbor many preconceptions and misconceptions about materials. These conceptions make the job of materials educators challenging, both in the classroom and a museum setting. There are several strategies and approaches that can help overcome these conceptions. With respect to terminology, when talking about materials, it is important to "clearly define words such as atom, molecule, and element, since laypersons tend to use this terminology interchangeably. To overcome this, consider addressing a common misconception, such as the interchange of atom and molecule with biological terms (DNA, cell) by making the differences explicit. The word "materials" has numerous meanings and may be interpreted in multiple ways."[1] Any discussion should begin with a clear, simple definition of "materials" in the context in which it is used. In conveying structures, the use of three-dimensional models of atomic structure will greatly enhance the experience of visitors to a museum exhibit. To illustrate size, it is best to provide a comparison to the human scale — for example, if atoms were the size of golf balls, how large would a person be? With regards to materials properties, many difficulties arise due to the different terminology used by materials scientists and the lay public. It is key to clearly "define words such as "hardness," "toughness," and "brittleness." It is also important to make the purpose behind testing materials explicit and, in a museum, to overtly state the connections between what visitors are doing with materials and what materials scientists do."[1]

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REFERENCES