The Subcommittee on Research and Science Education, of the House Committee on Science and Technology

HEARING:
"*Improving the Laboratory Experience for America's High School Students*"

TESTIMONY BY:
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H.R. 524: To Establish a Laboratory Science Pilot Program at the National Science Foundation.

As the spring baseball and softball season approaches, we can take a moment to imagine two teams getting ready to begin their season. Both teams have energetic players, dedicated coaches and supportive fans. Both teams have playing manuals, novel strategies and team building exercises. The only difference between the teams is that one practices using bats, balls and gloves while the other team listens to lectures and watches videotapes of professional players. If you wanted your children to win, which team would you put them on?

While it seems silly to think that some parents would want their children to play a sport without actually practicing, we have created a similar scenario in our high school science classrooms. Students in some classrooms investigate the processes of science by performing experiments, making measurements and drawing conclusions from this data. Students in other classrooms read about the processes of science, listen to stories about how experiments are conducted, and watch videotapes. If we want our children to be good scientists, which classrooms should we put them in?

The National Research Council of the National Academy of Sciences recently completed a study entitled, "*America's Lab Report: Investigations in High School Science*" at the request of the National Science Foundation. I had the opportunity to serve on that committee along with nine other colleagues and staff members of the NRC. The committee agreed on a definition of laboratory experience, reviewed the research on the goals and effectiveness of laboratory experiences in our high schools and arrived at a number of conclusions that are all relevant to this committee's deliberations.

The first conclusion of the committee focused on the need to create a definition of laboratory experience to insure that we agree on the instruction we are describing and in order to assist the research community in future studies. The committee's agreed-upon definition that "*Laboratory experiences provide opportunities for students to interact directly with the material world (or with data drawn from the material world), using the tools, data collection techniques, models and theories of science*" includes studies of friction on inclined surfaces, of how metals react with acids and observations of a drop of water with a microscope. It also recognizes that some laboratory experiences do not permit students to record data but instead involve analyzing data from large databases. For example, science researchers study climatic change by reviewing data recorded over the past centuries rather than recording this data themselves. It also does not restrict laboratory experiences to a lab room and includes field experiences where researchers study the ecology of deserts or rain forests.

The committee also culled from the research a list of goals of laboratory experiences which includes:

- Enhancing mastery of subject matter;
- Developing scientific reasoning;

- Understanding the complexity and ambiguity of empirical work;
- Developing practical skills;
- Understanding the nature of science;
- Cultivating interest in science and interest in learning science; and
- Developing teamwork abilities.

The legislation being considered by the committee includes references to the third conclusion of the study and a related concern: that "[t]he quality of current lab experiences is poor for most students", and "[s]tudents in schools with higher concentrations of non-Asian minorities spend less time in laboratory instruction than students in other schools, and students in lower level science classes spend less time in laboratory instruction than those enrolled in more advanced science classes."

Why do we care about lab experiences in high school classes? Why are the poor quality of labs and the unavailability of labs to segments of our population concerns?

No amount of watching other people do science is an adequate substitute for doing science oneself. For 25 years, I have watched my wife take two sticks and bang them back and forth and to and fro and then a sweater pops out. I really have watched at times with interest and fixed attention. What are the chances that you could give me knitting needles and some yarn and I would produce a sweater? Most people tell me that there's not a 50/50 chance, not even a 10% chance. Only the kindest people give me a 1% chance while most people give me no chance at all. If I cannot knit a sweater after watching my wife knit for 25 years, why do we expect that our science students will be able to conduct experiments when they have only observed teacher demonstrations at a distance or, even worse, have only viewed pictures of experiments in textbooks?

In addition to teaching students how to do science, laboratory work also creates a common experience among the students that can be used to improve discussions and increase achievement. The NY Times published an article listing the top ten most viewed television programs by whites and blacks in America. There were only 2 programs that appeared on both lists. The important message from that study is that every time I used a television reference in class, I disenfranchised students who are not like me. When I mentioned a specific popular television program in order to engage the students or provide an analogy, some students did not understand the reference. In most science books about waves, the author describes harmonic motion using the example of waves at the beach. While you and I have seen the ocean, many students in Boston and Los Angeles have never been to the beach and it is only 5 miles from their home. What is a student in Nebraska able to understand when the text reference is to the waves at the beach? In our wonderfully diverse schools and society, we cannot assume that everybody has seen the same TV programs or the same movies; we do not go to the same churches or go on the same vacations; we do not have the same experiences. The laboratory provides a place where students can observe water waves, measure water waves and draw conclusions about water waves. It provides a common experience for all students and, in that way, levels the playing field and provides all students an entry into the science lesson and does not limit that entry to students who have been fortunate enough to have vacationed at a beach.

Once we are convinced of the need for lab experiments in schools, then we must also address the quality of those labs. The NRC report is quite clear that the "typical" lab does not meet the goals of laboratory experiences while the "integrated instructional unit" does. With respect to laboratory experiences, the "integrated instructional units" should provide for exploration of what prior knowledge students bring to the classroom. The lab should then have them compare and contrast their prior knowledge with the results of their laboratory investigation. The lab should not be taught in isolation, but should relate to a larger unit of study. "Just because students *do* a laboratory activity, they may not *understand* what they have done." Moving teachers toward this more viable approach to labs requires teacher training – both pre-service and in-service. Teachers and curriculum developers should apply the following "four principles of instructional design," as enumerated in the report, to make the lab experiences "achieve their intended goals."

1. "[the labs] are designed with clear learning outcomes in mind,
2. they are thoughtfully sequenced into the flow of classroom science instruction
3. they are designed to integrate learning of science content with learning about the processes of science, and
4. they incorporate ongoing student reflection and discussion."

The present-day "typical" lab doesn't produce the intended goals of labs because the lab is often not part of a successful instructional sequence. The "typical" lab is sometimes presented before the discussion of the related concepts while other times it is presented weeks after the concept is discussed. Many times the lab is delayed until the lab room or equipment becomes available. The "typical" lab often asks students to follow a set of 'cookbook' instructions and does not mirror the inquiry aspects that can help students learn about and experience the processes of science.

In contrast, the "integrated instructional unit" follows the design principles outlined above. The labs are used to provide experiences to students prior to having them provide explanations of those experiences. The teacher role is to help students make sense of their data and their explanations and to assist the students in coordinating their observations with accepted scientific content and understandings.

Many science frameworks require that students understand the concept of density. If you were to pick up a traditional textbook, you may find the following paragraph: *Density explains why rocks sink and wood floats. Density is defined as the mass divided by the volume. D = M/V. Let's do a problem: A piece of wood has a mass of 4 grams and a volume of 5 cm*^{3}. *Calculate the density.* The text then goes on to solve this sample problem followed by a more difficult one where the mass and density are given and the student is required to calculate the volume. Students may learn the definition of density and be able to solve such problems, but have no idea why density is important or why we study it. They may or may not then go to the lab to actually make measurements of mass and volume and apply the definition. And, if they do go to the lab, they often engage in a "typical" lab where the steps are outlined and the purpose is to confirm what they have been told. Student misconceptions related to density are rarely addressed. An alternative approach to this concept is used in *Active Chemistry*, an NSF-supported high school science curriculum. Students are first asked to compare a kilogram of feathers and a kilogram of lead. This helps teachers to gauge their students' prior understanding of the concepts. The students then conduct an investigation where they measure the mass and volume of different amounts of water. When they divide the mass by the volume, they find the ratio is always 1g/cm^3. They repeat the same investigation with alcohol and find that the new ratio is always 0.79 g/cm^3. They repeat the same investigation with clay and find the ratio is now always 2.6 g/cm^3. Students are then asked the question, "If someone were to tell you the mass and volume of a material, could you determine if it were water, alcohol or clay." Students easily respond, "Sure. You divide the mass by the volume. If the ratio is 1, it's water; if the ratio is 0.79, it's alcohol; and if the ratio is 2.6, it's clay." When the teacher asks, "But what if I had only a small amount of the material?" the students respond, "Oh the amount doesn't matter. We know that because we tried it many different times with different amounts and the ratio always stays the same." The teacher can then explain that because of its importance, we give this ratio a name – we call it density. Density is a characteristic property of matter. It's one way in which we can determine if you have a diamond or glass ring or whether something is solid gold or gold-plated. Of course, the students then complete problems with calculations as required on exams. In this approach, the concept emerges from the students' experiences in the high school lab. The activity precedes the concept introduction and the concept precedes the introduction of vocabulary. This more closely mirrors how science evolves. Scientists do not invent words and then hope that these words will be linked to important and meaningful concepts. Unfortunately, too many science texts and science programs approach science in this way. In the preferred approach to density, students explore their prior understandings, find patterns in the data, draw conclusions about the importance of the ratio of mass to volume and then return to compare and contrast these findings with their prior understandings. In the *Active Chemistry* unit where this concept is introduced, students must also transfer this content knowledge to a new domain where they have to apply the concept of density to the creation of a special effect for a movie.

A large part of the NRC study surrounded the question of whether labs are effective means of instruction. In other words, do high school labs make a difference? After a careful review of the literature, the committee attempted to respond to this question by looking at each of the goals mentioned above. The review was complicated by the lack of a coherent definition of laboratory experience across the studies. In addition, many of the studies did not control for all variables nor did they take into account how other factors may affect performance. Other confounding factors also made the task of literature review and drawing conclusions from this review difficult.

What the committee was able to conclude was that the "typical laboratory experiences" did not meet the goals we have for lab investigations while the "integrated instructional units" showed promise in meeting the majority of the goals.

With regard to the first goal, mastery of subject matter, "exposure to these integrated instructional units leads to demonstrable gains in student mastery of a number of science topics in comparison to more traditional approaches." Specifically, "In physics, these subjects include Newtonian mechanics (Wells, Hestenes and Swackhamer, 1995; White 1993); thermodynamics (Songer and Linn, 1991); electricity (Shaffer and McDermott, 1992); optics (Bell and Linn, 2000; Reiner, Pea, and Shulman, 1995); and matter (Lehrer, Schaubl, Strom, and Pligge, 2001; Smith, Maclin, Grosslight, and Davis, 1977; Snir, Smith, and Ra, 2003). Integrated instructional units in biology have enhanced student mastery of genetics (Hickey, Kindfield, Horwitz, and Christie, 2003) and natural selection (Reiser et al., 2001). A chemistry unit has led to gains in student understanding of stoichiometry (Lynch, 2004)."

With regard to the second goal of developing scientific reasoning, typical laboratory experiments can help students improve on some of the aspects of scientific reasoning but fall short in assisting students in formulating research questions or designing experiments. In contrast, once again, integrated instructional units can assist students in developing all aspects of scientific reasoning. "They can learn to design experiments (Schauble et al., 1995; White and Fredericksen, 1998), make predictions (Friedler, Nachmias, and Linn, 1990), and interpret and explain data (Bell and Linn, 2000), and interpret and explain data (Bell and Linn, 2000; Coleman, 1998; Hatano and Inagaki, 1991; Meyer and Woodruff, 1997; Millar, 1998; Rosebery, Warrren, and Conant, 1992; Sandoval and Millwood, 2005). Engagement with these instructional units has been shown to improve students' abilities to recognize discrepancies between predicted and observed outcomes (Friedler et al, 1990) and to design good experiments (Dunbar, 1993; Kuhn et al, 1992; Schauble et al., 1995; Schauble, Klopfer, and Raghavan, 1991).

With regard to goal three, developing practical skills, there has been very little specific study in either typical lab experiences or in integrated instructional units. One study did show that girls handle lab equipment less frequently than boys and this is associated with less interest and less self-confidence in science ability in girls.

The remaining goals - understanding the nature of science, cultivating interest in science and interest in learning science, and developing teamwork abilities – follow a similar pattern. The research results are not uniformly consistent in whether the typical lab experiences or the integrated instructional units help students achieve these goals. However, it appears that the integrated instructional units show greater promise than the typical lab experiences.

From the evidence on the effectiveness of labs, the committee recommends that specific design principles mentioned earlier can help laboratory experiences meet their intended learning goals. In addition, the committee concluded that "a serious research agenda is required to build knowledge of how various types of laboratory experiences (within the context of science education) may contribute to specific science learning outcomes."

The introduction of a lab program into a high school is an expensive venture. Lab facilities and equipment require capital expenditures. The replenishment of supplies requires additional annual funds. In addition, safety requirements place limits on the number of students that can be properly supervised in a classroom. Too often, administrators ask teachers to accept unsafe conditions by packing too many students in the lab space. When teachers object, the administrator may suggest that we sacrifice the quality of teaching by not providing lab experiences at all. This Hobson's choice forces teachers to make a bad decision – unsafe conditions or poor instruction. In contrast, high schools across the United States support football teams that similarly require large expenditures for equipment and subscribe to required safety requirements. The football coach is never asked to use sub-standard helmets or to cancel play. High school science should not be considered less important than high school football.

Michael Faraday is arguably the most accomplished experimental physicist of the 19th century. Living as a poor boy in England, Faraday was apprenticed at a young age to a bookbinder. After little schooling and meager math skills, Faraday went on to solve the largest puzzle of his time – how to produce electricity. He accomplished this because of his access to laboratories and his hard work and true talent for experimentation. What would happen to a Michael Faraday in American schools today? As a poor student, he may attend an urban school where there are no labs. As a student with few math skills, he may be enrolled in a science class for underachieving students with no laboratory period. Either way, today's Faraday is denied the opportunity to discover his extraordinary talents in the laboratory and our society is impoverished as a result.

We must provide labs to high school students in order to give them experience with the processes of science in much the same way that I have to practice on knitting needles in order to make a sweater. We have to provide labs to students so that they have a common experience with which to explore science content. And we must insure that all students have equal access to labs regardless of their socio-economic status or whether they are enrolled in an honors class or a remedial class. These labs should reflect what we know about effective, high quality lab instruction as well as what we know about student learning.

If Olympic teams were performing as poorly as our American students are in international competitions, there would be a national cry for more attention, for improved coaching, for more opportunity, and for better equipment. We should have the same sense of urgency for our students. Instead of just being “science students,” they can be “student scientists.”

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Citations for all research studies quoted here can be found on pages 108-115 of *America’s Lab Report*. The text can be accessed at www.nap.edu

BIOGRAPHY: Arthur Eisenkaft is Distinguished Professor of Science Education at the University of Massachusetts Boston, where he also directs the Center of Science and Math in Context (COSMIC). He previously taught physics and served as science coordinator in New York public school districts for 28 years. He is a past president of the National Science Teachers Association and has been involved in a number of its projects, creating and chairing the Toshiba ExploraVisions competition and the Duracell science scholarship competition. He is project director of *Active Physics*, an NSF supported curriculum project, which is introducing physics instruction for the first time to all high school students. He is also project director of *Active Chemistry*. He initiated U.S. involvement in the International Physics Olympiad, was academic director for the first eight teams and then served as the executive director of the XXIV International Physics Olympiad in 1993 when the United States hosted the competition for forty participating countries. He holds a U.S. patent for an improved vision testing system using Fourier optics. At the National Research Council, he was a member of the curriculum working group that helped develop the National Science Education Standards, the Committee on Learning Research and Educational Practice, the Committee on Attracting Science and Mathematics Ph.D.s to K-12 Education, and the Committee on Assessing Technological Literacy. He is a fellow of the American Association for the Advancement of Science (AAAS), a recipient of the Presidential Award for Excellence in Science Teaching (1986) and the Disney Science Teacher of the Year (1991). He has been recognized for his contributions to science education by the American Association of Physics Teachers (AAPT), the American Physical Society (APS) and the National Science Teachers Association (NSTA). He has a B.S. and M.A. degrees from Stony Brook University and a Ph.D. from New York University.