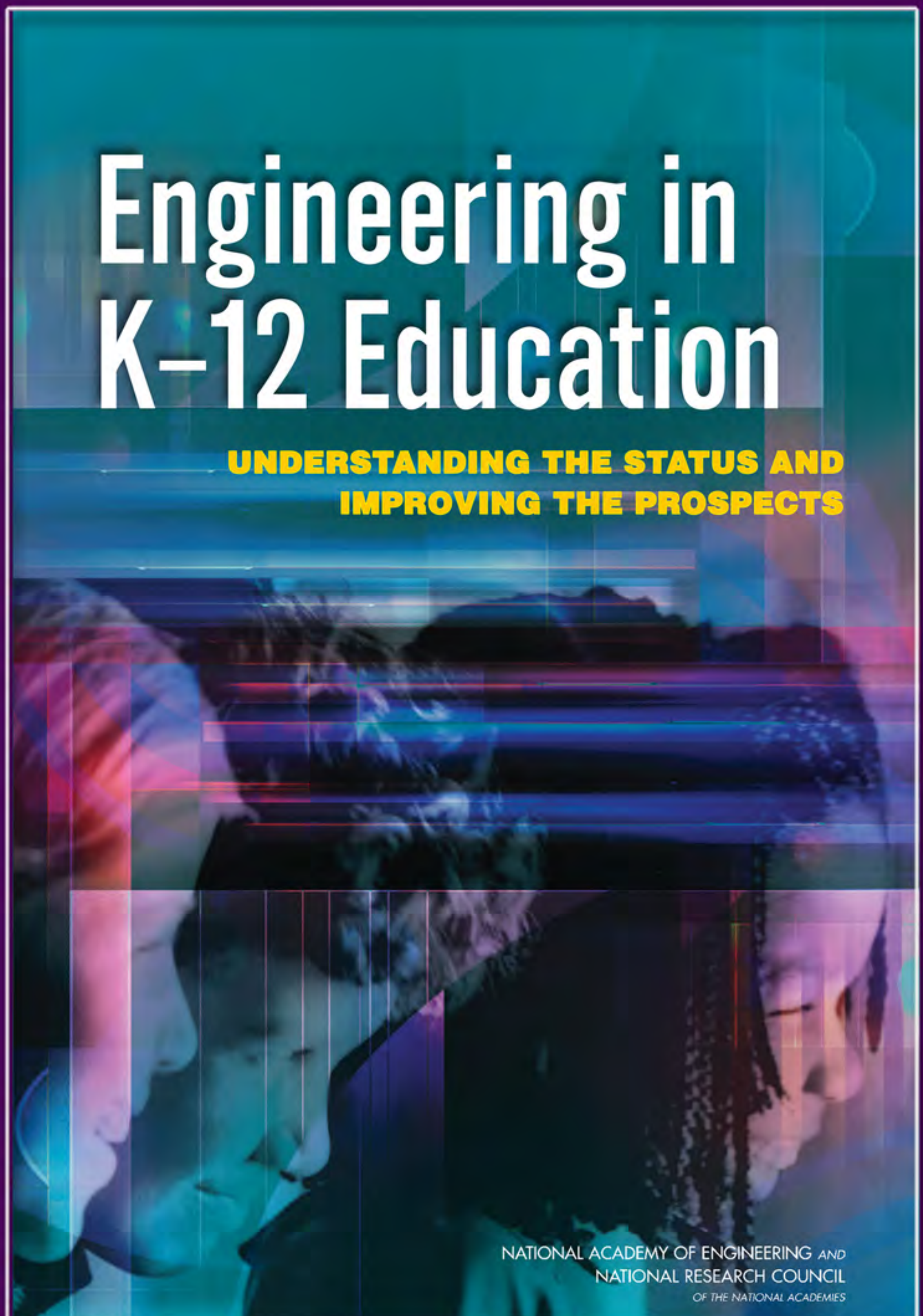
Materials World Modules in K-12 Education:

Excerpt from the National Academies Report



MWM

An Inquiry- & Design-Based STEM Education Program

http://www.materialsworldmodules.org/

Engineering in K–12 Education

UNDERSTANDING THE STATUS AND IMPROVING THE PROSPECTS

Committee on K–12 Engineering Education

Linda Katehi, Greg Pearson, and Michael Feder, *Editors*

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Appendix C

Curriculum Projects—
Detailed Analyses

Institution Northwestern University
1801 Maple Avenue
Box 37, Suite 2431
Evanston, IL 60208
Tel: (847) 467-2489
Fax: (847) 467-5544
E-mail: mwm@northwestern.edu
Web site: http://www.materialsworldmodules.org

Leader Robert Chang, Northwestern University

Materials World Modules

Northwestern University, Evanston, Illinois

The Materials World Modules (MWM) is a series of interdisciplinary modules based on topics in materials science. To date, the program offers modules on composites, ceramics, concrete, biosensors, biodegradable materials, smart sensors, polymers, food packaging, and sports materials. They are designed for implementation in middle and high school science, technology, and math classes. Their pedagogical approach centers on the principles of inquiry and design and utilizes hands-on learning activities that enable students to apply materials science concepts and skills to problems found in everyday life outside of school.

Inception and Development

Dr. Robert Chang launched the Materials World Modules (MWM) initiative in 1994 with a grant from the National Science Foundation. He is a Professor in the Department of Materials Science and Engineering at Northwestern University in Evanston, Illinois. He received his B.S. degree in Physics from the Massachusetts Institute of Technology and his Ph.D. in Astrophysics from Princeton University.

Prior to securing funding for the MWM project, Dr. Chang enjoyed "…being involved with teachers, learning from them, seeing how things work in their classrooms, and discovering the issues" that influence science education. One of the factors that helped inspire him to develop the MWM materials was the limited nature of the opportunities that were available for his own two children to cultivate an interest and appreciation for science. Another factor was a latent desire to attract students to the materials science program at Northwestern University. However, the need to simply improve the quality of science education overshadowed these earlier motives.

Dr. Chang said, "I started out working with the school districts to make changes but that is like climbing Mount Everest. I wouldn't see any genuine change in my lifetime. So, I decided to make these modules — something that might make a difference."

The project set out to develop, field test, and disseminate a series of supplementary materials for high school teachers and students. Given the pervasiveness of materials in everyday life, the project's authors felt the study of materials would facilitate students'discovery of the interconnections between science, technology, and society (STS). The authors also felt organizing instruction around topics from materials science would help students see how science relates to their lives. Therefore, they established teams of university faculty, high school teachers, professional editors, and graphic designers to develop instruction modules that center around the themes of materials science and engineering. Their goal was to engage students in scientific inquiry in the contexts of solving design problems that required knowledge of materials science. They wanted to create modules that required students to "…ponder design problems that scientists and engineers encounter every day in the workplace."

"My premise for what I do is to improve science literacy. Not everyone is going to be a scientist. A majority of the population… does need to appreciate the importance of science. We study music and art so we can appreciate things like music and art. We just want to bring science to the same level."

Robert Chang

Mission and Goals

The **mission** of the Materials World Modules is to improve science education by engaging students in the intellectual processes of inquiry and design. Consistent with this mission, the modules are designed to enhance the teaching of traditional science curricula by facilitating greater student awareness of the relationships between scientific and technological concepts and real-world applications.

The Materials World Modules program was developed to address the following goals. The authors purport that these goals are consistent with those published by the National Research Council (1996) in the *National Science Education Standards*.

- Develop the abilities necessary to do scientific inquiry. These include the ability to generate questions, design and conduct scientific investigations, formulate models, analyze alternative models, and communicate and defend explanations.

- Understand scientific inquiry. Understand that scientific inquiry is focused on logically consistent explanations, grounded in current knowledge and augmented by mathematics and technology.

- Become familiar with materials science. Develop an understanding of materials science by applying knowledge from physical, life, and earth sciences to create materials for specific purposes.

- Take part in iterative design. Provide opportunities to identify technological problems, propose designs, choose between alternative solutions, implement and evaluate a solution, redesign the product, and communicate the problems, process, and solution.

- Understand the relationship between science and technology. Understand the difference between the purposes and nature of scientific and technological studies and the interrelationship between the fields.

- Understand contemporary problems. Appreciate the use of science and technology to meet local, national, and global challenges, including problems of personal and community health, natural resources, environmental quality, and human-induced hazards.

- Present a historical perspective. View the history and nature of science as a human endeavor, producing new knowledge, supported by developing technology.

The MWM materials were also designed to address two complementary sets of goals for student achievement. One set of goals addresses content while the other targets skills. More specifically, the content goals target the science and technology principles. The process goals focus on the skills associated with thinking like a scientist, technologist, or an engineer. Together, these two sets of goals informed and guided the design of the activities that students performed in each module.

The content goals for the program are as follows:

- Learn scientific and mathematical principles by applying them to solve real-world problems
- Develop an understanding of the science and engineering of materials by applying knowledge from physical, life, and earth sciences to create materials for specific purposes
- Learn about the interrelationship between science and technology and their influences on local, national, and global environments
- Understand contemporary problems in society, including problems of personal and community health, natural resources, environmental quality, and human-induced hazards and appreciate the use of science and technology to meet these challenges
- View the history and nature of science as a human endeavor, producing new knowledge, supported by developing technology

The process goals for the modules are listed below.

- Ask and refine researchable, productive questions
- Plan and conduct a quantitative, hands-on laboratory investigation, using journals to guide investigation and record progress
- Work within a collaborative team to complete a design project
- Develop solutions through iterative design: challenge, problem definition comparing options, implementation, reflection, and redesign
- Develop a designer's eye to analyze trade-offs and decisions an engineer may encounter in creating artifacts

Conceptual Framework

Materials science is the study of the characteristics and uses of various materials, such as metals, ceramics, and polymers that are employed in science and technology. It is an interdisciplinary subject that employs and integrates concepts and techniques from a variety of disciplines, including chemistry, biology, physics, and mathematics.

The MWM program is an ongoing project that is dedicated to developing instructional materials that enrich existing high school science curricula with learning activities that show concrete linkages between the concepts and skills from various science disciplines and everyday life. Towards that end, the project structured its modules around topics that the authors believed were "critical" to a technological society. They also want to show how modern materials can be viewed as systems and disclose how they impact society. To date, nine modules have been published and the collection available to teachers includes the following titles.

- Biodegradable Materials
- Biosensors
- Ceramics
- Composites
- Concrete
- Food Packaging
- Polymers
- Smart Sensors
- Sport Materials

The following were recently developed and field-tested, but have not as yet been published.

- Bonding & Polarity
- Materials & the Environment
- Lights & Color
- Motion & Forces: Inquiry into Sports Equipment
- Properties of Solutions: Real-World Applications
- Biotechnology
- Electrical Conductivity
- Environment Catalysis
- Structure & Properties of Matter
- Introduction to the Nanoscale: Surface Area & Volume

The following two modules are currently undergoing field-testing.

- Manipulation of Light in the Nanoworld
- Nanoinvestigations: Measurement

Content

The following content analysis is limited to the modules that have been published.

<u>Biodegradable Materials</u> Students examine the attributes, advantages, and applications of biodegradable materials during this module. During the course of the module they will compare biodegradable and non-biodegradable packing materials, identify examples of biodegradable materials in everyday life, test the strength and compressibility of two gelatin-based films of varying density, measure the degradation rates of biodegradable materials, research biodegradable materials,

design a device for delivering medicine, and develop a new biodegradable material. The science concepts addressed include the meaning of the word biodegradable, natural versus synthetic polymers, natural degradation processes (i.e., microorganism, enzymes, hydrolysis, ultraviolet light), the nature of gelatin, the effects of temperature and pH on degradation rates, and the cross-linking of polymer chains. The technology content includes the invention of gelatin capsules and development biodegradable polymers.

Biosensors This module focuses on the nature and uses of biological molecules and biosensors. The lessons and activities include experimenting with biological molecules and bioluminescence, investigating enzymes and indicator molecules, making a peroxide biosensor, teaching a cholesterol biosensor, evaluating a home-use cholesterol biosensor, researching biosensors, and designing a glucose biosensor. The science addressed includes concepts related to bioluminescence and chemiluminescence (e.g., luciferase, luciferin, oxyluciferin), biological molecules (e.g., proteins, carbohydrates, lipids, nucleic acids), enzymes, peroxidase-catalyzed reactions, and cholesterol. The technology content includes the development and applications for common biosensors (e.g., home-use pregnancy tester, blood glucose tester for diabetics, testing for environmental contaminants, cholesterol testing).

Ceramics This module looks at the functions and properties of ceramics. The activities include categorizing materials like glass, metal and plastic based on their properties; identifying examples of ceramic objects and their applications; experimenting with ZnO powder; and exploring ways to eliminate porosity through slip casting. Students also examine how firing ceramics turns a weak, soft, and porous object into a dense, strong, and solid object. The design projects involve developing a low-clamping voltage suppressor and synthesizing a high-temperature superconductor. The salient science content includes classifying materials based on their properties (electrical conductivity, electrical resistively, thermal conductivity, chemical reactivity), the composition and characteristics of ceramics (especially, ZnO), the concepts of density and porosity. Some of the technology content focuses on historical as well as modern applications for ceramic materials. It also includes hydroplastic forming and slip casting. Lastly, the composition of semi-conductors is described and examined.

Composites During this module students study the characteristics, advantages, and application of composite materials. The activities include comparing pure ice with ice reinforced with paper, identifying examples of composite materials in everyday things, testing the strength and stiffness of a simple composite material, researching composite materials, designing a composite fishing pole, and developing a new composite material. During these activities, students study science concepts like natural versus synthetic composites, compressive and tensile forces on atoms, and strength versus stiffness. There is also a passing reference to covalent bonds, ionic bonds, metallic bonds, hydrogen bonds and van der Waals forces. The technology content focuses defining the term "composite materials," the different types of composite materials (i.e., particulate, laminar, fiber reinforced), the difference between structural and functional composite materials, historical examples of composite materials, and contemporary applications for composite materials.

Concrete The characteristics, advantages, and applications of concrete are the subjects of this module. It asks students to identify objects made of concrete in their surroundings; discover the physical and chemical changes in cement as it cures; compare the density, strength, and brittleness of different formulations of concrete; experiment with reinforced concrete. The design projects include developing a concrete roofing tile and creating a new product made out of concrete. The science content includes different kinds of cement and the concepts of hydration, compression, tension, and strength. The technology addressed in this unit includes the concept of infrastructure, historical and modern applications for concrete, the composition of concrete (i.e., cement, water, aggregates), and the concept and advantages of reinforcing concrete.

Food Packaging This module examines the properties and functions of food packaging. It begins with students taking apart and analyzing a bag for microwave popcorn. This is followed by analyzing different kinds of food packaging (e.g., the types of materials used, their properties, the function they serve), researching the materials used in food packaging, designing a protective package for tomato, and testing the insulating properties of packaging materials. The design project involves making a package that will keep a potato hot and developing an environmentally friendly package for a food item. The science content includes how various materials react to microwaves, concepts related to protecting food (e.g., potential energy, kinetic energy, absorbing energy), and concepts related to heat transfer and thermal conductivity (i.e., conduction, convection, radiation). The technology includes old as well as modern examples of food packaging, the materials used for food packaging, the environmental impact of food packaging, the protection function of packaging, and the techniques used to retain heat.

Polymers The subject of this module is the nature of polymers and their applications. During this unit students look at the absorption properties of polymer pellets and their potential use in gardening. They also identify common products made of polymers, compare the viscosity of liquids, and test the strength and water absorption of different polymer films. The design problems include designing a humidity sensor and developing a new product made out of a polymer. The science content includes the molecular composition of polymers and their ability to absorb water, natural versus synthetic polymers, the concepts related to polyethylene chains (e.g., linear polyethylene, branched polyethylene, cross-linked polyethylene), the relationship between molecular weight and viscosity, the factors that effect the strength of polymer film, and why adding polymers to paint provides a water barrier. The technology content includes different applications for types of polymers, how polymer films are manufactured, and the development of paint.

Smart Sensors Students study the features and applications of smart sensors in this module. Students begin by experimenting with a commercial piezoelectric motion detector and then they explore other kinds of sensors (their inputs, outputs, composition, and potential applications). The next lesson and activity engages them in making a piezoelectric microphone. This activity is followed by examining the piezo effect and the peizoelectric and pyroelectric responses of the polymer polyvinylidene fluoride (PVDF) film. The design problems involve developing a device that will count coins and inventing a new kind of sensor. The science content examines the sensitivity of materials to infrared radiation, plants that sense stimulus, the human ear as a natural sensor, the chemical structure of a piezoelectric material, and how PVDF works. The technology content looks at human-made sensors (piezoelectric sensors), practical applications for sensors, and the role of sensors in technological systems.

Sport Materials This module focuses on the characteristics of materials used for sports applications. Students study the features of different kinds of balls and speculate why they are made of different materials. Next, students measure the rebound of various balls using a drop test and investigate how materials absorb through deformation. They also look at how surfaces can impede how far a ball rolls and how well different kinds of balls roll across the same surface. Lastly, they compose a report about the materials used in a piece of sport equipment of their own choosing. The design problems include developing a mini-golf game and inventing an innovative piece of sports equipment. The science looks at the laws of nature acting on a golf ball, quantifying the performance of a ball by calculating its coefficient of restitution, the exchange of energy when a ball bounces, how molecular bonds absorb and release energy, and the impact of friction on the movement of objects (i.e., sliding friction, rolling friction, static friction). The technology looks at the composition of a golf ball and how its design reduces drag.

Most of the science concepts are presented in explanations that are similar to those one would find in an encyclopedia or trade book. The concepts are broken down into small pieces and presented in a logical sequence that progresses from simple to complex. Most of the explanations are supported with easy to understand analogies, common examples, and clear illustrations.

All of the modules feature scientific investigations that require students to declare their ideas by formulating hypotheses or making predictions. These hypotheses or predictions are tested with simple manipulatives that involve making observations, taking measurements, analyzing data, and presenting conclusions.

Most of the mathematics content is embedded in the various investigations that the students conduct (e.g., measurements, data analysis, graphing the relationship between two variables). The materials do not attempt to teach the mathematics that is required to quantify phenomena, to perform calculations, to analyze data, or to present results.

Engineering concepts and ways of thinking can be found in the culminating design problems at the end of each module. They all require students to apply what they have learned in previous lessons and laboratory activities to the development of a solution of a practical problem. The problems are typically presented in the context of a company that needs a new product. These problems often include a list of design constraints and, in some cases, minimum specifications for a successful design. The solutions developed by the students are always in the form of physical models that are constructed out of simple materials that are listed materials. More importantly, they can be tested and thus provide the data needed to determine the effectiveness of the design. In every case, students are asked to keep a design log that shows their brainstorming, thought processes, drawings, predictions, evaluation criteria, testing procedures, data, reflections, and results.

"The process we are using is relevant to teaching engineering. We pique their curiosity. They do some measurement. Once they get the feel of it, we try to get them to put it into words or simple equations. They develop a model and they test the model.."

Robert Chang

Pedagogical Principles

Each module in the series has three basic elements. First, instruction is initiated with an opening activity that is designed to create interest in the topic at hand. The introductory activity also requires the students to formulate a hypothesis about a cause and effect relationship related to the topic in question. Second, the introduction is followed by four or five hands-on learning activities that introduce the students to key principles, ideas, and methods related to the topic under study. Students conduct these activities in the context of one or more design problems. Lastly, each module culminates in a design project that requires the development of a prototype product as well as the application of the key materials science concepts and skills.

The contents and the design of the materials suggest the authors were attentive to the need for **scaffolding**, **continuity**, and **coherence**. All the modules clearly start with something relatively simple and they progress to more complex concepts and tasks in a very incremental and deliberate manner. Furthermore, each lesson features a series of modest narratives that link it to the previous lesson, describes how it connects to the next lesson, and ultimately how it applies to the culminating design problem.

Each module features a series of lessons that model basic pedagogical principles. More specifically, the lessons include clearly defined objectives, interest building strategies for initiating instruction, brief overviews, sequential learning activities, potential multidisciplinary connections, strategically placed reviews, ways for engaging students in reflection and lastly, strategies for assimilating content.

A Socratic approach to teaching and learning underpins the lesson instruction and students' learning activities. Questions can be found throughout the materials and they play prominent roles initiating lessons, exploring examples, guiding investigations, reviewing results, identifying applications, informing design projects, and checking for understanding.

All of the Materials World Modules are based on the pedagogical principle of "**inquiry through design**." More specifically, they are designed to engage students in scientific inquiry that helps them discover how materials science concepts and skills are applied to everyday design problems.

One of the fundamental premises underpinning the modules is the notion that doing scientific inquiry and addressing design problems can work together in a synergistic manner to help students to better understand science principles and develop scientific habits of mind. The authors believe engaging students in scientific inquiry helps them to uncover the important scientific principles that they need to address their design problem. Inversely, engaging students in design activities creates a genuine need to explore the scientific principles that will inform their solution to the design problem. This approach unites the abstract, quantitative methods of scientific inquiry with the concrete methods of technological design, helping students develop and integrate these complementary skills in a unique way.

"*What is unique about the US is we have the freedom to do this and that. We had to tap into that freedom to explore and try things. But we discovered we had to train students and adults how to ask good questions.*"

Robert Chang

The design problems are presented to students in scenarios that are typically framed in the context of a fictitious company that has a problem that needs to be solved. The teachers are given specific and detailed lists of the tools and materials that need to be available for the students to address the problem. Some of the design problems require students to develop multiple solutions to the problem, to test each prototype against the design criteria, and use the results to develop the optimal solution. Each design problem culminated with some form of reporting the thought processes, design, and testing results.

"I grew up with electronics — making radios from kits — going to the electronics store and finding things to make. I wanted the students to build something."

Robert Chang

Interdisciplinary education is another pedagogical principle that underpins the MWM materials. Mathematics, chemistry, physics, biology, and technology are typically taught as discrete subjects at the high school level. The architects of the MWM program espoused that the "compartmentalization of knowledge leads students to understand these fields as sets of decontextualized techniques and facts rather than integrated disciplines that complement each other and that are frequently used as instruments to solve real problems." Therefore, the MWM program strives to use materials science as an integrating context for studying science, mathematics, technology, and society. Instead of teaching principles of chemistry, physics, and mathematics in isolation of each other, the MWM program frames the instruction around real problems and societal issues that require students to draw on several disciplines at once. Furthermore, according to the projects leaders, “approaching science and technology with a social context helps students see how science is relevant to their lives, empowering them to make better decisions as citizens of the world.”

Curriculum Implementation

The Materials World Modules project offers workshops that are conducted by master teachers that have experience with the MWM materials. These workshops are conducted in what the MWM project calls “hub sites.” A hub site is a central location with approximately a 50-mile radius where 15 to 20 teachers can gather for training. The number of modules, the length of the training session, and number of teachers in attendance can vary from site to site. The agenda can include things like guest speakers from industry or the research community, feedback from field tests, discussions about reflective practice, demonstration of iterative design, techniques for composing questions, and classroom video clips.

Each workshop provides participants an overview of the pedagogical principles that were used to design the instruction in modules. The workshops also provide teachers an opportunity to experience the hands-on activities in the modules. The activities enable teachers to experience the scientific and technological techniques used in the module. The facilitators strive to familiarize teachers with the activities that their students will be doing in class. Due to their experience with the modules, they provide advice on how to best use the materials, address student misconceptions, encourage design ideas, and capitalize on interdisciplinary connections.

The teacher network provides a natural conduit for continuous exchange among the practitioners of the Materials World Modules (MWM). MWM is committed to establishing and cultivating informal communication and support networks among developers and users of these materials science modules. This kind of linkage is absolutely essential for supporting and stimulating teachers who implement curricular reform and for achieving long-term impact.

The MWM listserv provides a mechanism for ongoing dialog between the project staff, seasoned teachers, and teachers implementing the materials for the first time. Teachers use the listserv to exchange project design ideas, ask questions, and develop lessons. The network provides a medium for collaboration across schools, states, and even countries.

There are some costs associated with integrating one or more of the Materials World Modules into an existing curriculum. First, the teacher’s edition for each module costs $40. Student editions cost $14 each and a classroom set of 24 would cost about $336. Starter kits for conducting the laboratory activities cost between $142 and $417 depending on the module being implemented. Similarly, the refill kits for replacing consumables cost between $33 and $379.

Implementing a module can require one to three weeks of class time depending on the module being implemented, the number of enrichment activities included in the instruction, and the scope of the design project presented to the students. They can also be implemented in one of two ways. Selected modules can be used as self-contained units of instruction that supplement an existing high school or middle school science, math, or technology class. They can also be linked together in a series to form a one-year class. In light of the interdisciplinary nature of the modules, the course would be akin to those developed under the auspices of the Science, Technology, and Society (STS) movement.

Diffusion and Impact

The module on Composites was the first one developed, and it has been implemented in the widest range of high school and middle school classes. Smart Sensors, Biodegradable Materials, Concrete, and Sports Materials are also popular among various disciplines due to their interdisciplinary nature. The high school subjects that used the modules with the greatest frequency are chemistry, general science, and biology. Lastly, the Department of Defense Education Activity is currently implementing MWM modules in a STS curriculum in overseas high schools.

The Materials World Modules project reported that over 40,000 students in schools nationwide have used its materials. Extensive field-testing in 48 states has enabled the developers of the MWM program to solicit feedback from a wide range of teachers and students. Teachers in all subject areas reported that the use of the modules enabled students to make connections between concepts from the traditional curriculum and the world around them more frequently than ever before. They also identified numerous skills that students have demonstrated, both during and after the experience of using the modules in class. These skills fall into several categories, including:

- Laboratory skills: measuring, manipulating equipment, recording data, graphing, performing mathematical computations, devising and conducting controlled experiments, making predictions
- Communication skills: collaborating to achieve shared goals, brainstorming, explaining ideas to others, persuading, employing problem-solving strategies, working to reach a consensus, translating observations into discussion, employing new terminology and vocabulary in group work, leading other students
- Application of scientific and mathematical knowledge: exploring new ways to integrate scientific, mathematical, and technological concepts; synthesizing information to create a new product or design; preparing technical reports on computers using programs like Excel.

The latest round of field-testing focused on eight of the ten recently developed modules. *Environment Catalysis* and an *Introduction to the Nanoscale: Surface Area*

& Volume were not included because of conceptual differences in content and design. According to Dr. Chang, these results can be generalized to the original nine modules because they follow the same format and instructional design.

The modules in question were field-tested in 118 science classrooms addressing a wide range of topics (e.g., physical science, AP chemistry, biotechnology, physics, introduction to engineering). The field-test sites were randomly selected from 42 states representing six different regions of the nation. The project secured data representing 2,026 students with a return rate of 88.2 percent. Project leaders reported the following findings from their analysis of the data collected.

- The students across the 118 classrooms demonstrated an average gain of 31.75% in subject matter knowledge as a result of completing the modules.
- At least half of the students in each of the 118 classrooms reported improvements in the areas of teamwork, connecting science to everyday life, planning design projects, analyzing data, understanding science concepts, and overcoming failures.
- The teachers in the 118 classrooms reported their students improved in the areas of discussing design issues and design constraints, planning design projects, working as a member of a team, analyzing and overcoming failures, retaining science concepts, and being able to discuss materials science concepts.
- The students demonstrated statistically significantly gains on items that assess the level of “science esteem” in a classroom (e.g., science classes are interesting, I talk about science with my friends, I enjoy designing useful things, science labs help me overcome my own mistakes).
- Students liked the design projects more than the other module activities.
- Female students demonstrated higher achievement and design scores than their male counterparts.
- The field-test teachers felt the modules required teaching a lot of material in a two-week period of time. They also reported the modules were very professional, enriched their curricula, added depth to the concepts being addressed, and were engaging for their students.
- Most of the teachers reported that they planned to use the modules in the future. There was also feedback that suggests the money and time required to implement the modules was at odds with pressure to prepare students for standardized tests.
- Most of the teachers recognized how the module can be aligned with the National Science Education Standards, especially in the areas of Science Inquiry and Abilities of Technological Design.
- There wasn’t a relationship between student achievement and the teachers’ level of experience, but there was a correlation between class performance and teachers having Master’s degrees.